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Responses of 'Syrah' grapevine to deficit irrigation in the Brazilian semi-arid region

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ABSTRACT

Grapevine growing in areas with low rainfall as the Brazilian semi-arid requires irrigation to full fill plant water demand. The objective of this study was to evaluate the physiological and yield responses of grapevine to irrigation strategies in the Lower Middle São Francisco Valley, in Petrolina, State of Pernambuco, Brazil. The experiment was carried out over three consecutive growing seasons of drip irrigated 'Syrah' grapevine, grafted on 1103 Paulsen and planted in an Ultisol (Soil Taxonomy, USA). Full irrigation (FI), regulated deficit irrigation (RDI), and deficit irrigation (DI) treatments were designed in a randomized block with four replications. Mostly soil moisture depletion was observed until 0.6 m soil depth while higher moisture values and their small variation over the time were observed below 0.6 m and until 1.20 m depth as consequence of dense soil layers. RDI and DI promoted moderate water stress in plants (pre-dawn water potential from −0.2 to 0.4 MPa), reducing water consumption and gas exchange. Intrinsic water use efficiency was higher in RDI and DI (121 and 115 μmol CO_2 mol $H_20^{-1,}$ respectively). Tritratable acidity reduced to 5.81 and 6.28 g L^{-1} tartaric acid as water deficit increased, except in the third season. Soluble solids were influenced by treatments only in the second season, when it decreased in FI plants (22.6° brix). Weight of 100 berries was influenced by treatments in all seasons, with lower values for DI and RDI grapevines (less than 155 g). Number (15) and weight (2.2 kg) of cluster per grapevine and yield (7284 kg) were significantly higher in FI only in the third growing season, while average cluster weight was greater in FI in the first and third seasons (84 and 149 g, respectively). Irrigation water productivity did not differ among irrigation strategies. Deficit irrigation strategies allowed water saving.

1. Introduction

The cultivation of grapevine has extended worldwide and in Brazil it achieved 74.826 ha with a total grape production of 1.416.398 ton in 2020. In its semi-arid region, in Northeastern Brazil, significant area has been cultivated with grapes, being 8.299 ha in the state of Pernambuco and 1.969 ha in the state of Bahia in 2020 (IBGE, 2021). Around 48% of this total grape production has been destined to grape processing - wine, juice and other derived products (Mello and Machado, 2020). In 2019, Brazil stands at 81.000 ha of surface area vineyard (OIV, 2020b) and has an estimated wine production volume of 2.2 million of hectoliters in 2019 (OIV, 2020a).

Over the last few decades, the Lower Middle São Francisco Valley, along the border of states of Pernambuco and Bahia, has appeared as one of the main tropical wine production areas in that country, typically growing under irrigation conditions and trained mainly in vertical shoot-positioning systems. With proper irrigation and crop management practices, the farmers can produce grapes and carry out winemaking at any time of the year, allowing a potential average of between two and three vineyard-growing cycles per year, in accordance with and depending on each variety (Teixeira et al., 2017). Since then, there is an increasing demand for high-quality wine by winemakers in that region. As grapevine water demand is full filled by irrigation due to low rainfall pattern, one of the challenges facing winemakers is to improve grape quality in irrigated vineyards throughout an appropriate balance between vegetative and reproductive development (Souza et al., 2009).

In irrigated grapevines for wine production, it is important to know the effects of water supply on yield, grape composition and wine quality to achieve an adequate irrigation scheduling. Commonly, reduced soil water availability and/or plant water stress is performed for desirable

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outcomes as controlling plant vigor (Dry and Loveys, 1998; Chaves et al., 2007; Chacón-Vozmediano et al., 2020; Romić et al., 2020), enhancing berry quality for winemaking (Chaves et al., 2007; Acevedo-Opazo et al., 2010; Bucchetti et al., 2011; Zarrouk et al., 2012; Romero et al., 2015; Uriarte et al., 2016; Ramos et al., 2020), reducing water consumption by plants (Bassoi et al., 2007; Chaves et al., 2007; Acevedo-Opazo et al., 2010; Silva et al., 2018) and increasing intrinsic water use efficiency (Chaves et al., 2007; Silva et al., 2018; Romić et al., 2020). Limited water availability and climate changes (Trigo-Córdoba et al., 2015; Intrigliolo et al., 2016; Franck et al., 2020; Mirás-Avalos and Intrigliolo, 2020; Jordan and Speelman, 2020) also become a concern regarding the water addressed for irrigation in grapevines.

Deficit irrigation has emerged as a potential strategy to allow crops to withstand mild water stress with little or no decreases of yield, and potentially a positive impact on fruit quality. For this, the understanding of the physiological and molecular bases of grapevine responses to this water deficit is fundamental to optimize deficit irrigation management (Chaves et al., 2010). One of the most promising management irrigation techniques utilized in vineyards in semi-arid areas is regulated deficit irrigation (RDI) as it offers greater potential to reduce vine vigor, stabilize yield, improve berry quality and increase water use efficiency in different varieties and edaphoclimatic conditions (Romero et al., 2013). RDI strategy in wine vineyards implies dynamic irrigation according to the phenological stage, rather than simple implication of constant deficit irrigation. High water availability during early berry development enhanced vegetative growth and increased berry size and yield of ‘Merlot’ grapevines. Reducing water supply in order to create a certain level of drought stress during late berry development did not damage yield or berry maturation. RDI combining higher irrigation from flowering to bunch closure and lower irrigation from bunch closure to harvest has the potential to generate the best balance between vegetative growth, high yield and wine with enhanced color and aroma compounds (Munitz et al., 2017).

However, there are apparent contradictory results about the success of applying regulated deficit irrigation to achieve higher quality grapes, which may be related to the accuracy of plant water status monitoring to regulate and to manage the physiological changes imposed to the grapevines by deficit irrigation (Acevedo-Opazo et al., 2010; Romero et al., 2013). In Southern Portugal, irrigation did not significantly affect ‘Castelão’ and ‘Moscatel’ berry sugar accumulation and pH and those results were in contrast with other authors who observed either an increase or a decrease in berry sugars induced by high soil water availability (Chaves et al., 2007). In Northwestern Spain, the differences on plant water status, rainfed and irrigated ‘Godello’ and ‘Treixadura’ grapevines did not alter stomatal conductance and chlorophyll fluorescence, and irrigation increased yield only for ‘Treixadura’ in only one season of three evaluated. Must quality was slightly affected by irrigation, but differences were not observed in wines. Water productivity was greater in rain-fed vines in the case of Godello, whereas in ‘Treixadura’ no significant differences between treatments were detected. Gross incomes were not increased by the irrigation practice except for ‘Treixadura’ in the last year (Trigo-Córdoba et al., 2015). Reducing irrigation water supply from 100% to 70% of crop evapotranspiration (ETc) between fruit set to harvest slightly decreased mid-day leaf water potential and no impact on leaf gas exchange, canopy development, yield and intrinsic water use efficiency of ‘Cabernet Sauvignon’ vines in Southeastern Washington, USA (Keller et al., 2016). Meanwhile, the effects of post-veraison deficit irrigation (0.25, 0.50, and 0.75 ETc) on ‘Cabernet Sauvignon’, water use efficiency decreased with increasing water application and this effect was statistically significant in the more irrigated treatment (Intrioglio et al., 2016). Mirás-Avalos and Intrigliolo (2017) reported that despite the huge amount of work aiming at assessing the effects of water status on vine yield and grape composition, no clear relationships could be established between stem water potential and berry size and composition. This is due to the large number of factors involved in grape composition development, indicating that water status might not be its main driver. Cultivar, timing of exposure to water restrictions and rootstock have a great influence on must and wine composition. Nevertheless, other factors, such as climate, leaf surface/yield ratio, training systems, amongst others, might interact with water stress and salinity.

‘Syrah’ is the most cultivated wine grapevine in the Lower Middle São Francisco Valley. High solar radiation availability and irrigation feasibility throughout the year make the grapevine cultivation possible any time. Therefore, deficit irrigation practices in ‘Syrah’ grapevines in that region have been previously studied on physiological and yield bases. In the first three growing seasons, yield difference appeared only in the third one, with higher cluster weight for full irrigated (FI) grapevines, followed by regulated deficit irrigated (RDI) and deficit irrigated (DI) plants, while average cluster weight was lower in DI in the first and third seasons. Differences on soluble content were found only in the third season (lower for FI), while titratable acidity was always lower for DI grapevines (Bassoi et al., 2011, 2015). The authors found at maximum moderate plant water stress in DI grapevines by measuring pre-dawn leaf water potential. Still in relation to that region, wines originated from grapes from RDI and DI vines showed higher values of alcohol content, malic and lactic acids, flavonols, stilbenes, anthocyanins, epicatechin, epicatechin gallate and procyanidin A2, TPI, and color intensity, and can be classified as aged wine, while wine originated from full irrigation vines showed the highest values of ascorbic and tartaric acids, lowest alcohol content and phenolic compounds in general, and can be classified as young wines. This enabled the production of wines with specific characteristics that should please many consumers with different tastes (Nascimento et al., 2016; Oliveira et al., 2018).

Thus, the major goal of this study was to investigate the yield and ecophysiological mechanisms in ‘Syrah’ grapevines cultivated under deficit irrigation practices in Lower Middle São Francisco Valley.

2. Material and methods

2.1. Experimental site

The experiment was carried out at in vineyard located at Experimental Field of Bebedouro, Embrapa Semi-Arid, in Petrolina, state of Pernambuco, Brazil (latitude 9° 8′ 8.09’’ S, longitude 40° 18’ 33.6’’ W, altitude 373 m). The soil is classified as a medium-textured Typic Acrustox (Souza et al., 2009) with plain landscape. The grapevine ‘Syrah’ grafted on Paulsen 1103 rootstock was planted on 30 Apr 2009. Plants were spaced 1.0 m within rows and 3.0 m between north-south oriented rows (Bassoi et al., 2015). An espalier trellis system was used and grapevines were trained on a bilateral Royat Cordon and spur-pruned. The first, second and third wires were 0.8 m, 1.3 m, and 1.8 m above the ground, respectively.

The work reported here in was carried out during three consecutive growing seasons, with pruning and harvesting, respectively, on 10 Apr 2013 and 9 Aug 2013 (first growing season - 1GS), 8 Oct 2013 and 28 Jan 2014 (second growing season – 2GS), and 7 May 2014 and 3 Sep 2014 (third growing season – 3GS). Growing season lengths were 121, 112 and 119 days, respectively, for 1GS, 2GS, and 3 GS.

2.2. Irrigation system and management

An on-surface drip irrigation system was used with emitters spaced at 0.5 m within the plant row, with a flow rate of 2.5 L h^{-1} measured in field test, at pressure of 100 kPa. The replacement of soil nutrients was carried out by means of fertigation in each season, applying 20 kg ha^{-1} of N and 40 kg ha^{-1} K_2O. The fertilizers used were urea and potassium sulfate.

The reference evapotranspiration (ETo, mm) was daily estimated by Penmam Monteith method (Allen et al., 1998) using data measured by an automatic weather station installed in the field, about 60 m from the experimental plot. The crop evapotranspiration (ETc, mm) was estimated by the product of ETo and the crop coefficient (kc). The kc values (Bassoi et al., 2007) were used observing the occurrence of phenological phases according to Baggiolini (1952): 0.7 - from pruning to bud burst, remaining the same value during the phases of initial leaf development, separated clusters and early flowering; 1.0 - from early flowering until the beginning of berry ripening; 0.8 - from the beginning of maturation to ripe cluster; and 0.5 - from ripe cluster to harvesting. During the period between growing seasons (resting time) the kc adopted was 0.3. The irrigation time was calculated by Eq. (1):

$$IT = ETc \cdot S_1 \cdot S_2 \cdot k_r / E_a \cdot n \cdot q_e \quad (1)$$

where IT is irrigation time (h), ETc is the crop evapotranspiration (mm dia^{-1}), S_1 and S_2 are the plant and row spacings (m), k_r is reduction factor previously determined I a field test (0.5), E_a is the application efficiency (0.9), n is the number of emitters per plant, and q_e is the flow rate emitter (L h^{-1}). Irrigation was performed on daily basis (five days a week) in FI treatment and until the interruption of water application in RDI and DI treatments. Rainfall was taken in account to adjust IT, subtracting it from the ETc. According to Myburgh (2004), canopy effects on rainfall interception in vineyards are relatively small.

2.3. Irrigation strategies

Three irrigation strategies were evaluated. In the full irrigation (FI), water was applied for the replacement of the crop evapotranspiration (ETc, mm), throughout the growing season. In the regulated deficit irrigation (RDI), irrigation was performed until the phenological phase of close cluster (Baggiolini, 1952), when maturation has already started, and then irrigation was performed according to the soil water monitoring in the effective root depth (0.60 m) (Bassoi et al., 2002, 2003), when soil water storage at this layer reached around 50–60% of its capacity. In 1GS, irrigation occurred until 43 days after pruning (dap) and thereafter, 64, 65, 83, 84, 85, 103, 104 and 105 dap (13 and 14 June; 2, 3, 4, 22, 23 and 24 July 2013). In 2GS, water was applied until 45 dap, and then at 62, 99, 100 and 101 dap (9 Dec 2013; 15, 16 and 17 Jan 2014). In 3GS, irrigation was performed up to 51 dap, and later at 82, 83, 97, 98 and 99 dap (28 and 29 July; 12, 13 and 14 Aug 2013). In the irrigation deficit (ID), water was applied until 43, 45 and 51 dap (phenological stage of close cluster) in 1GS, 2GS, and 3GS, respectively, and then irrigation was cut-off until harvesting.

The experimental design was a randomized complete block with three irrigation treatments (FI, RDI and DI), with four replications. Each plot consisted of 48 grapevines in two rows with 24 plants each, and 12 of them (middle portion of plot) were used for measurements.

2.4. Fertigation

The replacement of soil nutrients was carried out by means of fertigation in each season, applying 20 kg ha^{-1} of N and 40 kg ha^{-1} K_2O. In all growing seasons, the fertilizers used were urea and potassium sulfate and they were weekly applied in all irrigation strategies until flowering and before irrigation interruption in RDI and DI treatments.

2.5. Plant and soil water relations

The pre-dawn (Ψ_{pd}) and the mid-day (Ψ_{md}) leaf water potentials were measured on two expanded leaves using the Scholander pressure chamber (Model 1000, PMS Instrument Co., Corvallis, OR, USA), in each treatment at two different times, from 03h00 to 04h00 and from 12h00 to 13h00, respectively. Leaves were collected from the median portion of branches in different plants and in each of four replicates per treatment. The Ψ_{pd} and Ψ_{md} measurements were performed at 57, 68, 85 and 111 dap (6 and 17 June and 4 and 10 July 2013) in 1GS; at 63 and 99 dap (10 Dec 2013 and 15 Jan 15 2014) in 2GS; and at 78 and 107 dap (24 July and 22 Aug 2014) in 3GS, between phenological stages of close cluster and mature cluster.

Soil water content (θ) was determined by neutron moderation technique (503 Hydroprobe, CPN, Concord, CA, USA), in 12 aluminum tubes installed inside the plant rows and between two emitters, four by strategy. Measurements were taken before and after irrigation at depths of 0.15, 0.30, 0.45, 0.60, 0.75, 0.90, 1.05 and 1.20 m. Probe was previously calibrated in the experimental plot.

2.6. Gas exchange

The grapevine gas exchange was assessed only in third growing season, using a portable infrared gas analyzer - IRGA (Model LI-6400XT, Li-Cor, Lincoln, NE, USA) described in A. R. M. Chaves et al., (2016). Measurements of net photosynthesis (A), transpiration (E) and stomatal conductance (g_s) were initiated before the interruption of irrigation in RDI and DI treatments, and were ended close to harvesting. Evaluations were carried out after 51, 79 and 107 dap. Measurements were performed at four different times throughout the day (07h00, 10h00, 13h00 and 15h00), always the same adult and healthy leaves which showed good and uniform characteristics as color, age and size.

2.7. Yield

In harvesting of all growing seasons, the number and weight of cluster per plant were assessed, for subsequent estimation of average cluster weight (g) and yield (kg ha^{-1}).

2.8. Irrigation water productivity and water use efficiency

The irrigation water productivity (IWP) for each treatment and in all growing seasons was obtained by the ratio between yield (kg ha^{-1}) and applied irrigation water (m^3 ha^{-1}), as described by Fernández et al. (2020).

The instantaneous water use efficiency and intrinsic water use efficiency (WUE) were estimated, respectively, by (A/E) and (A/g_s) ratios, as described by During (1994) and Flexas et al. (1998).

2.9. Berry analysis

In each harvesting, and in each repetition per treatment, 200 berries were collected on opposite sides of the cluster in the upper, middle and basal regions, packed in plastic bags, and transported inside styrofoam boxes with ice to the Laboratory of Enology at Embrapa Semi-Arid. The mass of 100 berries was determined by a digital scale. Afterwards, berries were macerated and their must was used for analyses of soluble solid content (SS, °Brix), using portable refractometer ATAGO brand, Pocket PAL 1 model; of titratable acidity (TA) expressed in g L^{-1} of tartaric acid, according to IAL (2005); and of pH, using digital gauge.

2.10. Carbon isotopic composition ($\delta^{13}C$)

In the harvesting of 1GS, berries were collected from opposite sides of the cluster, and at its upper, median, and basal portions. The berries were packed, frozen and transported to the Centre for Stable Isotopes, Institute of Biosciences, Sao Paulo State University, Botucatu, Brazil. $^{13}C/^{12}C$ isotopic ratios of the must samples were obtained according to Dutra et al. (2011).

2.11. Statistical methods

ANOVA (F test at 5% probability) and Tukey test at 5% probability were performed using SISVAR version 4.0. (DEX/UFLA, Lavras, MG, Brazil).

3. Results and discussion

3.1. Growing season, weather and irrigation data

Higher ETo and ETc values were observed in 2GS than the others, because it occurred in the period of year with the highest ET demand in Petrolina. However, in that season, there was a high magnitude rainfall, specifically between 66 and 75 dap, during which there was no irrigation. Hence, gross irrigation depth (GID) in FI treatment was slightly lower than in other two seasons (1GS and 3GS). There were no high magnitude rainfalls in 1GS and 3GS seasons (Table 1). In the experimental site the lower rainfall pattern observed in 1GS (April to August) and 3GS (May to September) is usually observed in that period of the year (autunn and winter seasons) while 2GS (October to January) was carried out within the spring and summer seasons in which rainfall pattern is higher.

3.2. Soil water content

As GID applied was the same for all treatments until the beginning of irrigation interruption at 43, 45, and 51 dap, respectively for 1GS, 2GS, and 3GS, which means that there were no major differences in θ values among all treatments until these dates, but subsequently, θ up to 0.60 m depth in RDI and DI has become smaller than FI treatment (Figs. 1, 2, and 3). It is noteworthy that for the edaphic conditions in Lower Middle São Francisco Valley, the effective depth of the root system of irrigated grapevine was 0.60 m (Bassoi et al., 2002, 2003). However, in 2GS (Fig. 2), it happened a lower influence of irrigation on θ behavior after the interruption of water application than in 1GS (Fig. 1) and 3GS (Fig. 3), due to higher rainfalls from 70 to 76 dap (146 mm). In RDI, when irrigation was performed based on θ monitoring, an increase of θ was observed up to 0.45 m depth in 1GS (Fig. 1) because of water application at 64, 65, 83, 84, 85, 103, 104 and 105 dap, and in 3GS (Fig. 3) because of irrigations at 82, 83, 97, 98 and 99 dap. In 2 GS (Fig. 2) this increase of θ in RDI occurred up to 0.60 m depth because of water application at 62, 99, 100 and 101 dap but in that season it happened a lower influence of irrigation on θ behavior after the interruption of water application, due to higher rainfalls from 70 to 76 dap (146 mm). In the deeper soil depths (0.75, 0.90, 1.05, and 1.20 m), θ increased over the time until the irrigation interruption, and after that decreased slightly in 1GS and 3GS (Fig. 1, and 3, respectively), except in 2GS (Fig. 2) as consequence of the high magnitude rainfalls.

The increase in the density of an Ultisol in depth in areas of the semiarid region of Northeastern Brazil under natural vegetation (Caatinga biome) and under irrigation in Petrolina was evaluated from the soil surface down to a depth of 1 m, in 10 cm layers, using computed tomography, and results suggest a density increase at depths below 0.4 m (Fante Junior et al., 2002). The presence of these hardsetting soil layers are common in that region in consequence of changes in the arrangement of soil particles (structure), decreasing pore volume and increasing soil density and mechanical resistance to penetration of roots, water and nutrients. A simple texture gradient and a double layer of clay accumulation are presented between the surface and subsurface soil horizons soils (Silva et al., 2004). This subsurface hardsetting is due to pedogenetic processes like eluviation and iluviation of clay which acts as pore sealing, as well as plinthitization processes and clay dispersion, influenced by alternate cycles of wetting and drying (Silva et al., 2008). Then, this soil condition which occurs in an Ultisol is crucial for the presence of higher values of θ in deeper soil depths of that area which has been irrigated throughout the year and for several years, since grape production is an intensive agricultural exploitation under irrigation in that region. It is important to highlight that shallow soils probably do not provide water storage to plants below effective rooting zone, which makes relevant the importance of soil survey for deficit irrigation purposes.

Table 1
Growing seasons of wine grapevine 'Syrah', reference evapotranspiration (ETo), crop evapotranspiration (ETc), rainfall (R) and gross irrigation depth (GID) in full irrigation (FI), regulated deficit irrigation (RDI) and deficit irrigation (DI) treatments.

	First season – 1GS Apr 10 - Aug 9 2013	Second season – 2GS Oct 8 2013-Jan 28 2014	Third season – 3GS May 7 - Sep 3 2014
Length (day)	121	112	119
Total ETo (mm)	624.2	703.5	596.7
Average ETo (mm day^{-1})	5.1	6.2	5.0
Maximun ETo (mm day^{-1})	7.4 (35 dap, 15 May)	10.4 (95 dap, 11 Jan)	9.4 (115 dap, 30 Aug)
Total ETc (mm)	460.0	528.1	431.1
Average ETc (mm day^{-1})	3.8	4.7	3.6
Maximum ETc (mm day^{-1})	6.7 (29 dap, 9 May)	9.4 (23 dap, 31Oct)	7.4 (80 dap, 26 Jul)
Irrigation interruption	43 dap*, 23 May	45 dap*, 22 Nov	53 dap*, 28 Jun
Total R (mm)	25.4 (14 +21.4**)	219.2 (19.8 +199.4**)	15.5 (5.1 +10.4**)
Total GID FI (mm)	494.6	410.7	464.8
Days of irrigation FI	79	59	85
Average GID FI (mm)	5.0	7.0	5.6
Total GID RDI mm)	253.3	284.0	248.8
Days of irrigation RDI	39	36	42
Average GID RDI (mm)	5.6	7.9	5.9
Total GDI DI (mm)	209.6	266.6	226.4
Days of irrigation DI	29	33	37
Average GID DI (mm)	6.3	8.1	6.1

dap - days after pruning; *rainfall before and after irrigation interruption in RDI and DI treatments

3.3. Leaf water potential

The measurements of leaf water potential in 1GS are shown in Fig. 4, left. At 57 dap, there were differences regarding Ψ_{pd} and Ψ_{md} among FI treatment and others (RDI and DI), which did not differ. From the second reading (68 dap), Ψ_{pd} and Ψ_{md} only differentiated between FI and DI treatments. The FI treatment plants showed Ψ_{pd} values close to or below −0.20 MPa, indicating that in this treatment grapevines showed good water conditions (Ojeda, 2007). The Ψ_{pd} values of RDI and DI treatments characterized a level of water restriction as light to medium (−0.2 to −0.4 MPa), except at 111 dap in DI treatment, which showed water restriction level of between medium to strong (−0.4 to −0.6 MPa), as pointed out by Ojeda (2007).

The Ψ_{pd} values found in this study are slightly below those found (−0.6 MPa and – 0.4 MPa) for the grapevine subjected to water deficit during two growing seasons in Valencia, Spain (Intrigliolo and Castel, 2009). Souza et al. (2009) and Chaves et al. (2010) found Ψ_{pd} values close to - 0.2 MPa in grapevine 'Syrah' submitted to water deficit.

In 2GS, there were only two Ψ measurements, due to rainfall which occurred after the irrigation interruption in the RDI and DI treatments (Fig. 4, middle). The Ψ_{pd} values of FI treatment were also close to – 0.20 MPa, indicating good plant water status, while RDI and DI treatments were lower, between - 0.20 and - 0.40 MPa, with a light to moderate water restriction level. At 63 dap, Ψ_{pd} and Ψ_{md} values of RDI and DI treatments did not differ between them but were different from the FI treatment. However, at 99 dap, Ψ_{pd} values of DI treatment did not differ statistically from the other treatments. Regarding Ψ_{md}, their

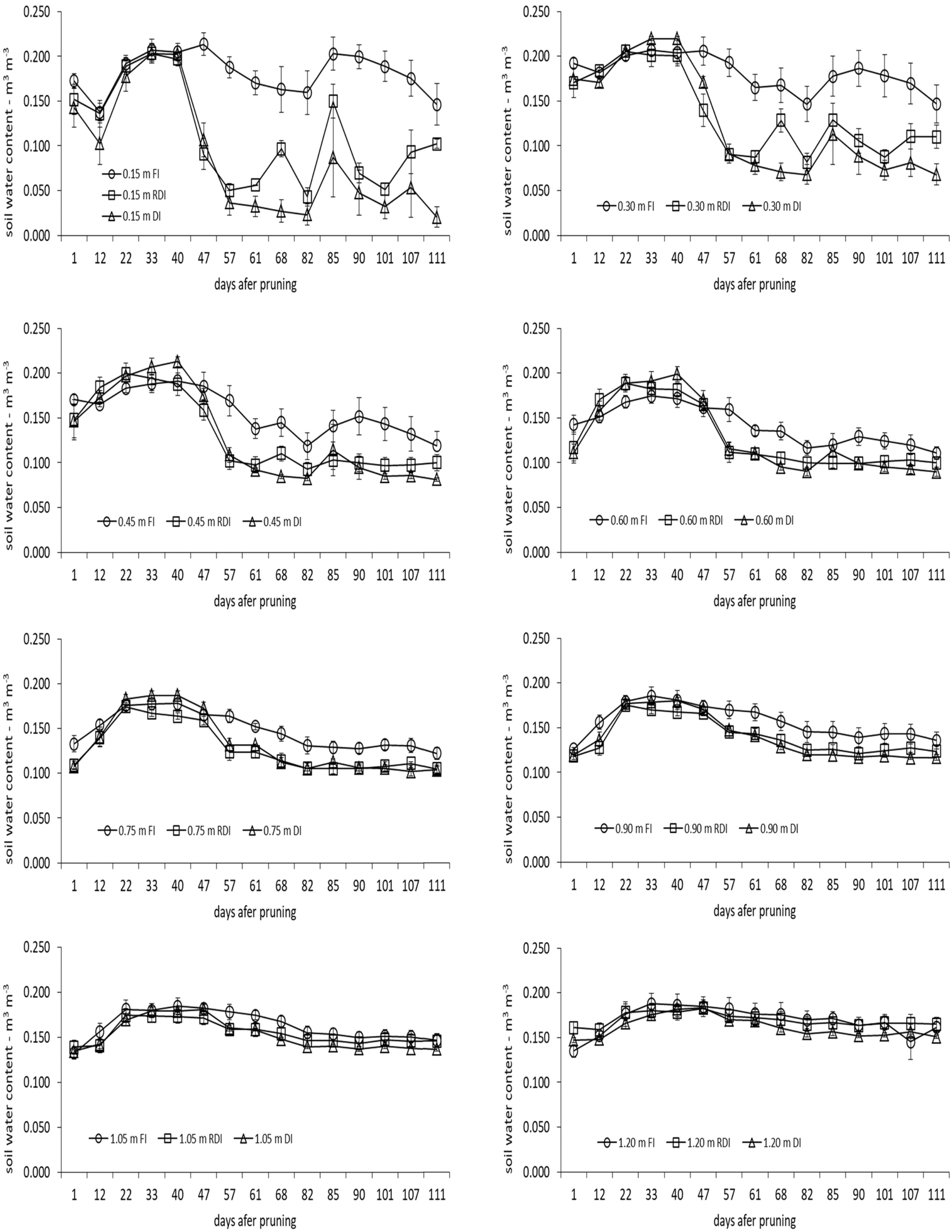

Fig. 1. Soil water content (average value com standart error) at several depths throughout the first growing season of 'Syrah' grapevines under full irrigation (FI), regulated deficit irrigation (RDI) and deficit irrigation (DI) strategies. Irrigation was interrupted at 43 days after pruning.

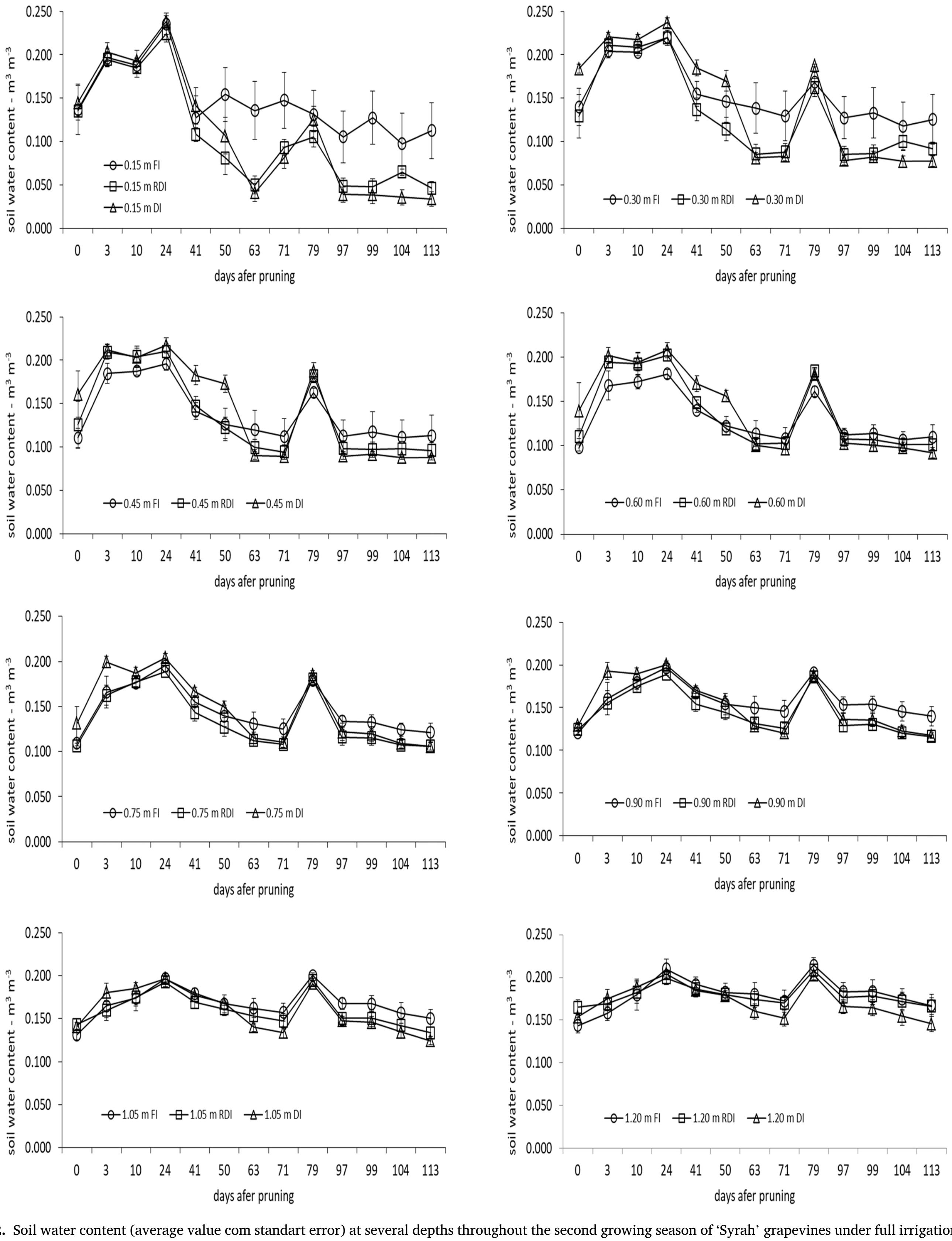

Fig. 2. Soil water content (average value com standart error) at several depths throughout the second growing season of 'Syrah' grapevines under full irrigation (FI), regulated deficit irrigation (RDI) and deficit irrigation (DI) strategies. Irrigation was interrupted at 45 days after pruning.

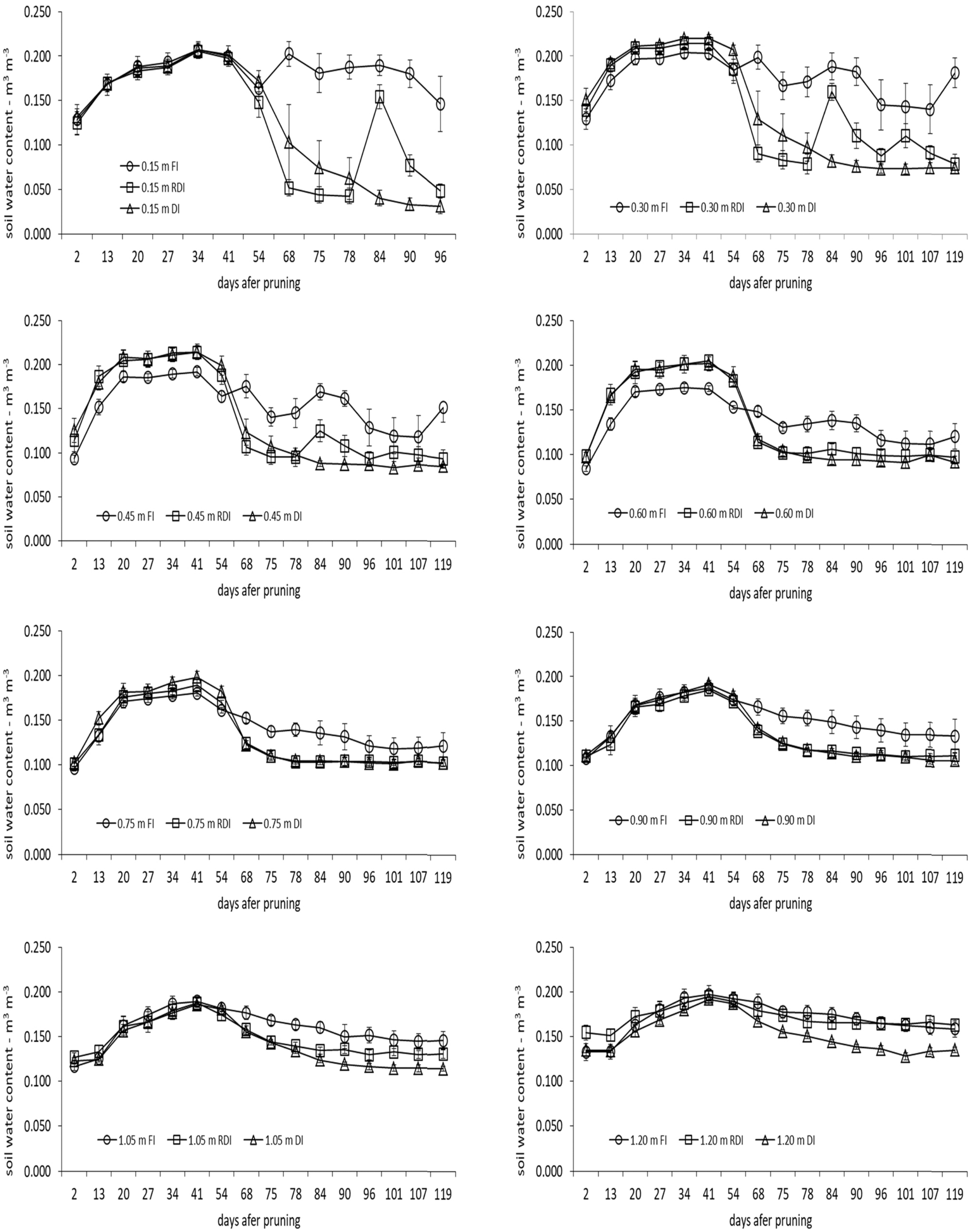

Fig. 3. Soil water content (average value com standart error) at several depths throughout the third growing season of 'Syrah' grapevines under full irrigation (FI), regulated deficit irrigation (RDI) and deficit irrigation (DI) strategies. Irrigation was interrupted at 51 days after pruning.

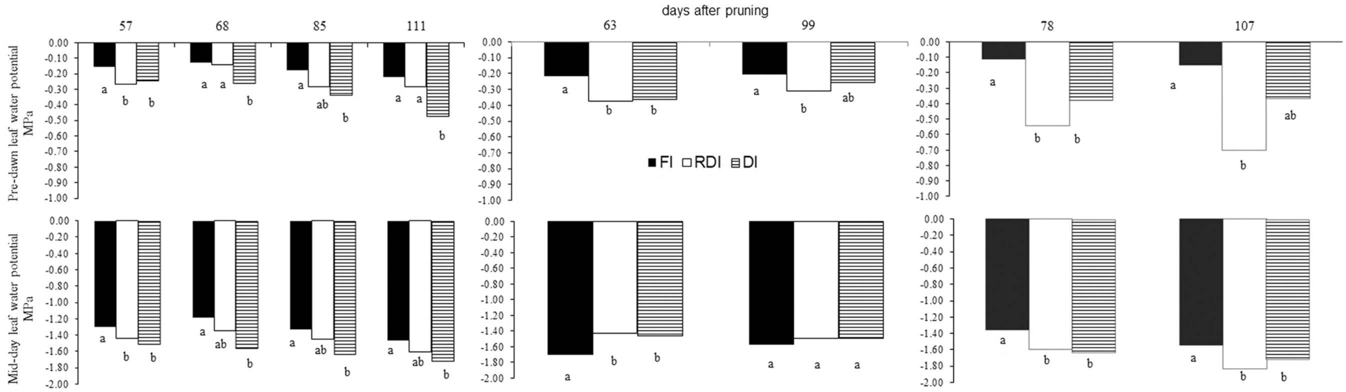

Fig. 4. Pre-dawn and mid-day leaf water potential on first (left), second (middle) and third (right) growing seasons of 'Syrah' grapevines under full irrigation (FI), regulated deficit irrigation (RDI) and deficit irrigation (DI) strategies.

values did not differ among treatments. This was possibly due to rainfall occurred during the second growing season.

In 3GS (Fig. 4, right), Ψ_{pd} values of FI treatment at 78 dap were higher than the RDI and DI treatments. However, at 107 dap, FI and RDI treatments differed between them but DI didn't differ from both. The FI treatment showed values above −0.20 MPa, indicating good plant hydration, while RDI plants were −0.54 MPa and - 0.70 MPa, presenting medium to strong water restriction levels. DI treatment presented readings near −0.4 MPa indicating light to medium water restriction level. The Ψ_{md} was higher in the FI treatment. The Ψ_{md} values were lower than those of Ψ_{pd} due to higher deficit of vapor pressure which occurs during the day, causing increased transpiration and consequently, lower hydration plant (Pinheiro et al., 2004).

3.4. Carbon isotopic concentration

The main factor that affects the $^{13}C/^{12}C$ ratio is water stress (Farquhar et al., 1989; Yu et al., 2021), and higher values of $\delta^{13}C$ indicate less discrimination due to lower values of intercellular CO_2 and more efficient water use (Farquhar et al., 1982; Buchmann and Kaplan, 2001). In 1GS, the FI treatment had lower values than RDI and DI treatments, confirming the presence of greater water stress in the grapevines. This result is due to stomatal closure in plants under water stress, confirmed by the results of g_s, having greater values of $\delta^{13}C$. A similar behavior was observed in grapevines with and without water deficiency (Souza et al., 2005). Gaudillere et al.(2002) studied the variation of the water status in different varieties of grapevines and obtained $\delta^{13}C$ values for the 'Syrah' grapevine of − 23.7‰, higher compared to the present study. A comparison of the effect water deficiency with $\delta^{13}C$ can be used with good precision on grapevines subjected to water stress. $\delta^{13}C$ is related to the ratio *Ci*/*Ca* and IWP. Moreover, most of the $\delta^{13}C$ change in yield grapevines was related to water stress and demonstrated a significant correlation between $\delta^{13}C$ measured in sugar of ripe berries and plant water status measured as the minimum predawn leaf water (Gaudillère et al., 2002).

3.5. Gas exchange and water use efficiency

The gas exchange measurements in 3GS were performed at 51, 79 and 107 dap (Fig. 5), and no differences were observed at 51 dap because the water depth applied up to this data had been the same for all treatments. In the results of net photosynthesis (*A)*, transpiration (*E*) and stomatal conductance (g_s) at 79 and 107 dap, large reductions occurred in RDI and DI in comparison with FI treatment plants due to water restriction imposed by the irrigation interruption and higher soil water availability in FI strategy. Stomata closed when plants are under water stress in order to avoid complete leaf dehydration. Then, CO_2 diffusion is limited to the leaf mesophyll which causes photosynthesis decrease (Chaves et al., 2009). In the field, plant stomatal closure controls water loss and midday leaf water potential and as grapevine is an isohydric species (Tardieu and Simonneau, 1998) it promotes high IWP related net photosynthetic activity and describe tolerant genotypes to water deficit (Jones, 1983).

Higher *A* rates were found by Santos et al. (2013) in an experiment conducted in the same field and with the same grapevine cultivar without water restriction with measurements between 08h00 and 10h00, which is comparable to FI treatment. Chaves et al. (2010) reported higher *A* values in 'Syrah' grapevines under drought in Southern Portugal, which is comparable to DI and RDI irrigation strategies. Romero et al. (2013) found minimum *A* values in grapevines under water restriction in semi-arid region of Spain. The g_s response of plants under different irrigation strategies was similar to *A* values indicating stomatal closure in plants subjected to water stress and decrease in CO_2 assimilation. These values were also found by Chaves et al. (2010) in 'Syrah' grapevines under drought. Stomatal conductance of *Vittis vinifera* with water availability were higher in Teszlák et al. (2013), which are higher when compared to the FI treatment of this study. This result may have been caused by climatic factors, as the high vapor pressure deficit recorded during the measurements in this study (Fig. 6), with maximum values near to 4 kPa.

Besides being distinct mechanisms, *A* and *E* are associated by leaf stomata aperture and closure that connect the plant to the atmospheric air and by which plants perform their gas exchange. At 79 dap, *E* decreased in RDI and DI plants due to stomatal closure caused by water deficit and consequently lower *A*. The FI treatment showed the highest average *A* values since there was a water replacement according to plant needs, thus indicating the influence of the treatments on grapevine physiological behavior. This is also presented in the Ψ_{pd} and Ψ_{md}, also indicating medium level of water stress. This study showed variation of *E* values of RDI and DI treatments and below from those obtained by Souza et al. (2009) in 'Syrah' grapevine under DI irrigation strategy.

The complex mechanism of plant gas exchange is an important factor in semi-arid conditions, which decreases *E* and consequently, the *A*, growth and production. Thus, there is a connection between *A* and *E* and to better evaluate this duality it is necessary the analysis of the water use efficiency by the instantaneous efficiency of water use (*A*/*E*) or intrinsic efficiency of water use (A/g_s) ratios (During, 1994; Flexas et al., 1998). At 79 and 107 dap, RDI and DI plants showed higher values of the A/g_s and FI treatment had lower one (Fig. 6). In semi-arid conditions the plants with good soil water availability have higher *A* and g_s (Intrigliolo and Castel, 2009), as in the present work on FI treatment, with lower values of A/g_s. Grapevines under moderate water deficit usually present *E* rates decline, with pre-dawn leaf water potential lower than stomatal conductance. As a result, the A/g_s is generally higher in grapevine under

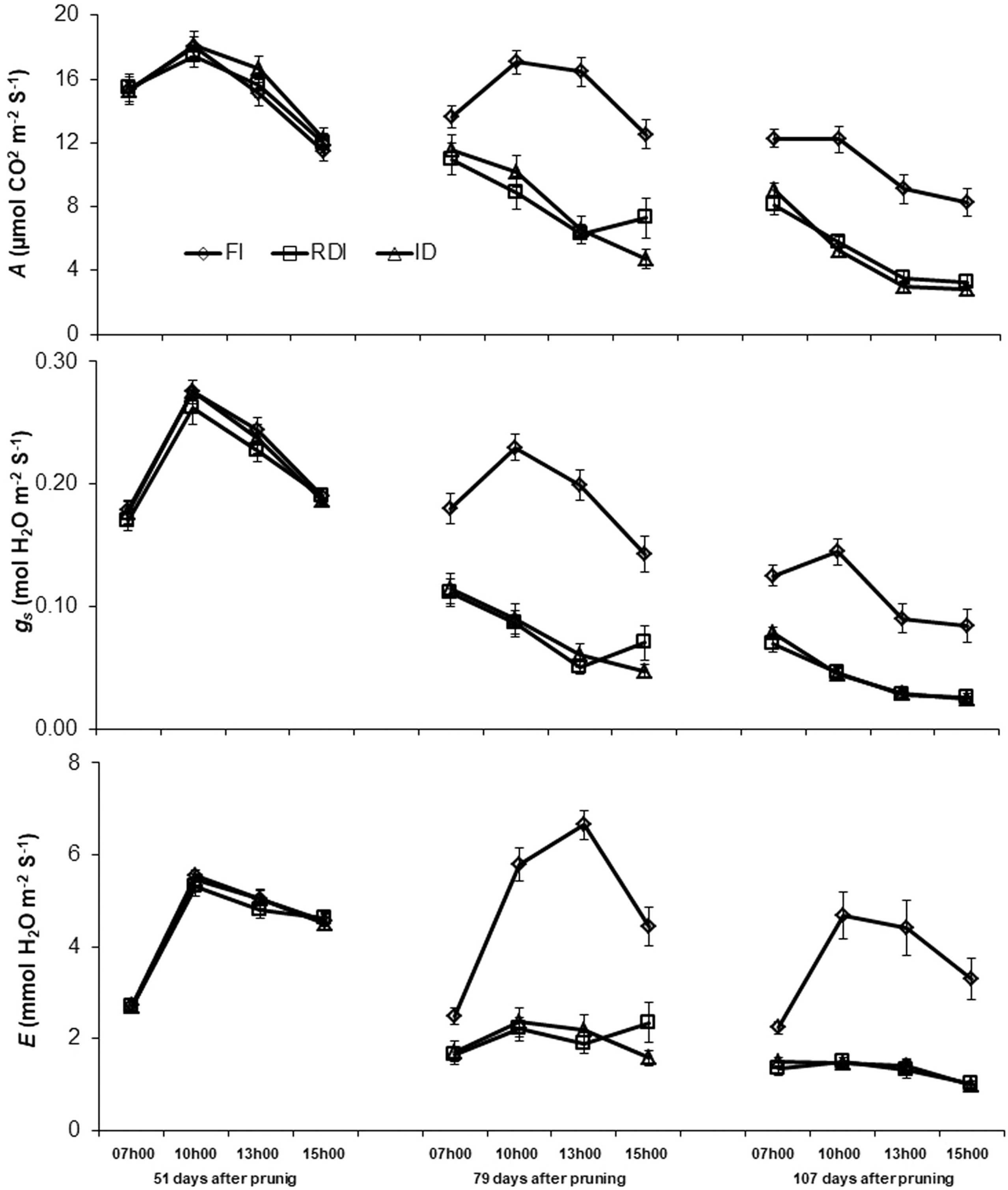

Fig. 5. Net photosynthesis (*A*), stomatal conductance (g_s) and transpiration (*E*) in the third growing season of 'Syrah' grapevines under full irrigation (FI), regulated deficit irrigation (RDI) and deficit irrigation (DI) strategies.

deficit irrigation (light to moderate water stress) than under well-watered conditions. This is reflected in lower water use and higher A/g_s by crops, which is the objective of deficit irrigation strategies applied in vineyards, especially in semi-arid region (Gaudillère et al., 2002; Chaves and Oliveira, 2004; Souza et al., 2005). The results of A/E in FI treatment presented lower values in the measurements taken at 07h00 and 10h00 (Fig. 6), due to lower VPD in the first hours of the day, higher stomata aperture in RDI and DI grapevines, as well as higher *A* and lower *E* values (Fig. 5), and consequent increase of the A/E.

Measurements taken at 13h00 and 15h00 presented most VPD, decreasing *A* due to decreased g_s in both deficit irrigation strategies, and no difference related to A/E occurred in these times among all treatments. Measurements of the C_i/C_a at 79 dap, and at all times (Fig. 6), were higher in the FI treatment. This result can be confirmed by higher

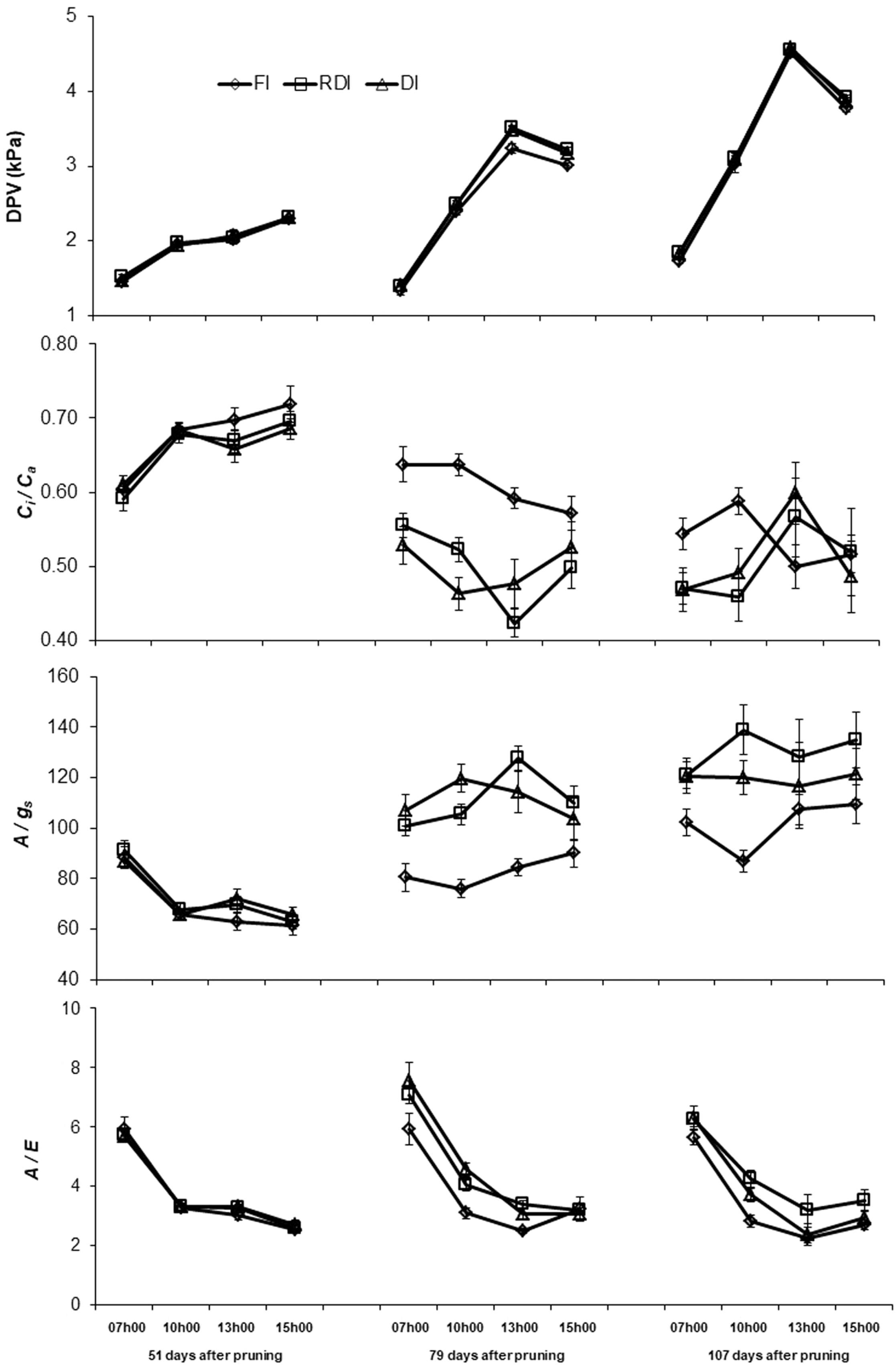

Fig. 6. Vapor pressure deficit (VPD), intracellular CO_2 concentration and environment CO_2 concentration ratio (C_i/C_a), intrinsic water use efficiency (A/g_s) and instantaneous water use efficiency (A/E) in the third growing season of 'Syrah' grapevines under full irrigation (FI), regulated deficit irrigation (RDI) and deficit irrigation (DI) strategies.

average values of A, g_s and E in FI treatment (Fig. 5). Grapevines under water deficit (RDI and DI) presented lower g_s values (partial stomatal closure) and lower (C_i/C_a) values in plants of the RDI and FI treatments, which indicate stomatal limitation. In order to reduce excessive water loss in proportion to an increase in VPD, the plants promote the stomata closure, but this limited the entry of CO_2 with consequent reduction in A (M. M. Chaves et al., 2016).

3.6. Yield components

Total number and weight of cluster per grapevine and yield presented significant differences ($p < 5\%$) only in 3GS, while average cluster weight differed among treatments in 1GS and 3GS, decreasing as irrigation water restriction increased (RDI and DI) (Table 2). Specifically in 2GS, high CV values for number of cluster per vine, average cluster weight, cluster weight per vine, yield and IWP were found due to high rainfall (166.4 mm) which occurred from 66 to 75 dap, after irrigation interruption at close cluster (45 dap). In Chile, Acevedo-Opazo et al. (2010) reported high CV values of 'Cabernet Sauvignon' grapevine measurements under RDI, i.e., cluster per plant (28.2–30.5%), cluster weight (22.3–25.1%), and yield (36.0–42.3%). In Southern Italy. Sofo et al. (2012) found CV values of 50.0% and 50% in yield, 29.4% and 29.3% in number of cluster per plant, 50.6% and 47.1% in cluster weight, respectively, for irrigated and non-irrigated 'Agilanico' grapevines.

Table 2
Number of cluster per grapevine, average cluster weight, cluster weight per grapevine, yield and irrigation water productivity (IWP) in full irrigation (FI), regulated deficit irrigation (RDI) and deficit irrigation (DI), in three consecutive growing seasons of 'Syrah' grapevine.

	Treatment	First season – 1GS Apr 10 - Aug 9 2013	Second season – 2GS Oct 8 2013 - Jan 28 2014	Third season – 3GS 7 May - 3 Sep 2014
Cluster per grapevine	FI	17.10 a	10.43 a	14.55 a
	RDI	15.73 a	9.38 a	14.26 ab
	DI	15.36 a	6.65 a	11.98 b
	CV (%)	13.74	24.82	7.91
	LSD	4.79	4.75	2.33
Average cluster weight (g)	FI	84.41 a	83.81 a	148.88 a
	RDI	69.01 ab	80.29 a	119.00 b
	DI	66.02 b	70.35 a	106,14 b
	CV (%)	11.18	8.00	10.52
	LSD	17.74	13.56	28.45
Cluster weight per grapevine (kg)	FI	1.45 a	0.89 a	2.19 a
	RDI	1.13 a	0.76 a	1.70 ab
	DI	1.03 a	0.47 a	1.28 b
	CV (%)	17.26	33.41	19.09
	LSD	0.45	0.51	0.71
Yield (kg ha^{-1})	FI	4834.00 a	2945.34 a	7283.63 a
	RDI	3779.75 a	2514.99 a	5654.59 ab
	DI	3425.51 a	1558.75 a	4261.00 b
	CV (%)	17.18	33.51	19.07
	LSD	1494.87	1700.50	2371.64
IWP (kg m^{-3})	FI	0.93 a	0.47 a	1.52 a
	RDI	1.35 a	0.50 a	2.14 a
	DI	1.46 a	0.32 a	1.76 a
	CV (%)	21.01	32.09	16.31
	LSD	0.57	0.30	0.64

CV - coefficient of variation. LSD - least significant difference. Means followed by same letter do not differ at 5% probability by Tukey test.

3.7. IWP

IWP did not differ among irrigation strategies in all seasons despite the marked effects on leaf gas exchange, because lower water supply was associated with some lower yield components, i.e., cluster per grapevine in 3GS, average cluster in 1GS and 3GS, and cluster weight per grapevine and yield in 3GS (Table 2). In Southeastern Spain, RDI saved more water and was more efficient in water use from a productive point of view than 40% of the ETc throughout the 3-year period of 'Monastrell' (Romero et al., 2013). Over 4 year period, Romero et al. (2015) did not find differences related to IWP in 'Monastrel' irrigated by partial rootzone drying and RDI. Intrigliolo et al. (2016), in Valencia, Spain, and Keller et al. (2016), in Washington State, USA, did not find differences on IWP in three growing seasons of 'Cabernet Sauvignon' grapevines under water replacement based on total or partial values of ETc. The highly linear relationship between biomass produced and water consumed by a given species has been demonstrated (Steduto et al., 2007).

3.8. Berry characteristics

No differences occurred in berry pH among treatments in all seasons. Soluble solids were influenced by treatments only in 2GS, when it decreased in well-watered plants (FI). Finally, weight of 100 berries was influenced by treatments in all seasons, with lower values for DI (1GS and 2GS) and RDI (3GS) grapevines (Table 3). Tritratable acidity differed between FI (higher value) and DI (lower value) in 1GS and 2GS, as reported by Bassoi et al. (2011, 2015). Uriarte et al. (2016) observed the quality berry parameters in 'Tenpranillo' in four seasons and among irrigated (25%, 50% and 100% of ETc) and rainfed grapevines. No differences were observed in pH and TSS, but TA increased with irrigation in three seasons. Similar results were reported herein.

3.9. Differences among growing seasons

The efficiency of deficit irrigation practices in modulating water use

Table 3
pH, soluble solids, tritratable acidity and weight of 100 berries in full irrigation (FI), regulated deficit irrigation (RDI) and deficit irrigation (DI), in three consecutive growing seasons of 'Syrah' grapevine.

	Treatment	First season – 1GS Apr 10 - Aug 9 2013	Second season – 2GS Oct 8 2013 - Jan 28 2014	Third season – 3GS May 7 - Sep 32,014
pH	FI	3.67 a	3.65 a	3.44 a
	RDI	3.66 a	3.66 a	3.52 a
	DI	3.58 a	3.69 a	3.56 a
	CV (%)	1.80	0.94	6.76
	LSD	0.14	0.07	0.51,
Soluble solids (°brix)	FI	22.4 a	22.6 b	20.7 a
	RDI	23.1 a	24.3 a	20.9 a
	DI	22.3 a	25.1 a	20.9 a
	CV (%)	4.26	2.42	2.54
	LSD	2.09	1.26	1.15
Tritratable acidity (g L^{-1} tartaric acid)	FI	6.64 a	7.33 a	7.90 a
	RDI	5.96 ab	6.81 ab	7.43 a
	DI	5.81 b	6.28 b	7.91 a
	CV (%)	5.93	4.35	3.63
	LSD	0.79	0.64	0.61
Weight of 100 berries (g)	FI	141.78 a	153.01 a	167.05 a
	RDI	139.64 a	144.42 ab	129.31 b
	DI	121.66 b	136.53 b	155.95 ab
	CV (%)	2.85	5.03	11.33
	LSD	8.29	15.79	37.06

CV - coefficient of variation. LSD - least significant difference. Means followed by same letter do not differ at 5% probability by Tukey test.

efficiency, growth and grape berry composition is dependent on the variety characteristics (vigor and drought avoiding traits), the type of soil and the prevailing weather (rainfall and temperature), as commented by Chaves et al. (2010). Ramos et al. (2020) also observed that due to different climatic conditions recorded during 10 years, differences in the grape composition during maturation were observed, both in timing and in the final characteristics. Weather conditions, mainly rainfall and ET, varied among all seasons evaluated, since they occurred in different periods of the year, and consequently the volume of water applied through drip irrigation system differed too. Therefore, plant responses have changed from one growing season to another.

4. Conclusion

We evaluated the regulated deficit irrigation and deficit irrigation strategies, applied from the close cluster stage to harvesting, in comparison with full irrigation over three consecutive growing seasons of drip irrigated 'Syrah' grapevine in the semi-arid region of Northeastern Brazil. The soil investigated herein presents hardsetting layers at soil depths below effective rooting zone of grapevine (0.4–0.6 m). This condition promotes a higher soil water availability at deeper soil profile (between 0.6 and 1.0 m depth) even when deficit irrigation strategy is applied. Consequently, moderate plant water stress and decreased on plant water consumption were observed in all growing seasons. Irrigation water productivity did not differ among irrigation strategies in all seasons, but intrinsic efficiency of water use was higher when deficit irrigation was applied. A small reduction on average cluster weight was observed in two growing seasons due to water restriction. Soluble solid content differed just in 2GS, while tritatable acidity was different among treatments in 1GS and 2GS. Hence, deficit irrigation strategies can be applied for water saving purposes. and monitoring soil water content at profile will be helpful for that. Future research should address alterations in canopy size and microclimate as weel as a long term observation as deficit irrigation should led to a decline in vine capacity and yield. Deeper analysis of berries and wines should be worthly too.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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