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Olive oil quality response to irrigation cut-off strategies in a super-high density orchard

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ABSTRACT

An increase in olive oil consumption has occurred worldwide in the last decades and has resulted in more land area being dedicated to olive orchards in several southern hemisphere countries. In order to achieve sustainable productivity under the increasing water scarcity, optimal water use is essential. Thus, a field experiment was conducted during four consecutive growing seasons (2010–2011 to 2013–2014) to evaluate olive oil quality in response to irrigation cut-off strategies applied after fruit set using midday stem water potential (Ψ_{stem}) thresholds in a super-high density olive orchard (cv. Arbequina) located in the Pencahue Valley, Maule Region, Chile. The experimental design was completely randomized with four treatments and four replicates. In treatment T_1 (control), Ψ_{stem} was between -1.4 and -2.2 MPa (100% of actual evapotranspiration) throughout the season, while the T_2, T_3 and T_4 treatments did not receive irrigation from fruit set until they reached a Ψ_{stem} threshold of approximately -3.5, -5.0, and -6.0 MPa, respectively. Once these thresholds were reached, irrigation was reestablished and maintained as T_1 in all treatments until olives were harvested. Fruit oil and water content (%) at harvest were not affected by the different treatments. Free acidity was also not affected, while peroxide and extinction coefficients only showed minor differences between treatments that were within the limits established for commercial extra virgin oil quality. Total polyphenols at harvest were much higher in the water deficit treatments and showed a significant linear relationship each year with the water stress integral. The percentages of the main fatty acids were not affected by the treatments. However, they were significantly different between seasons. Sensory tests indicated that the higher total polyphenol content positively contributed to more pronounced bitter and pungent attributes of olive oil from trees with higher water deficit. Thus, the irrigation cut-off strategies evaluated at our four-year study can be an excellent management tool to both improve the oil quality of cv. Arbequina and reduce water use in super-high density orchard.

1. Introduction

In recent years, the consumption of olive oil has increased worldwide, even in countries that do not have a long-standing tradition of olive growing (Morello et al., 2006). This is due in part to olive oil being linked to lower incidences of cardiovascular and neurodegenerative diseases, type 2 diabetes and even cancer (Guasch-ferre et al., 2015; Mateos et al., 2013; Pérez-Jiménez et al., 2007). In order to meet the new demand for olive oil, new plantations have been established in many parts of the world including South American countries such as Chile and Argentina (García-González et al., 2010; Rondanini et al., 2011). Irrigation application is common in these new orchards, which are increasingly being planted in higher densities (≥1000 trees ha^{-1}) and trained as hedgerows to allow for a more efficient use of mechanical harvesters (Fernandes-Silva et al., 2013; Gómez del Campo, 2013a, 2013b). Under this scenario, the cultivar that best adapts to mechanical harvesting is 'Arbequina', due to its small size, precocity and branch flexibility (Gómez del Campo, 2013b; Torres and Maestri, 2006).

The application of irrigation water has become common in olive orchards because several studies have proven the benefits of water supply on olive yield (Lodolini et al., 2014; Martín-Vertedor et al., 2011; Moriana et al., 2003; Patumi et al., 1999, 2002; Tognetti et al., 2007). However, the increasing water scarcity globally and the increased water demand for other uses in our society has caused pressure to reduce the water used in irrigation (Fereres and Soriano, 2007). For

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this reason, regulated deficit irrigation (RDI) has been suggested for optimizing water application in super-high density olive orchards (Fernández et al., 2013; Gómez del Campo, 2013a, 2013b). In this regard, cutting-off irrigation until reaching a predetermined water potential threshold can be used as a management tool to save water without affecting fruit and oil yields (Dell'Amico et al., 2012; Trentacoste et al., 2015).

Irrigation does not often affect the oil concentration in the fruit (on a dry weight basis). Therefore, the oil yield is mostly affected by RDI strategies when fruit number and subsequent yield are reduced (García et al., 2013; Gómez-Rico et al., 2007; Iniesta et al., 2009; Patumi et al., 2002). Based on this information, RDI strategies may have an advantageous effect since water use efficiency for olive oil production increases (Iniesta et al., 2009). Moreover, trees grown under RDI strategies often have similar, or even better, olive oil quality compared to trees that are well irrigated (Fernandes-Silva et al., 2013). García et al. (2013) found that irrigation strategies do not significantly affect parameters of oil quality such as free acidity, peroxide value, and extinction coefficients (K_{232}, K_{270}). Moreover, Motilva et al. (2000) observed that the application of RDI strategies applied to cv. Arbequina induced a significant increase in polyphenol concentration and oil stability. Fernandes-Silva et al. (2013) also observed that total polyphenols were strongly related to the water stress integral. Furthermore, Gómez del Campo and García (2013) observed that the application of RDI in summer caused a significantly higher oxidative stability, which coincided with a significantly higher content of phenol derivatives. These compounds are of great interest because they influence the quality and the palatability of olive oils and increase their shelf life by slowing the formation of polyunsaturated fatty acid hydroperoxides (Abaza et al., 2005).

Moreover, olive oil fatty acid composition is often not affected by RDI strategies (Motilva et al., 2000), although other studies indicate that irrigation strategies cause small variations in the oleic and palmitic acids (Dabbou et al., 2010; Fernandes-Silva et al., 2013). Genotype (i.e., cultivar) and environmental conditions appear to have a stronger effect on the oil's fatty acid composition, especially for palmitic and oleic acids (Borges et al., 2017; Rondanini et al., 2011). Among the environmental factors, temperature can play an essential role in fatty acid composition (Hernández et al., 2011). In this context, García-Inza et al. (2014) indicated that high temperatures increase polyunsaturated fatty acid content (linoleic and linolenic acids).

Deficit irrigation can also influence the sensory attributes of olive oil. In cultivars such as 'Arbequina', which normally has low phenolic concentrations, deficit irrigation is beneficial due to the greater polyphenol concentrations. More phenolics contribute to better balanced oils with a more sophisticated pungent and bitter flavor (Fernandes-Silva et al., 2013). Deficit irrigation can also reduce hay-like and greasy defects in olive oils (Dabbou et al., 2010).

In the literature, it has been reported that irrigation cut-off strategies in olive trees (cv. Morisca) have caused decreased shoot growth using a Ψ_{stem} threshold value of -2.0 MPa (Moriana et al., 2012). Also, this strategy with a Ψ_{stem} threshold value of -2.5 MPa increased water productivity twofold with respect to the control (Ψ_{stem} around -1.2 MPa). However, oil yield may not necessarily be reduced with such strategies. While Moriana et al. (2012) observed that oil yield (cv. Morisca) decreased using a Ψ_{stem} threshold of -2.0 MPa, Trentacoste et al. (2015) indicated that oil yield (cv. Frantoio) was not significantly affected using a Ψ_{stem} threshold of -2.5 MPa. Finally, Ahumada-Orellana et al., 2017 indicated that oil yield (cv. Arbequina) was also not reduced when irrigation was cut-off from fruit set until reaching a Ψ_{stem} threshold $= -3.5$ MPa, but it was significantly decreased with Ψ_{stem} thresholds < -5.0 MPa. Despite these assessments of oil yield, there is little information about the effect of irrigation cut-off on the olive oil quality. For this reason, the objective of this study was to evaluate the effect of irrigation cut-off strategies on quality attributes of monovarietal extra virgin olive oil from cv. Arbequina.

2. Materials and methods

2.1. Site description and experimental design

The site description and experimental design are described in detail by Ahumada-Orellana et al. (2017) who evaluated the yield and water productivity responses to irrigation cut-off strategies applied after fruit set using Ψ_{stem} thresholds in a super-high density olive orchard. Briefly, an experiment was conducted during four consecutive growing seasons (2010–2011 to 2013–2014) in a 6-year-old drip-irrigated olive orchard (*Olea europaea* L. cv. Arbequina) located in the Pencahue Valley, Maule Region, Chile (35°, 232′ L.S; 71° 442′ W; 96 m altitude). The olive trees were trained under a hedgerow system with a planting density of 1333 tree ha^{-1} (1.5 × 5.0 m) and irrigation was performed using two 2.0 L h^{-1} drippers per tree using good quality water pumped from a nearby river. At the experimental site, the climate is Mediterranean with rainfall occurring mostly during the winter months, and the soil has a clay-loam texture with a field capacity and wilting point of 31 and 16 $cm^3\ cm^{-3}$, respectively.

The olive water requirements were calculated according to the standard FAO56 approach for crop evapotranspiration (ETc = ETo × Kc) where ETo is the reference evapotranspiration (mm day^{-1}) and Kc is the crop coefficient. Climate data for calculating ETo were collected from an automated weather station installed over a reference grass and located about 2 km from the experimental site. Values of ETo were estimated using the Penman–Monteith equation (Allen et al., 1998; Ortega-Farías et al., 1995) while those of Kc were between 0.56 and 0.42 (see López-Olivari et al., 2016).

The experimental design was completely randomized with four treatments (T_1, T_2, T_3 and T_4) and four replications (five trees per replication). T_1 was irrigated with 100% of ETc during the growing season (from September to April). For T_2, T_3 and T_4, the irrigation was cut-off from fruit set (about 20 days after full bloom) until reaching Ψ_{stem} thresholds of approximately -3.5, -5.0 and -6.0 MPa, respectively. Upon reaching these thresholds, the irrigation was restored and maintained as T_1 in all treatments until olives were harvested. It is important to indicate that the period after fruit set always coincides with high atmospheric demands for water vapor and pit hardening which is the least sensitive to water deficit (Goldhamer, 1999; Gómez del Campo and García, 2013).

2.2. Plant water status measurements

The midday stem water potential (Ψ_{stem}) was measured weekly to monitor plant water status. These measurements were performed between 12:30 and 14:00 h (Gómez del Campo et al., 2008; Moriana and Fereres, 2002) using two apical twigs per plot from the current year (with at least 10 leaves), located in the middle of the canopy (Rousseaux et al., 2008; Secchi et al., 2007). These twigs were covered in the canopy with a plastic bag and aluminum foil for 1–2 h before the measurements (Meyer and Reicosky, 1985). Thereafter, the twigs were removed from the tree for measurement using a Scholander-type pressure chamber (PMS Instrument Company, Model 1000 Pressure Chamber Instrument) (Scholander et al., 1965).

Lastly, in order to describe the accumulated effect of the irrigation cut-off strategies, the water stress integral (SΨ) was calculated (Myers, 1988) as:

$$S_{\Psi} = \left|\sum (\overline{\Psi}_{stem} - c)n\right| \tag{1}$$

where Ψstem is the average of stem water potential for any interval (MPa), c is the value of the maximum stem water potential during the season, and n is the number of the days in each interval (Ahumada-Orellana et al., 2017; Moriana et al., 2007).

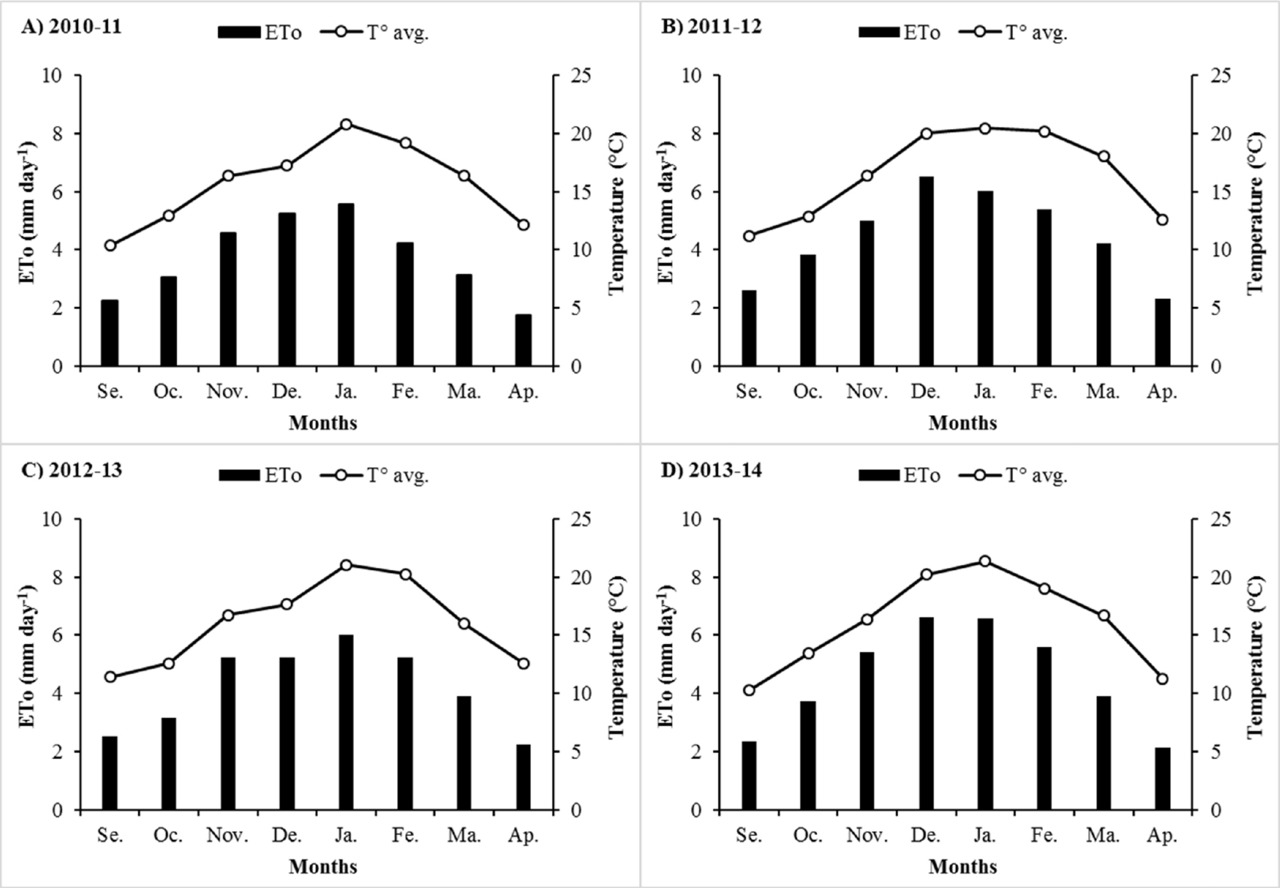

Fig. 1. Daily reference evapotranspiration (ETo) and average temperature (T° avg) for each month during the 2010–11, 2011–12, 2012–13 and 2013–14 growing seasons.

2.3. Fruit maturity index, water content and oil content

At harvest, fruit were handpicked from each tree using small rakes. Fruit were harvested manually on 130, 131, 134, and 127 DOY in 2011, 2012, 2013, and 2014, respectively. Fruit were separated from leaves and a sample was taken per plot (25–30 kg per treatment). In the laboratory, the water content of the olive paste was determined by desiccation and oil content by Soxhlet extraction, which was expressed as a percentage of fresh olive paste weight (Martín-Vertedor et al., 2011).

Moreover, a sample of 100 olives from each plot was used for calculating the fruit maturity index (MI). The 100 olives were distributed in eight groups according to the color of their skin and pulp. Group 0, bright-green skin; group 1, green-yellowish skin; group 2, green skin with reddish spots; group 3, reddish-brown skin; group 4, black skin with white pulp; group 5, black skin with < 50% purple pulp; group 6, black skin with > 50% purple pulp; and group 7, black skin and purple pulp. Finally, MI was calculated as (Garcia and Yousfi, 2005):

$$MI = \frac{\sum ini}{100} \tag{2}$$

where i is the group number and *ni* the number of olives in each group.

2.4. Oil quality

Free acidity was determined as the percentage (%) of oleic acid. Peroxide value (PV) was expressed as milliequivalents of active oxygen per kilogram of oil (meq O2/kg). Extinction coefficients (K_{232}, K_{270} ΔK) were measured in a spectrophotometer at wavelengths of 232, 266, 270 and 274 nm (Frías Ruiz et al., 2001). Total polyphenols were determined by a colorimetric method using the Folin-Ciocalteu reagent by spectrophotometry at 725 nm. The result was expressed as ppm of caffeic acid (Tsimidou, 1998).

The oil fatty acid composition was determined by gas chromatography (Frías Ruiz et al., 2001). In this study, the main oil fatty acids were palmitic acid, palmitoleic acid, stearic acid, oleic acid, linoleic acid and linolenic acid. Moreover, the following variables were calculated based on the fatty acid composition:

$$\text{Saturated fatty acid (SAFA)} = \text{palmitic acid} + \text{stearic acid} \tag{3}$$

$$\text{Unsaturated fatty acid (UNFA)} = \text{palmitoleic acid} + \text{oleic acid} + \text{linoleic acid} + \text{linolenic acid} \tag{4}$$

$$\text{Monounsaturated fatty acid (MUFA)} = \text{palmitoleic acid} + \text{oleic acid} \tag{5}$$

$$\text{Polyunsaturated fatty acid (PUFA)} = \text{linoleic acid} + \text{linolenic acid} \tag{6}$$

2.5. Sensory analysis

Sensory analysis of olive oil from each of the treatments was evaluated by quantitative descriptive analysis (QDA), which was carried out by five evaluators. The samples were provided in blue glass tumblers covered with another glass at room temperature (approximately 20 °C). Each evaluator classified the following terms: olive fruit, apple, other fruits such as almonds and nuts, bitter, pungent, sweet and cut-grass on a numerical scale from 0–5 with 0 being imperceptible and 5 being an extreme perception of the intensity.

2.6. Statistical analysis

Treatment effects were evaluated by analysis of variance (ANOVA) using the statistical software Infostat (Universidad Nacional de Córdoba, Argentina). The significant differences among the treatments

Table 1
Daily maximum, minimum and mean daily temperature (°C) during the fruit growth period and the latter period of oil accumulation for each season.

Seasons	Fruit growth period[Y]			Latter period of oil accumulation[Z]		
	T. max.	T. min.	T. avg.	T. max.	T. min.	T. avg.
2010 − 11	26.6	7.7	17.1	20.8	4.4	12.2
2011 − 12	28.7	8.2	18.3	23.3	3.9	12.8
2012 − 13	28.3	7.5	15.5	24.2	3.6	12.6
2013 − 14	29.1	6.7	17.7	21.9	2.1	11.3

[Y] Period of fruit growth is defined as the period from fruit set to harvest.

[Z] Latter period of oil accumulation for each season refers to the last 40 days before harvest.

were assessed using Tukey's multiple range test ($P < 0.05$). A regression analysis was performed to determine the relationship between water stress integral and total polyphenols.

3. Results

3.1. Environmental conditions

The accumulated effective rainfall ranged beetwen 12.6 and 84.9 mm with maximum and minimum values observed during 2010–2011 and 2011–2012 growing seasons, respectively. Both daily ETo and daily average temperature showed a similar pattern with maximum values occurring during December and January for this southern hemisphere location (Fig. 1). Cumulative ETo ranged between 986 and 1099 mm while daily average temperatures were between 15.5 and 18.3 °C for the four growing season. Furthermore, during the latter period of oil accumulation (i.e., the 40 days before harvest), the lowest and highest values of daily maximum temperature were observed during the 2010–11 and 2012-13 seasons, respectively (Table 1). Under these climatic conditions, the net irrigation amount for T_1 was between 183 and 268 mm season^{-1} (Fig. 2). For the four seasons, the water application for the T_2, T_3, and T_4 treatments ranged between 75 and 83, 62–76 and 56–70% of T_1, respectively.

3.2. Plant water status

The plant water status was described in detail by Ahumada-Orellana et al. (2017). The water status of each treatment is briefly described below. The plant water status was similar for all treatments between the start of the irrigation season (October) and fruit set (i.e., the start of water restriction). In treatment T_1, Ψ_{stem} values oscillated between −1.3 and −2.2 MPa throughout the first season of study, whereas in the other three seasons some lower values (i.e., a minimum of −2.8 MPa) did occur late in the summer when ETo was high. The treatments with irrigation cut-off strategies (T_2, T_3 and T_4) decreased their Ψ_{stem} progressively from the start of water restriction at fruit set until their predetermined threshold value was reached. The T_2 treatment reached its minimum value (−3.5 MPa) during pit hardening after about 35 days without irrigation. The T_3 treatment reached its minimum Ψ_{stem} (−5.0 MPa) 49–53 days after irrigation cut-off, except for the 2012–13 season, where it was 71 days. The T_4 treatment reached the Ψ_{stem} threshold of around −6.0 MPa after 67–78 days without irrigation for most seasons, but in the 2012–13 growing season, it reached a minimum Ψ_{stem} of only −5.2 MPa after 97 days. Once these minimum values were reached, the irrigation was restored in the T_2, T_3, and T_4 treatments and their Ψ_{stem} returned to values similar to those of the T_1 treatment at harvest. The average water stress integral ($S\Psi$) for the T_1 through T_4 treatments was 100.1, 125.2, 210.1, and 255.4 MPa day^{-1}, respectively.

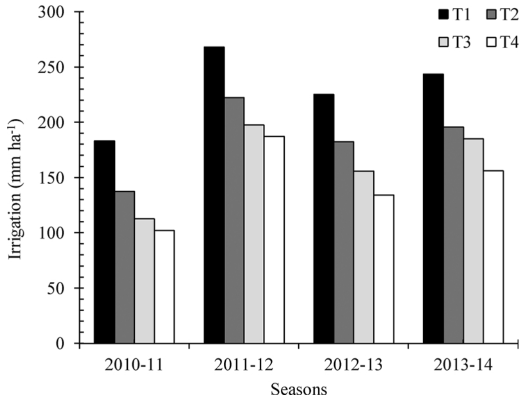

Fig. 2. Irrigation water applied in each treatment during the 2010–11, 2011–12, 2012–13 and 2013–14 seasons.

Table 2
Effect of irrigation cut-off strategies on maturity index, fruit oil content (%) and fruit water content (%) for each treatment and season[Z].

		Maturity index	Oil content (fwb%)	Water content (%)
Treatments				
	T_1	1.47	0.21	0.59
	T_2	1.42	0.20	0.58
	T_3	1.47	0.20	0.68
	T_4	1.56	0.20	0.57
Seasons				
	2010–11	1.56 a	0.18 c	0.64 a
	2011–12	1.69 a	0.25 a	0.56 b
	2012–13	1.56 a	0.21 b	0.55 b
	2013–14	1.11 b	0.16 c	0.56 b
ANOVA (*P-values*)				
Treatments		0.329	*0.697*	*0.651*
Seasons		*< 0.001*	*< 0.001*	*< 0.001*

fwb: fresh weight basis.

[Z] Within each column, data followed by different letters are significantly different according to the Tukey multiple comparison test ($P < 0.05$).

3.3. Fruit maturity index, water content and oil content

The average maturity index (MI) of the treatments at harvest in the four seasons was between 1.42 and 1.56, but there were no significant differences among them (Table 2). Moreover, there were no significant differences among treatments for either fruit water content (%) or oil content (% on a fresh weight basis) at harvest, which had values between 57 and 68% and 20–21%, respectively. Oil content on a dry weight basis also did not show differences among treatments. Nevertheless, there were significant differences among seasons in MI as well as fruit water and oil content. In 2013–14, the MI (1.11) was lower than in the other seasons, while oil content was statistically lower in both the 2013–14 and 2010–11 seasons than that observed in the 2011–12 season.

3.4. Oil quality

For the four seasons, the values of free acidity, peroxide and extinction coefficients (K_{232}, K_{270} and ΔK) were within the limits established for commercial extra virgin olive oil quality. Values of free acidity for the different irrigation treatments ranged between 0.21% and 0.32% with no significant differences among them (Table 3). The peroxide values presented significant differences among treatments, being lower in treatments that had experienced a higher water deficit. However, the difference was only significant between the T_1 and T_3 treatments. There were also significant differences among treatments for K_{232} and K_{270} extinction coefficients, where the higher values were found in treatments with higher water deficit (T_3 and T_4). In contrast,

Table 3
Effect of irrigation cut-off strategies on free acidity, peroxide value, extinction coefficients (K_{232}, K_{270} and ΔK) and total polyphenols for each treatment and season[Z].

		Free acidity (% oleic)	Peroxide value (meq O2 kg − 1)	K_{270}	K_{232}	ΔK	Total polyphenols (mg kg^{-1})
Treatments							
	T_1	0.32	5.29 a	0.11 b	1.51 b	−0.0025 a	209.4 c
	T_2	0.28	5.18 ab	0.11 b	1.51 b	−0.0029 ab	265.5 b
	T_3	0.24	4.57 b	0.13 a	1.57 ab	−0.0034 b	318.3 a
	T_4	0.21	4.85 ab	0.13 a	1.61 a	−0.0033 b	312.2 ab
Seasons							
	2010–11	0.15b	4.21 c	0.13 a	1.52 b	−0.0039 c	282.4 b
	2011–12	0.13b	5.38 b	0.13 a	1.69 a	−0.0038 c	335.2 a
	2012–13	0.50a	6.64 a	0.10 b	1.47 b	−0.0018 a	159.8 c
	2013–14	0.27b	3.65 c	0.12 b	1.51 b	−0.0027 b	327.9 a
ANOVA (*P-values*)							
Treatments		*0.207*	*0.035*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*
Seasons		*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*

[Z] Within each column, data followed by different letters are significantly different according to the Tukey multiple comparison test ($P < 0.05$).

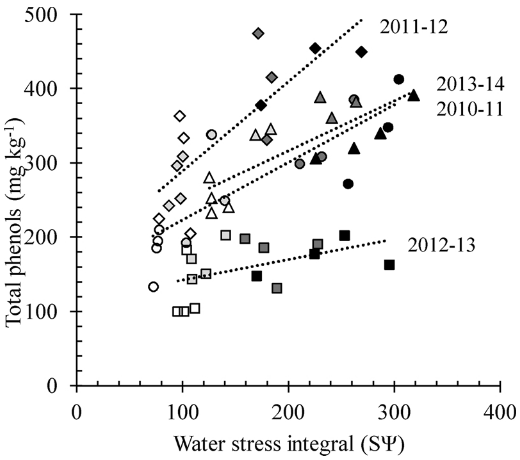

Fig. 3. Relationship between the total polyphenols in the oil and the water stress integral (S_{Ψ}) for 2010–11 (circles, r^2:0.65), 2011–12 (diamonds, r^2:0.65), 2012-13 (squares, r^2:0.22) and 2013–14 (triangles, r^2:0.64) seasons. White symbols correspond to T_1, light gray to T_2, dark gray to T_3 and black to T_4.

the values of ΔK were more negative in the T_3 and T_4 treatments compared with T_1. Total polyphenols were higher in the water deficit treatments compared with T_1. Also, total polyphenols of treatment T_3 were significantly higher than T_2. Moreover, total polyphenols showed a high linear correlation with S_{Ψ}, which explained the higher content of total polyphenols in treatments with water deficit in each season. Furthermore, this relationship was strongly influenced by season (Fig. 3). Polyphenols showed high values at harvest in the 2011–12 and 2013–14 seasons, but were much lower in 2012–13 (Table 3). In contrast, the 2012–13 season showed the highest values of free acidity, peroxide and ΔK compared to the other seasons.

As shown in Table 4, there were no significant effects of irrigation cut-off on most of the olive oil fatty acids such as palmitic, oleic, linoleic and linolenic acid. However, stearic acid was significantly higher in T_3 and T_4, while palmitoleic acid was significantly higher in the T_2 treatment compared with T_4. Also, there was a significant effect of season on the fatty acid composition. In the 2010–11 season, the samples presented the lowest level of palmitic acid, while samples from the 2013–14 season presented the highest oleic acid and the lowest linoleic acid.

The ratios of UNSA/SAFA and MUFA/PUFA were not significantly affected by the irrigation cut-off treatments (Table 5). Values of UNFA/SAFA and MUFA/PUFA had a narrow range between 5.66–5.82 and 10.94–11.05, respectively. However, there were significant differences among seasons with maximum values observed in the 2013–14 season.

3.5. Sensory analysis

The sensory profiles of the olive oils from the four seasons are shown in Fig. 4. The bitter and pungent attributes were more pronounced in olive oils from trees with higher water deficit (T_3 and T_4) compared with non-stressed trees (T_1) in all seasons. Moreover, olive oil samples from the 2011–12 season showed the highest presence of fruity, bitter and pungent attributes compared with other seasons. None of the olive oils presented defects in the organoleptic evaluations.

4. Discussion

Our Chilean study site has a Mediterranean-type climate with rainfall principally occurring during the winter, and a summer that is usually dry and hot (Ortega-Farías and López-Olivari, 2012). During the four seasons in which this study was conducted, the meteorological conditions were as expected with maximum atmospheric demand during the summer. However, some differences in temperature between seasons were observed during the latter part of the oil accumulation period.

The results suggest that the irrigation cut-off strategies implemented after fruit set did not affect olive ripening. This was also observed by Gómez del Campo and García (2013), who indicated that water deficit in the summer did not affect the maturity index in a super-high density olive orchard (cv. Arbequina) in Spain. The fruit oil and water contents (%) in our study were also not affected by the irrigation cut-off strategies. These same variables were previously found to not be greatly affected by water deficit treatments that reached a Ψ_{stem} of around −4.0 MPa in summer (Gómez-Rico et al., 2007; Iniesta et al., 2009). The lack of change in oil content (%) in the T_2 and T_3 treatments is likely a function of water stress mostly occurring during the pit hardening period rather than afterwards when most oil accumulation occurs. However, even the longer T_4 treatment did not lead to reduced oil content. Additionally, the fruit oil and water contents (%) were similar to those found in other cv. Arbequina olive orchards from other regions with a Mediterranean climate (Diez et al., 2016; García et al., 2013; Grattan et al., 2006; Iniesta et al., 2009; Patumi et al., 2002).

In terms of olive oil quality parameters, free acidity was not affected by the irrigation cut-off strategies, which is consistent with several previous studies of water deficit in olive trees (García et al., 2013; Gómez del Campo, 2013b; Patumi et al., 2002). Peroxide values showed a tendency to decrease with water deficit, coinciding with Tovar et al. (2002). In contrast, many studies have reported no relationship between irrigation and peroxide values (García et al., 2013; Gómez del Campo and García, 2013; Patumi et al., 2002). Lastly, Dag et al. (2008) observed that while peroxide content in the oil was not affected by irrigation, other factors such as mechanical harvesting, which is common in super-high density olive orchards, can affect peroxide

Table 4
Effect of irrigation cut-off strategies on fatty acid composition (%) of oil each treatment and season[Z].

		Palmitic acid	Palmitoleic acid	Stearic acid	Oleic acid	Linoleic acid	Linolenic acid
Treatments							
	T_1	12.91	0.95 ab	2.05 b	76.45	6.67	0.44
	T_2	13.15	1.01 a	2.09 b	76.04	6.64	0.48
	T_3	13.36	0.87 ab	2.25 a	75.77	6.69	0.44
	T_4	13.10	0.85 b	2.27 a	75.94	6.81	0.49
Seasons							
	2010–11	12.19 b	0.86 b	2.09 b	75.88 b	6.55 b	0.44 b
	2011–12	13.13 a	0.95 ab	2.10 b	75.65 b	7.20 a	0.46 ab
	2012–13	13.69 a	1.05 a	2.28 a	75.69 b	6.83 b	0.52 a
	2013–14	13.31 a	0.83 b	2.18 b	76.98 a	6.23 c	0.44 ab
ANOVA (*P-values*)							
Treatments		*0.2851*	*0.0307*	*0.0001*	*0.1211*	*0.4612*	*0.2549*
Seasons		*< 0.0001*	*0.0014*	*0.0044*	*< 0.0001*	*< 0.0001*	*0.0343*

[Z] Within each column, data followed by different letters are significantly different according to the Tukey multiple comparison test ($P < 0.05$).

Table 5
Effect of irrigation cut-off strategies on the ratios of unsaturated fatty acid (UNFA)/saturated fatty acid (SAFA) and monounsaturated fatty acid (MUFA)/polyunsaturated fatty acid (PUFA)[Z].

		UNFA/SAFA	MUFA/PUFA
Treatments			
	T_1	5.68	10.94
	T_2	5.66	11.04
	T_3	5.74	11.03
	T_4	5.82	11.05
Seasons			
	2010–11	5.89 b	11.02 b
	2011–12	5.48 c	10.01 c
	2012–13	5.28 c	10.49 bc
	2013–14	6.25 a	12.84 a
ANOVA (*P-values*)			
Treatments		*0.6522*	*0.4311*
Seasons		*< 0.0001*	*< 0.0001*

[Z] Within each column, data followed by different letters are significantly different according to the Tukey multiple comparison test ($P < 0.05$).

content. Mechanically harvested fruit was more prone to injury than hand-picked fruit in that study and this led to increased oxidation and hence peroxide values.

In the case of the extinction coefficients K232 and K270, higher values were obtained in the oils of the more severe water deficit treatments (T_3, T_4), which is in accordance with the results obtained by Ramos and Santos (2010) in oils from cv. Cordovil. Despite these differences between treatments for some parameters, the oils were within the limits established by the European Regulation EC 1989/03 for all treatments, allowing them to be classified as extra virgin oil quality.

Total polyphenols of the olive oils were higher in the treatments associated with greater water deficit intensity, as observed in other olive studies (Fernandes-Silva et al., 2013; Gómez-Rico et al., 2007; Lodolini et al., 2014; Motilva et al., 2000; Patumi et al., 2002; Tovar et al., 2002). Water stress, as well as other abiotic stresses such as excessive light, are generally well known to produce a greater synthesis of phenolic compounds in the fruit and leaves of many plant species (reviewed by Cheynier et al., 2013). Additionally, linear relationships between total polyphenols and S_Ψ were found in all four seasons (Fig. 3), which coincides with the results of Moriana et al. (2007). These results are very important because total polyphenols are also closely related to the oxidative stability of olive oil (Fernandes-Silva et al., 2013). Therefore, oil with a high polyphenol content will have a longer shelf life.

In relation to olive oil fatty acid composition, irrigation cut-off strategies did not affect the main fatty acids (palmitic, oleic and linoleic). These results coincide with Motilva et al. (2000) who observed that water deficit did not affect oil fatty acid composition in cv. Arbequina. In a fairly similar manner, Berenguer et al. (2006) did not find differences in fatty acids in cv. Arbequina except for a very minor increase in oleic acid due to severe water deficit in one of two seasons. Additionally, Salas et al. (1997) only observed differences in fatty acid composition between rain-fed and irrigated olive orchards, but differences between irrigation treatments were insignificant.

It is worth noting that the values of oleic acid content for cv. Arbequina found at our Chilean study site were high (about 75%), and that high oleic acid is a positive attribute in olive oils for human health (Covas et al., 2006). Such values are not uncommon in Mediterranean climates in Europe (Borges et al., 2017; Gómez del Campo and García, 2013), but they are much higher than values (about 50%) reported for more continental sites in Argentina where the climate is warmer (Rondanini et al., 2014, 2011). This is reaffirmed by Morello et al. (2006), who point out that the climatology may be more important in some cases than genetic factors in determining the chemical components that characterize olive oil quality. Among the environmental factors, temperature plays a relevant role in the composition of acids through regulating fatty acid desaturases (Hernández et al., 2011).

Environmental factors likely led to the statistically significant differences between seasons for fatty acid composition in our study, although the changes in the percentages of the individual fatty acids were not large. Similarly, other studies have also found differences in olive oil fatty acid composition between seasons (Fernandes-Silva et al., 2013; Tovar et al., 2002). In our study, the lowest concentrations of stearic and palmitic acids were found in the 2010–11 season and the highest concentrations in the 2013–14 season. This result may be explained by Borges et al. (2017), who indicated that saturated fatty acids were closely influenced by maximum temperature. In our study, the 2010–11 season had the lowest maximum temperature, while the 2013-14 season had the highest maximum temperature. Additionally, the olive oils from the 2011–12 and 2012–13 seasons had the highest concentration of palmitoleic and linolenic acids, which could be related to the temperature regime over the course of these seasons including high mean temperatures during the last period of oil accumulation. García-Inza et al. (2014) has previously reported that these fatty acids increase with temperature in manipulative heating experiments in cv. Arauco. However, it is somewhat counterintuitive based on many previous studies in cv. Arbequina (e.g., Mailer et al., 2010; Rondanini et al., 2014, 2011) that the statistically highest oleic acid, a monounsaturated fatty acid, was found in the 2013–14 season when temperature was maximum. This is likely related to the low maturity index at harvest in 2013–14 compared to other seasons, since oleic acid typically decreases in cv. Arbequina towards the end of the season as maturity index increases (Rondanini et al., 2014).

The sensory analysis showed that the bitter and pungent attributes were more pronounced in olive oils from trees with higher water deficit. These results coincide with Fernandes-Silva et al. (2013), who indicated

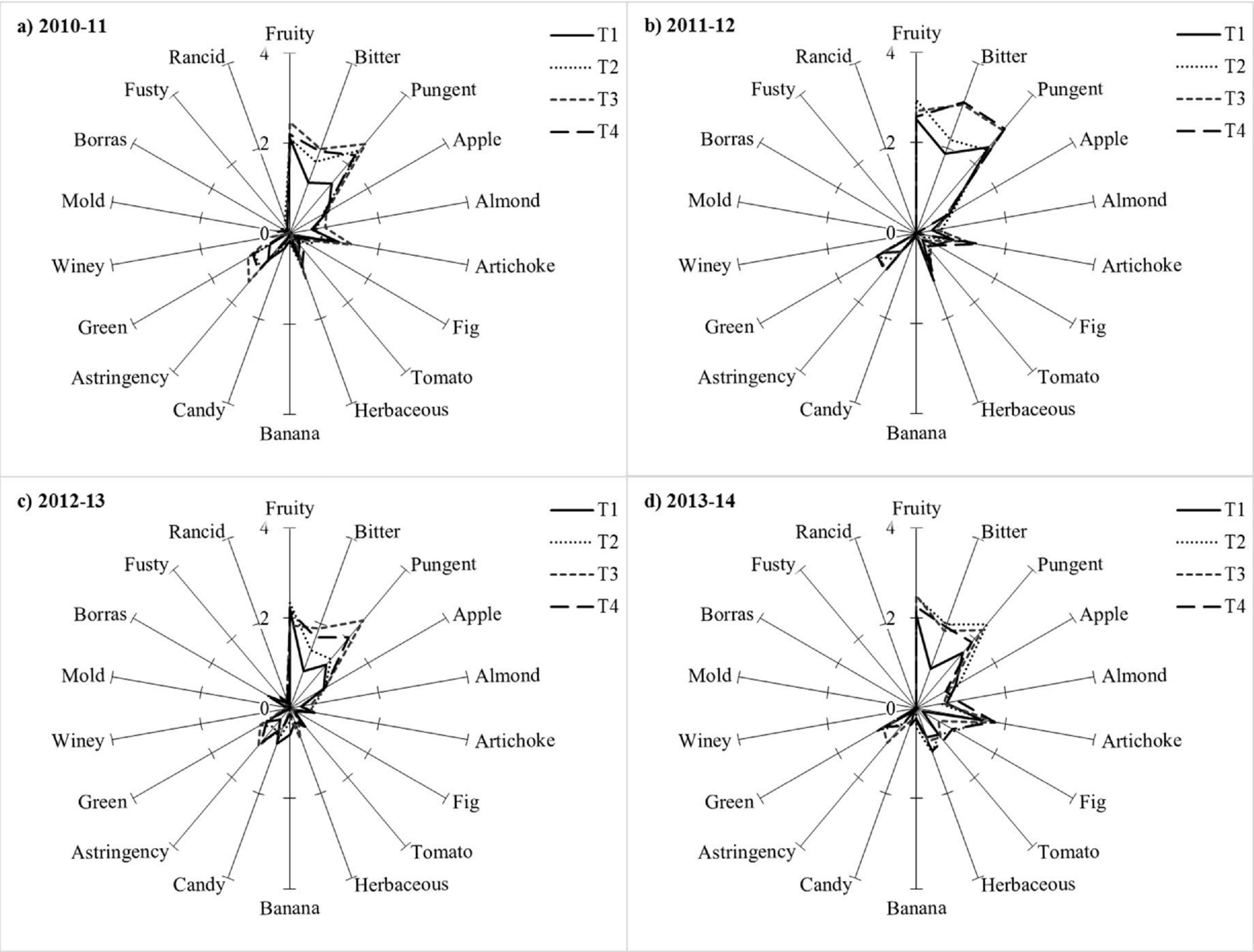

Fig. 4. Effect of irrigation cut-off strategies on organoleptic evaluation of olive oils of each treatment during four seasons; a) 2010–11, b) 2011–12, c) 2012–13 and d) 2013–14. Values are the means of four different VOO samples (n = 4).

that these attributes are more pronounced in oils from trees with water stress, because they have a strong relationship with polyphenol concentration. These findings are very important because oil from cv. Arbequina is normally characterized as having a very light pungency and bitterness, which often leads to its oil being blended with oils of other cultivars (Dabbou et al., 2010). Since irrigation cut-off strategies produce a desirable increase in the intensity of these two attributes, this could favor its consumption as a monovarietal oil.

5. Conclusion

In summary, our results indicate that the evaluated irrigation cut-off strategies, including those that reached values of −6.0 MPa., do not affect the fruit oil content (%). Some parameters of oil quality (peroxides and extinction coefficients) showed minor differences between irrigation treatments; however, all treatments were within the limits established for the commercial extra virgin quality. Additionally, main fatty acid compositions (palmitic, oleic, linoleic and linolenic acids) were not affected by irrigation cut-off strategies, although fatty acid composition was somewhat influenced by the climatic conditions of each season.

Most interestingly, our results over four seasons consistently showed that higher water deficit produced a greater polyphenol content, which should increase the oil shelf life. Moreover, greater polyphenols improved the organoleptic quality of the oil, which could favor the consumption of monovarietal cv. Arbequina olive oil. For these reasons, the more severe irrigation cut-offs (T3 and T4) improved the oil quality of cv. Arbequina and reduce water use by 30–40% at our Chilean site, although some reduction in oil yield is likely with such water deficits based on previous observations (Ahumada-Orellana et al., 2017).

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