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Influence of different irrigation strategies in a traditional Cornicabra cv. olive orchard on virgin olive oil composition and quality

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Abstract

The olive tree is generally grown under rain-fed conditions. However, since the yield response to irrigation, even with low amounts of water, is great there is increasing interest in irrigated agriculture. The main goal of this study was therefore to optimize sustainable irrigation conditions in the Cornicabra olive cultivar grown in Castilla-La Mancha, a region where the aquifers are over-exploited, and to study the effect of different irrigation strategies on the composition and quality of Cornicabra virgin olive oil. Different irrigation treatments, based on regulated deficit irrigation (RDI), 100% ET_c, 125% ET_c, and rain-fed as control, were applied to a traditional olive orchard (cv Cornicabra) in a randomized complete-block design with four replications. The average olive production of the trees grown under rain-fed conditions was much lower, about 35%, than that obtained by applying the different irrigation treatments studied, between which practically no difference were observed. The total phenol content, which affected the sensory bitterness in the oils, decreased significantly as the amount of supplied water increased. This is very relevant, as high levels of phenols, typical of Cornicabra virgin olive oils, may decrease consumer preference. Notably, one of the RDI strategies produced olive oil similar in composition and quality to that obtained by 100% ET_c but with reduced water usage.

Keywords: Irrigation; Olive oil; Production; Composition; Quality; Phenols; Sensory

1. Introduction

The olive tree is the most extensive arboreous crop in Spain, the number one olive oil producing country in the world. More than 280,000 ha are grown in the region of Castilla-La Mancha, accounting for 15% of the Spanish olive crop. The most important olive cultivar grown in this region is the Cornicabra, which produces virgin olive oil characterised by high oxidative stability and unique sensory characteristics (intense bitterness), which are both due to high levels of phenolic compounds.

The olive tree is generally grown under rain-fed conditions, especially in Castilla-La Mancha, a region with limited water resources. Nevertheless, since irrigation increases the yield of the olive orchard, even with a low amount of water, there is increasing interest in irrigated agriculture. This has led to a situation in which some of the traditional olive groves, and the majority of the new ones, are being adapted to irrigation techniques. Proper agriculture practices must contribute to healthy olive fruit production, which is the best guarantee of high quality olive oil production. Irrigation, even in areas where water is limited, is therefore an advisable technique from the

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point of view of both the production and quality of olive fruit, since high-quality olive oil cannot be obtained from olive fruit suffering from a high degree of water stress. Nevertheless, a satisfactory compromise between the amount of water applied and the improvement in the production and quality of the olive crop must be fully investigated.

There is scarce information available on the influence of irrigation on olive tree growth and production and on the composition and quality of the virgin olive oil obtained, especially in the case of the Cornicabra variety. Some recent research has shown differences in the chemical makeup and sensory characteristics of virgin olive oil from irrigated and rain-fed olive trees (Aparicio & Luna, 2002). The chemical components most influenced by irrigation are the phenolic compounds, which affect both the oxidative stability and the sensory characteristics, especially the bitterness attribute, showing in both cases an inverse relationship with the amount of water applied to the olive trees (D'Andria, Morelli, Martuccio, Fontanazza, & Patumi, 1996; Motilva, Romero, Alegre, & Girona, 1999; Motilva, Tovar, Romero, Alegre, & Girona, 2000; Tovar, Romero, & Motilva, 2001). This aspect is important in olive cultivars that produce virgin olive oils with high bitterness and pungency, such as, the Cornicabra variety in Castilla-La Mancha, and therefore just the right level of irrigation could enhance its sensory characteristics.

The main goal of this study was therefore to optimize sustainable irrigation conditions in the Cornicabra olive cultivar grown in Castilla-La Mancha, a region where aquifers are over-exploited, and to study the effect of different irrigation strategies on the composition and quality of Cornicabra virgin olive oil. Different irrigation treatments (based on 100% crop evapotranspiration, ET_c, also known as the FAO method, 125% ET_c, two different regulated deficit irrigation strategies and rain-fed) were applied to a traditional olive orchard (cv Cornicabra) planted at 70 trees per hectare in a randomized complete-block design with four replications.

2. Materials and methods

2.1. Experimental olive orchard

The study was carried out during the 2003/2004 and 2004/2005 olive crop seasons in an experimental olive orchard of Cornicabra cv. maintained by Conserjería de Agricultura y Medio Ambiente (Department of Agriculture and the Environment), located in Almodóvar del Campo (Ciudad Real, Spain). About three hundred and twenty 50-year-old trees, spaced $12 \times 12\ m^2$, were used in a randomised complete block design with four different treatments and four replications. Each experimental unit consisted of 4×3 trees, where only the central ones were used for sampling. The experimental olive orchard was enclosed by two outer rows of irrigated olives. All of the agronomical treatments applied to the experimental olive orchard were identical, with the exception of the amount of water applied.

2.2. Irrigation treatments

Four treatments were applied two years before the commencement of this assay: rain-fed (RF), regulated deficit irrigation (RDI), FAO and 125 FAO. Rain-fed treatment was used as the control to compare the results obtained with the three irrigation treatments studied. In the FAO treatment, the water requirements were obtained using methodology proposed by the Food and Agriculture Organization of the United Nations, by subtracting the effective precipitation (41 mm in 2003 and 138 mm in 2004) from the crop evapotranspiration (ET_c), this latter term being calculated using the effective crop coefficient (K_c), the reference crop evapotranspiration (ET_o; 822 mm in 2003 and 801 mm in 2004) obtained from an agronomic weather station and a reductor coefficient (K_r) that depended on the size of the tree ($ET_c = K_c \times ET_o \times K_r$; Doorenbos & Pruitt, 1977). In 125 FAO treatment, an irrigation dosage 25% higher than the FAO treatment was applied. As for the regulated deficit irrigation (RDI), a maximum amount of 75 mm of water was established since, in many Spanish irrigated olive areas, there is a legal limitation of 100 mm, and two different strategies were evaluated. In 2003, water was applied throughout the entire season with different rates of application (10% FAO in May and June, 4% FAO in July and August and 18% FAO in September); however, in 2004, based on the results obtained during the previous crop season, water was applied only from the beginning of August, when the oil formation starts in the fruit, with the purpose of investigating which RDI treatment is more effective in reaching similar olive production and olive oil quality to that obtained by the FAO method but considerably reducing the total amount of water applied. In all irrigation treatments, olive trees were irrigated daily with eight compensating drippers (4 l/h) placed around the trees.

The total water applied in 2003 for the different irrigation treatments was: 56 mm for RDI, 148 mm for FAO and 206 mm for 125 FAO; and in 2004: 60 mm for RDI, 124 mm for FAO and 154 mm for 125 FAO. In order to fully describe the different irrigation strategies used, the water stress integrals (MPa × day; as defined by Myers, 1998), calculated from the midday steam water potential data, and the minimum potential values are reported. These values during 2003 were: 332 MPa d and −4.1 MPa (observed in the middle of September) for RF; 316 MPa d, −4.1 MPa (middle of September) for RDI; 218 MPa d, −2.3 MPa (middle of September) for FAO; 172 MPa d, −1.8 MPa (middle of September) for 125 FAO. The following experimental data were observed in 2004: 269 MPa d and −4.1 MPa (middle of October) for RF; 223 MPa d, −2.9 MPa (beginning of August) for RDI; 176 MPa d, −2.2 MPa (end of September) for FAO; 159 MPa d, −1.7 MPa (middle of October) for 125 FAO.

2.3. Olive and olive oil samples

Olive fruit samples from rain-fed and irrigation treatments trees were harvested throughout ripening, from immature stage to normal harvest period for the Cornicabra variety. Five and three samplings were gathered in 2003/2004 and 2004/2005, respectively; the samples were collected by hand from the beginning of November to the end of December, whereas the fifth sampling collected from the 2003/2004 crop was collected by a mechanical shaker at the beginning of January. The olive fruit sampling of the different irrigation treatments was not always carried out on the same date, with a view to obtaining a more homogeneous pool of samples between the irrigation treatments studied. Four representative subsamples from each treatment (four subsamples × four treatments) were picked at each sampling and brought to the laboratory for oil extraction. Virgin olive oil samples of Cornicabra variety were then obtained using the Abencor method and analysed for this study.

2.4. Analytical determinations in olive fruits

Ripeness index. The olive ripeness index was determined according to the method proposed by the International Olive Oil Council (IOOC, 1984), based on the evaluation of the olive skin and pulp colours. Ripeness index values range from 0 (100% intense green skin) to 7 (100% purple flesh and black skin).

Industrial oil yield. An Abencor system was used to extract the virgin olive oil. The oil obtained was separated by decanting and the amount measured. The industrial oil yield was expressed as a percentage of fresh olive paste weight (Martínez, Muñoz, Alba, & Lanzón, 1975). Samples were filtered and stored at 4 °C in darkness using amber glass bottles without headspace until analysis.

Water and oil content. The water content of olive paste was determined by desiccation according to the UNE Spanish standard method. The fat content was determined by Soxhlet extraction and was expressed as a percentage of dry olive paste weight (UNE Spanish Standard 55032:1973).

2.5. Analytical determinations in virgin olive oil

All reagents used were of analytical, HPLC or spectroscopic grade, and were supplied by Merck (Darmstadt, Germany).

Free acidity, given as % of oleic acid, *peroxide value* (PV) expressed as milliequivalents of active oxygen per kilogramme of oil (meq O_2/kg), and K_{232} and K_{270} *extinction coefficients* calculated from absorption at 232 and 270 nm, were measured following the analytical methods described in European Regulation EEC 2568/91 and subsequent amendments.

For phenolic compounds a solution of the internal standard (250 µl of 15 mg/L of syringic acid in methanol) was added to a sample of virgin olive oil (2.5 g) and the solvent was evaporated with a rotary evaporator at 35 °C under vacuum. The oil was then dissolved in 6 ml of hexane and a diol-bonded phase cartridge (Supelco Co., Bellefonte, USA) was used to extract the phenolic fraction. The cartridge was conditioned with methanol (6 ml) and hexane (6 ml), the oil solution was then applied, and the SPE column was washed with hexane (2 × 3 ml) and with hexane/ethyl acetate (85:15, v/v; 4 ml). Finally, the phenols were eluted with methanol (15 ml) and the solvent was removed with a rotary evaporator at 35 °C under vacuum to dryness. The phenolic residue was dissolved in methanol/water (1:1 v/v; 250 µl).

HPLC analysis was performed using an Agilent Technologies 1100 series system equipped with an automatic injector, a column oven and a diode array UV detector. A Spherisorb S3 ODS2 column (250 × 4.6 id mm, 5 µm particle size) (Waters Co., Milford, Massachusetts, USA) was used, maintained at 30 °C, with an injection volume of 20 µl and a flow rate of 1.0 ml/min. Mobile phase was a mixture of water/acetic acid (95:5 v/v) (solvent A), methanol (B) and acetonitrile (C): from 95% (A) −2.5% (B) −2.5% (C) to 34% (A) −33% (B) −33% (C) in 50 min. Phenolic compounds were quantified at 280 nm using syringic acid as internal standard and the response factors determined as by Mateos et al. (2001).

Tocopherols were evaluated following the AOCS Method Ce 8-89. A solution of oil in hexane was analysed on an Agilent Technologies HPLC (1100 series) on a silica gel Lichrosorb Si-60 column (particle size 5 µm, 250 mm × 4.6 mm i.d.; Sugerlabor, Madrid, Spain) which was eluted with hexane/2-propanol (98.5:1.5) at a flow rate of 1 ml/min. A fluorescence detector (Thermo-Finnigan FL3000) was used with excitation and emission wavelength set at 290 and 330 nm.

Oxidative stability was evaluated by the Rancimat method (Laübli & Bruttel, 1986). Stability was expressed as the induction time (hours) measured with the Rancimat 679 apparatus (Metrohm, Switzerland).

Fatty acid composition was determined following the European Regulations EEC 2568/91 and subsequent amendments, corresponding to the AOCS method Ch 2-91. To determine fatty acid composition, the methyl-esters were prepared by vigorous shaking of a solution of oil in hexane (0.2 g in 3 ml) with 0.4 ml of 2 N methanolic potassium hydroxide and analysed by GC with a FID detector. A fused silica column (50 m length × 0.25 mm i.d.) coated with SGL-1000 phase (0.25 µm thickness; Sugerlabor, Spain) was used. The carrier gas was helium, at a flow through the column of 1 ml/min. The injector and detector temperatures were set at 250 °C and the oven temperature at 210 °C. The injection volume was 1 µl.

Sensory evaluation was done by an International Olive Oil Council recognized Panel of assessors from the Protected Designation of Origin "Montes de Toledo" (Toledo, Spain) and the University of Castilla-La Mancha according to Annex XII of Regulation EC 796/2002 (amending ECC 2568/91).

Bitterness index (K_{225}) was determined by the method described by Gutiérrez-Rosales, Perdiguero, Gutiérrez, and Olías (1992), which consists of the extraction of the bitter components from a sample of 1.0 ± 0.01 g of oil dissolved in 4 ml of hexane passed through a C_{18} column (Bakerbond spe, J.T. Baker, Phillipsburg, NJ, USA) previously activated with methanol and washed with hexane. After elution, 10 ml of hexane was passed to eliminate the oil residues and then the retained compounds were eluted with methanol/water (1:1) to 25 ml. The absorbance of the extract was measured at 225 nm against methanol/water (1:1) in a 1-cm cuvette.

Chlorophyll and carotenoid compounds (mg/kg) were determined at 472 and 670 nm in cyclohexane using specific extinction values, by the method described by Mínguez-Mosquera, Rejano, Gandul, Sánchez, and Garrido (1991).

All experiments and analytical determinations were carried out at least in duplicate.

2.6. Statistical Analysis

Statistical analyses were performed using SPSS 11 statistical software (SPSS Inc. Chicago, IL).

3. Results and discussion

3.1. Production of the olive grove

The olive production data of the experimental olive orchard studied, expressed as weight of fruits per olive tree throughout the 2001/2002 to 2004/2005 crop seasons for the different irrigation treatments studied, rain-fed (RF), regulated deficit irrigation (RDI), FAO (Food and Agriculture Organization methodology, based on the crop evapotranspiration, ET_c), and 125% FAO, are listed in Table 1.

The average olive production of the trees grown under rain-fed conditions (39.2 kg/tree) was much lower, about 35%, compared with that obtained applying the different irrigation treatments studied (from 51.8 to 52.7 kg/tree), between which practically no differences were observed. This observation agrees with the results obtained by Patumi et al. (1999) and Pastor et al. (1999), who reported a rise in olive production using irrigation, but no statistically significant difference between the irrigation doses used. The reported data also show the typical high and low fruit load behaviour of the olive trees in successive crop seasons, especially in the case of the RF conditions.

Table 1
Olive production in the different irrigation treatments studied

Crop Season	Olive Production (kg/tree)			
	Rain-fed	Deficit irrigation	FAO	125 FAO
2001/2002	47.4	54.3	62.0	50.2
2002/2003	27.0	58.3	52.5	52.4
2003/2004	62.3	61.1	67.2	80.1
2004/2005	20.1	35.5	28.9	24.4
Mean	39.2	52.3	52.7	51.8

3.2. Characteristics and composition of the olive fruit

Table 2 lists the olive fruit characteristics and composition, as affected by the different irrigation treatments studied and the ripeness index of the fruits for the two crop seasons studied (2003/2004 and 2004/2005).

The olive fruit sampling of the different irrigation conditions was not always carried out on the same date, with a view to obtaining a more homogeneous pool of samples between the irrigation treatments studied. For this reason a discussion of the statistically significant difference in the ripeness index of the olive fruit, among the different irrigation treatments studied, cannot be performed. Nevertheless, taking into account the harvesting date of the different olive sampling (data not shown), it should be noted that, with the exception of the last sampling, the olive fruits of the FAO irrigation treatment generally had a higher ripeness index than those of rain-fed conditions. For the 125 FAO treatment, corresponding to the higher amount of water applied, this tendency was not observed, due to the greater olive production obtained with this treatment in the crop season 2003/2004 (Table 1), given that, as olive production rises, fruit ripening slows down.

In crop season 2003/2004 the fresh fruit weight and the pulp/pit ratio of the olive fruit were consistently higher in the irrigation treatments than in rain-fed conditions which contributed to the higher production yield observed in the irrigated olive orchard (Table 2). Similar results were observed by Lavee, Nashef, Wodner, and Harshemesh (1990), Pastor et al. (1999), Patumi et al. (1999), Patumi et al. (2002), Moriana, Orgaz, Fereres, and Pastor (2003) among other researchers. The weight of the fruit in the 125 FAO irrigation treatment was slightly lower than in FAO and RDI, probably due, as previously mentioned, to the fact that, in the crop season 2003/2004, the production of 125 FAO was greater (about 80 kg per tree) than in the FAO and RDI treatments (65 and 60 kg per tree, respectively) and, as the olive tree production increases, the size of the fruit diminishes (Lavee & Wodner, 2004). In the 2004/2005 season, this behaviour, in terms of the weight of the fruit was not observed, probably due to the relatively high fruit damage produced by an olive fly attack which was not detected in the previous crop season (Table 2).

The fruit damage observed in the 2004/2005 crop (and that affected mainly the irrigated olive trees), as well as varying weather conditions, meant that a number of statistically significant differences observed in the previous crop season could not be fully confirmed at the following harvesting. As is well known, this is one of the most relevant limitations in experimental agronomical studies in which it is generally necessary to monitor the evolution of one crop for several years running to reach a general conclusion on the effect of the factors studied.

Table 2
Olive fruit characteristics and composition, as affected by the different irrigation treatments studied and the ripeness index of the fruits

	Ripeness index	Fresh wt. (g/olive)	Pulp/pit ratio	Fruit damage (%)	Water content (%)	Oil content Soxhlet (%)
2003/2004						
Rain-fed	$1.5 \pm 0.5^{a,w}$	$2.14 \pm 0.23^{a,w}$	3.49	nd	$50.4 \pm 1.6^{a,w}$	$39.5 \pm 6.8^{a,w}$
Deficit irrigation	$1.8 \pm 0.6^{ab,w}$	$2.65 \pm 0.96^{a,w}$	4.50	nd	$53.9 \pm 2.3^{b,x}$	$39.8 \pm 5.8^{a,w}$
FAO	$2.5 \pm 0.4^{b,w}$	$2.93 \pm 0.45^{a,w}$	4.30	nd	$52.2 \pm 1.9^{ab,y}$	$42.2 \pm 4.5^{a,w}$
125 FAO	$2.0 \pm 0.3^{ab,v}$	$2.56 \pm 0.45^{a,w}$	3.82	nd	$52.0 \pm 2.3^{ab,x}$	$39.1 \pm 3.9^{a,w}$
Rain-fed	$2.7 \pm 0.3^{a,x}$	$2.13 \pm 0.19^{a,w}$	3.60	nd	$47.9 \pm 2.9^{a,w}$	$42.9 \pm 6.0^{a,wx}$
Deficit irrigation	$2.8 \pm 0.4^{a,x}$	$2.67 \pm 1.02^{a,w}$	4.05	nd	$49.8 \pm 3.4^{a,wx}$	$42.3 \pm 2.2^{a,w}$
FAO	$3.1 \pm 0.3^{a,x}$	$2.80 \pm 0.49^{a,w}$	4.20	nd	$49.5 \pm 1.8^{a,xy}$	$43.5 \pm 4.1^{a,w}$
125 FAO	$2.8 \pm 0.2^{a,w}$	$2.42 \pm 0.51^{a,w}$	3.62	nd	$50.2 \pm 4.5^{a,wx}$	$42.9 \pm 3.6^{a,w}$
Rain-fed	$3.2 \pm 0.3^{a,xy}$	$2.14 \pm 0.22^{a,w}$	3.69	nd	$47.3 \pm 3.0^{a,w}$	$43.8 \pm 4.9^{a,wx}$
Deficit irrigation	$3.5 \pm 0.4^{a,xy}$	$2.55 \pm 0.88^{a,w}$	4.19	nd	$51.1 \pm 1.9^{a,wx}$	$44.3 \pm 2.6^{a,w}$
FAO	$3.6 \pm 0.4^{a,xy}$	$2.81 \pm 0.54^{a,w}$	4.38	nd	$49.5 \pm 2.0^{a,xy}$	$46.7 \pm 1.3^{a,w}$
125 FAO	$3.4 \pm 0.3^{a,x}$	$2.42 \pm 0.41^{a,w}$	3.76	nd	$48.2 \pm 3.5^{a,wx}$	$43.5 \pm 5.1^{a,w}$
Rain-fed	$3.7 \pm 0.2^{a,y}$	$2.11 \pm 0.25^{a,w}$	3.75	nd	$46.5 \pm 4.0^{a,w}$	$46.2 \pm 5.1^{a,wx}$
Deficit irrigation	$3.8 \pm 0.3^{a,y}$	$2.27 \pm 0.64^{a,w}$	3.80	nd	$48.2 \pm 3.9^{a,x}$	$46.0 \pm 4.6^{a,w}$
FAO	$4.0 \pm 0.4^{a,y}$	$2.72 \pm 0.38^{a,w}$	4.25	nd	$47.8 \pm 2.5^{a,wx}$	$47.4 \pm 3.4^{a,w}$
125 FAO	$3.9 \pm 0.1^{a,y}$	$2.39 \pm 0.35^{a,w}$	3.74	nd	$45.8 \pm 2.8^{a,w}$	$43.1 \pm 4.8^{a,w}$
Rain-fed	$5.7 \pm 0.4^{b,z}$	$2.52 \pm 0.19^{a,x}$	4.12	nd	$47.3 \pm 3.0^{a,w}$	$49.2 \pm 4.5^{a,x}$
Deficit irrigation	$5.4 \pm 0.5^{ab,z}$	$2.84 \pm 0.87^{a,w}$	4.60	nd	$49.4 \pm 3.5^{a,wx}$	$42.8 \pm 8.5^{a,w}$
FAO	$5.5 \pm 0.3^{ab,z}$	$2.95 \pm 0.43^{a,w}$	4.57	nd	$46.1 \pm 1.6^{a,w}$	$46.1 \pm 2.6^{a,w}$
125 FAO	$4.9 \pm 0.1^{a,z}$	$2.62 \pm 0.44^{a,w}$	4.12	nd	$48.2 \pm 1.2^{a,wx}$	$43.2 \pm 4.0^{a,w}$
2004/2005						
Rain-fed	$2.8 \pm 0.2^{b,w}$	$2.44 \pm 0.10^{a,w}$	–	$5.5 \pm 0.0^{a,w}$	$50.3 \pm 1.1^{b,x}$	$42.9 \pm 0.5^{a,w}$
Deficit irrigation	$2.3 \pm 0.1^{a,w}$	$2.72 \pm 0.21^{b,w}$	–	$25.8 \pm 0.1^{b,w}$	$50.8 \pm 0.2^{b,x}$	$40.1 \pm 1.8^{a,w}$
FAO	$2.5 \pm 0.2^{ab,w}$	$2.56 \pm 0.00^{a,w}$	–	$17.8 \pm 0.0^{b,w}$	$46.7 \pm 0.6^{a,x}$	$40.2 \pm 0.1^{a,w}$
125 FAO	$2.4 \pm 0.1^{a,w}$	$2.47 \pm 0.11^{a,w}$	–	$30.8 \pm 0.1^{b,wx}$	$49.8 \pm 0.9^{b,x}$	$40.1 \pm 2.7^{a,w}$
Rain-fed	$3.4 \pm 0.0^{a,x}$	$2.57 \pm 0.28^{b,w}$	–	$4.0 \pm 0.0^{a,w}$	$48.7 \pm 1.2^{a,x}$	$46.7 \pm 0.4^{a,w}$
Deficit irrigation	$3.4 \pm 0.0^{a,x}$	$2.55 \pm 0.17^{b,w}$	–	$35.0 \pm 0.1^{c,x}$	$50.1 \pm 1.4^{a,x}$	$42.9 \pm 4.2^{a,w}$
FAO	$3.4 \pm 0.0^{a,x}$	$2.37 \pm 0.08^{a,w}$	–	$17.0 \pm 0.0^{b,w}$	$49.6 \pm 0.6^{a,y}$	$48.7 \pm 0.0^{a,x}$
125 FAO	$3.5 \pm 0.1^{a,x}$	$2.66 \pm 0.37^{b,w}$	–	$36.0 \pm 0.0^{c,x}$	$47.7 \pm 0.7^{a,x}$	$42.2 \pm 2.6^{a,w}$
Rain-fed	$4.1 \pm 0.1^{a,y}$	$2.40 \pm 0.05^{a,w}$	–	$4.5 \pm 0.0^{a,w}$	$43.2 \pm 1.3^{a,w}$	$43.8 \pm 3.4^{a,w}$
Deficit irrigation	$4.2 \pm 0.0^{a,y}$	$2.39 \pm 0.14^{a,w}$	–	$23.5 \pm 0.0^{b,w}$	$43.5 \pm 0.7^{a,w}$	$43.6 \pm 3.1^{a,w}$
FAO	$4.2 \pm 0.0^{a,y}$	$2.39 \pm 0.07^{a,w}$	–	$22.5 \pm 0.0^{b,w}$	$44.0 \pm 0.3^{a,w}$	$47.3 \pm 1.5^{a,x}$
125 FAO	$4.2 \pm 0.0^{a,y}$	$2.15 \pm 0.14^{a,w}$	–	$25.5 \pm 0.0^{b,w}$	$42.1 \pm 1.0^{a,w}$	$40.6 \pm 1.4^{a,w}$

Different letters within a column (a–c) indicate significant differences ($p < 0.05$) with respect to irrigation treatment in each sampling. Different letters within a column (w–y) indicate significant differences ($p < 0.05$) with respect to ripeness index for each treatment. nd, not detected.

Moreover, in the discussion of the experimental results observed in the two crop seasons studied, it is important to note that a different RDI strategy was employed each year (see details in Section 2), with the purpose of investigating which RDI treatment was more effective in attaining similar olive production and olive oil quality to that obtained by the FAO method but considerably reducing the total amount of water applied to the olive grove.

Although the mean value of the water content of the olive fruit (Table 2) was generally slightly lower under RF conditions than under irrigation, especially in the crop season 2003/2004, practically no statistically significant differences were observed. Apparently, the evolution of the fruit water content was not affected by the ripeness index. Similar results were also reported by Motilva et al. (2000).

The industrial oil content, determined by the Abencor method, and the Soxhlet fat yield of the olive fruit generally increased during ripening (Table 2). However, at the higher end of the ripeness index (greater than 3.5–4.0) these increases were modest (similar to rain-fed conditions) or even slightly less in terms of the values observed (as in the irrigation treatments), similar to results previously reported by Salvador, Aranda, and Fregapane (2001) for the same olive variety. The irrigation treatment apparently did not affect the oil accumulation in the Cornicabra fruit since no statistically significant differences in the oil yield were observed in the present study. In contrast, Lavee and Wodner (1991), Motilva et al. (2000) did observe a slight delay in oil accumulation in fruits from non-irrigated olive trees as a consequence of hydric stress at the end of the summer season.

3.3. Virgin olive oil quality and composition

3.3.1. Quality indices

The observed free acidity ranging from 0.09% to 0.20%, and peroxide value, from 1.7 to 3.4 meqO_2 kg^{-1}, of the different types of virgin olive oils studied in this assay in the crop season 2003/2004 (Table 3) were considerably lower than the upper limit of 0.8% as oleic acid and 20 $meqO_2\ kg^{-1}$, respectively, established by EU legislation for extra virgin olive oil. Moreover, these two quality indices were not influenced by irrigation, since no statistically significant differences in oil from rain-fed and irrigation treatments in the crop season 2003/2004 were obtained. This was also observed by Tovar et al. (2001) in virgin olive oils from Arbequina cultivar, by Dettori and Russo (1993) in Leccino, Nociara and Ogliarola Salentina cultivars and Patumi et al. (1999) in Nocellara del Belice and Ascolana Tenera cultivars.

On the contrary, in crop 2004/2005, a statistical difference for free acidity and peroxide value was indeed obtained between RF and the irrigation treatments, due to the higher degree of fruit damage as a consequence of the olive fly attack (Table 3). Nevertheless, the values of free acidity and the peroxide value of the olive oil obtained from partially damaged fruit were not high from an olive oil quality point of view: a maximum acidity of 0.4% and a 5.4 peroxide value were observed.

In both crop seasons, a slight increase in free acidity was generally observed during the ripening of the olive fruit.

Spectrophotometric absorption characteristics in the UV region at 270 and 232 nm decreased at later ripeness index in all treatments. Statistically significant differences were obtained in K_{232} and K_{270} between oils from rain-fed conditions and the different irrigation treatments studied. These indices were always higher in RF and decreased by increasing the amount of the water employed in the irrigation. This effect is probably caused by the interference of the phenolic compounds content, which absorbs in the UV region in these analytical determinations. In fact, the observed effect of irrigation on UV characteristics could not be confirmed in the 2004/2005 crop in which the phenolic compounds were less affected by the amount of water applied.

All the virgin olive oils obtained using the different irrigation treatments of the trees studied were classified as 'extra virgin' oil by mean of the organoleptic evaluation carried out by an IOOC (International Olive Oil Council) recognized olive oil taster panel, as shown in Table 4.

Sensory attributes affected by irrigation were "bitterness", "pungency" and "fruitiness", according to what has previously been described for other olive cultivars (Salas, Pastor, Castro, & Vega, 1997; Tovar et al., 2001; Tovar, Romero, Alegre, Girona, & Motilva, 2002). As is known, the intensity of sensory pungency, and especially bitterness, are related to the phenol content in the olive oil, which, as expected, was higher in oils obtained under rain-fed conditions. In all cases, a slight decrease in the

Table 3
Virgin olive oil quality indices, as affected by the different irrigation treatments studied and the ripeness index of the fruits

	Ripeness index	Free acidity (%)	Peroxide value ($meqO_2$/kg)	K_{232}	K_{270}
2003/2004					
Rain-fed	$2.7 \pm 0.3^{a,x}$	$0.10 \pm 0.01^{a,w}$	$2.9 \pm 0.3^{ab,w}$	$1.90 \pm 0.05^{b,xy}$	$0.18 \pm 0.00^{b,y}$
Deficit irrigation	$2.8 \pm 0.4^{a,x}$	$0.10 \pm 0.03^{a,w}$	$2.4 \pm 0.6^{a,w}$	$1.74 \pm 0.08^{a,xy}$	$0.16 \pm 0.02^{ab,x}$
FAO	$3.1 \pm 0.3^{a,x}$	$0.10 \pm 0.03^{a,w}$	$2.5 \pm 0.2^{a,wx}$	$1.67 \pm 0.06^{a,y}$	$0.14 \pm 0.01^{a,x}$
125 FAO	$2.8 \pm 0.2^{a,w}$	$0.10 \pm 0.02^{a,w}$	$3.4 \pm 0.8^{b,w}$	$1.64 \pm 0.11^{a,xy}$	$0.14 \pm 0.02^{a,xy}$
Rain-fed	$3.7 \pm 0.2^{a,y}$	$0.10 \pm 0.01^{a,w}$	$2.4 \pm 0.2^{ab,w}$	$1.84 \pm 0.02^{b,x}$	$0.16 \pm 0.01^{b,x}$
Deficit irrigation	$3.8 \pm 0.3^{a,y}$	$0.09 \pm 0.01^{a,w}$	$2.4 \pm 0.5^{ab,w}$	$1.65 \pm 0.10^{a,wx}$	$0.13 \pm 0.02^{a,w}$
FAO	$4.0 \pm 0.4^{a,y}$	$0.10 \pm 0.02^{a,w}$	$2.0 \pm 0.3^{a,w}$	$1.54 \pm 0.05^{a,wx}$	$0.11 \pm 0.01^{a,w}$
125 FAO	$3.9 \pm 0.1^{a,y}$	$0.12 \pm 0.01^{a,w}$	$2.8 \pm 0.4^{b,w}$	$1.54 \pm 0.09^{a,wx}$	$0.12 \pm 0.01^{a,wx}$
Rain-fed	$5.7 \pm 0.4^{b,z}$	$0.14 \pm 0.02^{ab,x}$	$2.6 \pm 1.2^{a,w}$	$1.68 \pm 0.04^{c,w}$	$0.15 \pm 0.01^{b,w}$
Deficit irrigation	$5.4 \pm 0.5^{ab,z}$	$0.11 \pm 0.02^{a,w}$	$1.7 \pm 0.5^{a,w}$	$1.56 \pm 0.04^{b,w}$	$0.12 \pm 0.01^{a,w}$
FAO	$5.5 \pm 0.3^{ab,z}$	$0.18 \pm 0.07^{ab,x}$	$2.3 \pm 0.4^{a,wx}$	$1.47 \pm 0.03^{a,w}$	$0.11 \pm 0.00^{a,w}$
125 FAO	$4.9 \pm 0.1^{a,z}$	$0.20 \pm 0.06^{b,x}$	$2.6 \pm 0.5^{a,w}$	$1.45 \pm 0.08^{a,w}$	$0.11 \pm 0.01^{a,w}$
2004/2005					
Rain-fed	$2.8 \pm 0.2^{b,w}$	$0.14 \pm 0.01^{a,w}$	$2.7 \pm 0.3^{a,w}$	$1.67 \pm 0.14^{a,w}$	$0.15 \pm 0.01^{a,w}$
Deficit irrigation	$2.3 \pm 0.1^{a,w}$	$0.23 \pm 0.02^{b,w}$	$3.4 \pm 0.5^{a,w}$	$1.73 \pm 0.03^{a,x}$	$0.15 \pm 0.00^{ab,w}$
FAO	$2.5 \pm 0.2^{ab,w}$	$0.25 \pm 0.01^{b,w}$	$3.1 \pm 0.1^{a,w}$	$1.74 \pm 0.00^{a,y}$	$0.16 \pm 0.00^{ab,x}$
125 FAO	$2.4 \pm 0.1^{a,w}$	$0.25 \pm 0.02^{b,w}$	$5.4 \pm 0.1^{b,w}$	$1.73 \pm 0.02^{a,y}$	$0.17 \pm 0.00^{b,y}$
Rain-fed	$3.4 \pm 0.0^{a,x}$	$0.15 \pm 0.01^{a,w}$	$2.7 \pm 0.2^{a,w}$	$1.59 \pm 0.11^{a,w}$	$0.13 \pm 0.01^{a,w}$
Deficit irrigation	$3.4 \pm 0.0^{a,x}$	$0.31 \pm 0.09^{b,w}$	$3.6 \pm 0.6^{ab,w}$	$1.63 \pm 0.01^{a,w}$	$0.14 \pm 0.02^{a,w}$
FAO	$3.4 \pm 0.0^{a,x}$	$0.28 \pm 0.05^{b,w}$	$3.7 \pm 0.1^{b,x}$	$1.63 \pm 0.01^{a,x}$	$0.14 \pm 0.00^{a,wx}$
125 FAO	$3.5 \pm 0.1^{a,x}$	$0.32 \pm 0.07^{b,w}$	$3.4 \pm 0.0^{ab,w}$	$1.53 \pm 0.01^{a,x}$	$0.13 \pm 0.00^{a,x}$
Rain-fed	$4.1 \pm 0.1^{a,y}$	$0.17 \pm 0.03^{a,w}$	$2.2 \pm 0.0^{a,w}$	$1.62 \pm 0.17^{a,w}$	$0.13 \pm 0.02^{a,w}$
Deficit irrigation	$4.2 \pm 0.0^{a,y}$	$0.32 \pm 0.03^{b,w}$	$4.1 \pm 0.8^{ab,w}$	$1.64 \pm 0.03^{a,w}$	$0.13 \pm 0.00^{a,w}$
FAO	$4.2 \pm 0.0^{a,y}$	$0.31 \pm 0.00^{b,w}$	$3.9 \pm 0.0^{ab,y}$	$1.58 \pm 0.02^{a,w}$	$0.13 \pm 0.01^{a,w}$
125 FAO	$4.2 \pm 0.0^{a,y}$	$0.38 \pm 0.01^{b,w}$	$4.4 \pm 1.1^{b,w}$	$1.43 \pm 0.00^{a,w}$	$0.11 \pm 0.01^{a,w}$

Different letters within a column (a–c) indicate significant differences ($p < 0.05$) with respect to irrigation treatment in each sampling. Different letters within a column (w–y) indicate significant differences ($p < 0.05$) with respect to ripeness index for each treatment.

Table 4
Virgin olive oil organoleptic evaluation, as affected by the different irrigation treatments studied and the ripeness index of the fruits

	Ripeness index	Grade	Sensory attributes			K_{225}
			Fruity	Bitterness	Pungency	
2003/2004						
Rain-fed	$2.7 \pm 0.3^{a,x}$	Extra virgin	$6.1 \pm 0.2^{b,x}$	$8.2 \pm 0.4^{b,w}$	$7.8 \pm 0.3^{a,w}$	$0.78 \pm 0.01^{c,x}$
Deficit irrigation	$2.8 \pm 0.4^{a,x}$	Extra virgin	$6.2 \pm 0.5^{b,w}$	$8.0 \pm 0.3^{b,wx}$	$8.0 \pm 0.3^{a,wx}$	$0.67 \pm 0.07^{b,x}$
FAO	$3.1 \pm 0.3^{a,x}$	Extra virgin	$5.5 \pm 0.1^{b,w}$	$7.7 \pm 0.5^{ab,w}$	$7.7 \pm 0.3^{a,w}$	$0.66 \pm 0.04^{b,yz}$
125 FAO	$2.8 \pm 0.2^{a,w}$	Extra virgin	$4.9 \pm 0.3^{a,w}$	$7.2 \pm 0.3^{a,wx}$	$7.6 \pm 0.3^{a,w}$	$0.56 \pm 0.07^{a,xy}$
Rain-fed	$3.7 \pm 0.2^{a,y}$	Extra virgin	$5.4 \pm 0.2^{ab,w}$	$8.5 \pm 0.2^{c,w}$	$8.4 \pm 0.2^{ab,w}$	$0.77 \pm 0.01^{c,x}$
Deficit irrigation	$3.8 \pm 0.3^{a,y}$	Extra virgin	$6.2 \pm 0.3^{b,w}$	$8.3 \pm 0.2^{c,x}$	$8.5 \pm 0.1^{b,w}$	$0.64 \pm 0.07^{b,wx}$
FAO	$4.0 \pm 0.4^{a,y}$	Extra virgin	$5.5 \pm 0.2^{ab,w}$	$7.7 \pm 0.3^{b,w}$	$8.0 \pm 0.2^{ab,w}$	$0.56 \pm 0.04^{ab,x}$
125 FAO	$3.9 \pm 0.1^{a,y}$	Extra virgin	$5.3 \pm 0.2^{a,w}$	$6.9 \pm 0.4^{a,w}$	$8.0 \pm 0.2^{a,w}$	$0.49 \pm 0.08^{a,wx}$
Rain-fed	$5.7 \pm 0.4^{b,z}$	Extra virgin	$5.4 \pm 0.3^{ab,wx}$	$8.3 \pm 0.2^{a,w}$	$8.1 \pm 0.2^{ab,w}$	$0.66 \pm 0.05^{c,w}$
Deficit irrigation	$5.4 \pm 0.5^{ab,z}$	Extra virgin	$6.2 \pm 0.1^{b,w}$	$7.5 \pm 0.5^{a,w}$	$7.7 \pm 0.1^{a,x}$	$0.57 \pm 0.03^{b,w}$
FAO	$5.5 \pm 0.3^{ab,z}$	Extra virgin	$5.0 \pm 0.3^{a,w}$	$7.7 \pm 0.3^{a,w}$	$7.9 \pm 0.2^{a,w}$	$0.46 \pm 0.03^{a,w}$
125 FAO	$4.9 \pm 0.1^{a,z}$	Extra virgin	$6.0 \pm 0.1^{b,x}$	$8.0 \pm 0.3^{a,x}$	$8.0 \pm 0.2^{b,w}$	$0.41 \pm 0.09^{a,w}$
2004/2005						
Rain-fed	$2.8 \pm 0.2^{b,w}$	Extra virgin	$6.4 \pm 0.3^{a,w}$	$7.6 \pm 0.2^{a,w}$	$8.0 \pm 0.3^{a,w}$	$0.66 \pm 0.09^{a,w}$
Deficit irrigation	$2.3 \pm 0.1^{a,w}$	Extra virgin	$6.0 \pm 0.2^{a,x}$	$7.4 \pm 0.5^{a,w}$	$7.9 \pm 0.6^{a,wx}$	$0.70 \pm 0.00^{a,x}$
FAO	$2.5 \pm 0.2^{ab,w}$	Extra virgin	$5.6 \pm 0.4^{a,w}$	$6.7 \pm 0.3^{a,w}$	$7.5 \pm 0.2^{a,w}$	$0.67 \pm 0.00^{a,x}$
125 FAO	$2.4 \pm 0.1^{a,w}$	Extra virgin	$5.2 \pm 0.6^{a,w}$	$7.3 \pm 0.2^{a,w}$	$7.7 \pm 0.3^{a,w}$	$0.60 \pm 0.00^{a,y}$
Rain-fed	$3.4 \pm 0.0^{a,x}$	Extra virgin	$5.5 \pm 0.2^{ab,w}$	$7.0 \pm 0.5^{a,w}$	$7.4 \pm 0.5^{a,w}$	$0.60 \pm 0.08^{a,w}$
Deficit irrigation	$3.4 \pm 0.0^{a,x}$	Extra virgin	$4.9 \pm 0.4^{a,w}$	$7.0 \pm 0.3^{a,w}$	$7.1 \pm 0.3^{a,w}$	$0.60 \pm 0.03^{a,x}$
FAO	$3.4 \pm 0.0^{a,x}$	Extra virgin	$5.5 \pm 0.2^{ab,w}$	$6.9 \pm 0.4^{a,w}$	$7.6 \pm 0.2^{a,w}$	$0.59 \pm 0.03^{a,x}$
125 FAO	$3.5 \pm 0.1^{a,x}$	Extra virgin	$5.5 \pm 0.5^{b,w}$	$6.6 \pm 0.3^{a,w}$	$7.4 \pm 0.2^{a,w}$	$0.50 \pm 0.02^{a,x}$
Rain-fed	$4.1 \pm 0.1^{a,y}$	Extra virgin	$6.0 \pm 0.4^{a,w}$	$7.4 \pm 0.3^{ab,w}$	$7.6 \pm 0.4^{a,w}$	$0.59 \pm 0.12^{b,w}$
Deficit irrigation	$4.2 \pm 0.0^{a,y}$	Extra virgin	$5.4 \pm 0.3^{a,wx}$	$7.6 \pm 0.2^{b,w}$	$8.2 \pm 0.2^{a,x}$	$0.57 \pm 0.01^{b,w}$
FAO	$4.2 \pm 0.0^{a,y}$	Extra virgin	$5.4 \pm 0.3^{a,w}$	$7.4 \pm 0.3^{b,w}$	$7.5 \pm 0.3^{a,w}$	$0.54 \pm 0.01^{ab,w}$
125 FAO	$4.2 \pm 0.0^{a,y}$	Extra virgin	$5.9 \pm 0.2^{a,w}$	$6.6 \pm 0.4^{a,w}$	$7.4 \pm 0.3^{a,w}$	$0.36 \pm 0.04^{a,w}$

Different letters within a column (a–c) indicate significant differences ($p < 0.05$) with respect to irrigation treatment in each sampling. Different letters within a column (w–y) indicate significant differences ($p < 0.05$) with respect to ripeness index for each treatment.

intensity of these positive attributes was observed, more marked in the case of bitterness, by increasing the amount of water delivered through irrigation. This observation is very relevant from the olive quality and marketing point of view since, although bitterness is a positive sensory attribute in virgin olive oil, a high level of bitterness could cause consumers to reject the oil. A high level of bitterness is a unique characteristic of the Cornicabra variety virgin olive oils' sensory profile, and therefore the use of irrigation could produce a desirable descent in the intensity of this attribute and hence increase consumer preference.

However, in the 2004/2005 crop season no statistically significant differences were obtained in the positive sensory attributes, including bitterness, between the olive oils obtained under rain-fed and irrigation conditions.

Olive oil bitterness can also be measured by the instrumental K_{225} parameter called bitterness index (Gutiérrez-Rosales et al., 1992). In the 2003/2004 crop, a dramatic decrease in the bitterness index was observed as the water dose applied to olive trees increased (Table 4), varying from 0.77 to 0.49, respectively, for RF and 125 FAO for the sampling close to a ripeness index of 4.0. However, in the 2004/2005 crop, no statistically significant differences were obtained.

3.3.2. Fatty acid composition

The effect of irrigation and ripening on the main fatty acid composition of the different types of virgin olive oils is shown in Table 5.

In both crop seasons studied, and in all irrigation treatments studied, the palmitic acid content slightly decreased as fruit ripened, i.e., from 10.4% down to 9.1% and from 11.4% to 9.7%, respectively, for RF and FAO irrigation treatments, whereas oleic and linoleic acids showed an opposite trend, i.e., the oleic acid content varied from 78.4% to 79.5% and the linoleic acid from 3.7% to 4.6% under the FAO conditions. The increase in oleic acid content is due to the triacylglycerols active biosynthesis which takes place throughout fruit ripening, involving a fall in the relative percentage of the oil's palmitic acid content. On the other hand, the increase in linoleic acid content is due to the transformation of oleic acid into linoleic acid by the oleate desaturase activity which is active during triacylglycerol biosynthesis (Sanchez & Harwood, 2002). The content of the other fatty acids remained practically unchanged during fruit ripening.

In the 2003/2004 crop, rain-fed olive oils always showed a statistically significant higher content of oleic acid, whereas olive oils from irrigated trees had higher contents

Table 5
Virgin olive oil main fatty acid composition, as affected by the different irrigation treatments studied and the ripeness index of the fruits

	Ripeness index	C16:0 (%)	C18:1 (%)	C18:2 (%)
2003/2004				
Rain-fed	$2.7 \pm 0.3^{a,x}$	$10.4 \pm 0.4^{a,x}$	$80.2 \pm 0.4^{b,x}$	$3.5 \pm 0.3^{a,w}$
Deficit irrigation	$2.8 \pm 0.4^{a,x}$	$11.1 \pm 1.0^{ab,xy}$	$78.2 \pm 1.9^{a,w}$	$4.2 \pm 0.5^{b,w}$
FAO	$3.1 \pm 0.3^{a,x}$	$11.4 \pm 0.3^{ab,y}$	$78.4 \pm 0.2^{a,wx}$	$3.9 \pm 0.1^{ab,wx}$
125 FAO	$2.8 \pm 0.2^{a,w}$	$11.8 \pm 0.3^{b,y}$	$77.9 \pm 0.3^{a,wx}$	$3.8 \pm 0.1^{ab,wx}$
Rain-fed	$3.7 \pm 0.2^{a,y}$	$9.7 \pm 0.6^{a,wx}$	$80.8 \pm 0.5^{c,y}$	$3.7 \pm 0.2^{a,w}$
Deficit irrigation	$3.8 \pm 0.3^{a,y}$	$10.0 \pm 0.8^{ab,wx}$	$79.6 \pm 1.2^{b,w}$	$4.4 \pm 0.3^{b,w}$
FAO	$4.0 \pm 0.4^{a,y}$	$10.6 \pm 0.2^{bc,x}$	$78.7 \pm 0.3^{ab,x}$	$4.3 \pm 0.4^{b,yz}$
125 FAO	$3.9 \pm 0.1^{a,y}$	$11.0 \pm 0.4^{c,x}$	$78.2 \pm 0.5^{a,x}$	$4.2 \pm 0.5^{b,y}$
Rain-fed	$5.7 \pm 0.4^{b,z}$	$9.1 \pm 0.8^{a,w}$	$81.1 \pm 0.4^{c,y}$	$4.1 \pm 0.5^{a,w}$
Deficit irrigation	$5.4 \pm 0.5^{ab,z}$	$9.4 \pm 0.8^{ab,w}$	$79.7 \pm 1.2^{b,w}$	$4.7 \pm 0.3^{b,w}$
FAO	$5.5 \pm 0.3^{ab,z}$	$9.7 \pm 0.4^{ab,w}$	$79.5 \pm 0.6^{b,y}$	$4.6 \pm 0.3^{ab,z}$
125 FAO	$4.9 \pm 0.1^{a,z}$	$10.2 \pm 0.2^{b,w}$	$78.4 \pm 0.3^{a,x}$	$4.8 \pm 0.2^{b,z}$
2004/2005				
Rain-fed	$2.8 \pm 0.2^{b,w}$	$11.0 \pm 0.2^{a,x}$	$78.2 \pm 0.2^{a,w}$	$4.3 \pm 0.1^{c,w}$
Deficit irrigation	$2.3 \pm 0.1^{a,w}$	$11.7 \pm 0.0^{b,x}$	$78.8 \pm 0.1^{a,w}$	$3.3 \pm 0.1^{a,w}$
FAO	$2.5 \pm 0.2^{ab,w}$	$11.5 \pm 0.0^{b,y}$	$78.3 \pm 0.2^{a,w}$	$3.7 \pm 0.1^{b,w}$
125 FAO	$2.4 \pm 0.1^{a,w}$	$11.6 \pm 0.1^{b,y}$	$78.7 \pm 0.3^{a,w}$	$3.5 \pm 0.1^{ab,w}$
Rain-fed	$3.4 \pm 0.0^{a,x}$	$10.3 \pm 0.4^{a,wx}$	$78.9 \pm 0.5^{a,w}$	$4.4 \pm 0.0^{c,wx}$
Deficit irrigation	$3.4 \pm 0.0^{a,x}$	$10.9 \pm 0.0^{b,w}$	$79.1 \pm 0.1^{a,w}$	$3.7 \pm 0.0^{a,x}$
FAO	$3.4 \pm 0.0^{a,x}$	$10.7 \pm 0.0^{ab,x}$	$78.8 \pm 0.2^{a,w}$	$4.0 \pm 0.1^{b,w}$
125 FAO	$3.5 \pm 0.1^{a,x}$	$10.8 \pm 0.1^{ab,x}$	$78.9 \pm 0.1^{a,w}$	$3.9 \pm 0.1^{ab,x}$
Rain-fed	$4.1 \pm 0.1^{a,y}$	$9.9 \pm 0.2^{a,w}$	$78.8 \pm 0.2^{a,w}$	$4.9 \pm 0.2^{b,x}$
Deficit irrigation	$4.2 \pm 0.0^{a,y}$	$10.7 \pm 0.2^{b,w}$	$79.0 \pm 0.2^{a,w}$	$4.2 \pm 0.1^{a,y}$
FAO	$4.2 \pm 0.0^{a,y}$	$10.3 \pm 0.0^{ab,w}$	$78.7 \pm 0.2^{a,w}$	$4.6 \pm 0.1^{b,x}$
125 FAO	$4.2 \pm 0.0^{a,y}$	$10.5 \pm 0.0^{b,w}$	$78.7 \pm 0.1^{a,w}$	$4.6 \pm 0.0^{b,y}$

Different letters within a column (a–c) indicate significant differences ($p < 0.05$) with respect to irrigation treatment in each sampling. Different letters within a column (w–y) indicate significant differences ($p < 0.05$) with respect to ripeness index for each treatment.

palmitic and linoleic acids. As a consequence, the unsaturated/saturated and MUFA/PUFA ratios were significantly higher in oils obtained in rain-fed conditions, in line with the results obtained by Salas et al. (1997). However, these changes are very slight and do not have any nutritional relevance.

3.3.3. Natural antioxidants content

The values of the α-tocopherol and total phenol content and the oxidative stability of the oils from the different treatments studied are shown in Table 6.

The α-tocopherol content decreased slightly during ripening, whereas insignificant differences in its concentration were observed between the irrigation treatments studied.

Fig. 1 illustrates the evolution of the total phenol content of oils in the four irrigation treatments studied throughout fruit maturation in the 2003/2004 crop season. The total phenol content of the oils was significantly affected by the irrigation such that, as the water dose applied to olive trees increased, the amount of the phenolic compounds in the virgin olive oil obtained decreased significantly (Fig. 1 and Table 6). For example, in crop 2003/2004, in the case of rain-fed virgin olive oil samples, the total phenol content decreased from 1700 to 900 mg/kg through fruit ripening, whereas for olive oil samples under FAO treatment, the phenol content decreased from 1080 to 650 mg/kg. Panelli, Famiani, Servili, and Montedoro (1989), Salas et al. (1997), Patumi et al. (1999, 2002) observed similar behaviour for other olive cultivars, such as Picual, Nocellara del Belice, Kalamata and Ascolana Tenera. In the 2004/2005 crop, although the total phenol content in the olive oil samples was lower, a trend similar to that of the previous crop season with the water applied was observed (Table 6). Moreover, the regression lines of RDI and FAO treatments were closer (data not shown), showing that the RDI strategy employed in the second crop season, produced an olive oil whose composition, specifically regarding the phenolic compounds, was more similar to that of FAO than in the previous year, and therefore these RDI conditions are apparently more efficient.

As far as the ripening of the olive fruit is concerned, the mean concentration of phenolic compounds in the olive oils greatly decreased in both crop seasons studied, as previously described in the same olive variety (Salvador et al., 2001; Salvador, Aranda, Gómez-Alonso, & Fregapane, 2003).

The observed differences in phenol concentration in the oils could be a consequence of the different water stress level of olives from rain-fed to irrigation conditions that involve changes in the activity of enzymes responsible for phenolic compound synthesis, such as L-phenylalanine ammonia-lyase whose activity is greater under higher water

Table 6
Virgin olive oil antioxidants content and oxidative stability, as affected by the different irrigation treatments studied and the ripeness index of the fruits

	Ripeness index	α-Tocopherol (mg/kg)	Total phenols (mg/kg)	Oxidative stability (h)
2003/2004				
Rain-fed	$1.5 \pm 0.5^{a,w}$	$283 \pm 64^{a,x}$	$1719 \pm 130^{c,y}$	–
Deficit irrigation	$1.8 \pm 0.6^{ab,w}$	$284 \pm 59^{a,w}$	$1354 \pm 42^{b,y}$	–
FAO	$2.5 \pm 0.4^{b,w}$	$222 \pm 25^{a,w}$	$1076 \pm 122^{a,z}$	–
125 FAO	$2.0 \pm 0.3^{ab,v}$	$273 \pm 33^{a,x}$	$968 \pm 254^{a,y}$	–
Rain-fed	$2.7 \pm 0.3^{a,x}$	$235 \pm 43^{a,wx}$	$1380 \pm 62^{c,x}$	$38.3 \pm 0.5^{d,x}$
Deficit irrigation	$2.8 \pm 0.4^{a,x}$	$259 \pm 35^{a,w}$	$1084 \pm 146^{b,x}$	$34.0 \pm 0.4^{c,w}$
FAO	$3.1 \pm 0.3^{a,x}$	$212 \pm 25^{a,w}$	$998 \pm 85^{b,yz}$	$31.1 \pm 1.3^{b,x}$
125 FAO	$2.8 \pm 0.2^{a,w}$	$254 \pm 26^{a,wx}$	$805 \pm 125^{a,xy}$	$27.1 \pm 0.1^{a,w}$
Rain-fed	$3.2 \pm 0.3^{a,xy}$	$226 \pm 41^{ab,wx}$	$1294 \pm 64^{c,x}$	–
Deficit irrigation	$3.5 \pm 0.4^{a,xy}$	$252 \pm 29^{b,w}$	$946 \pm 40^{b,x}$	–
FAO	$3.6 \pm 0.4^{a,xy}$	$201 \pm 25^{a,w}$	$868 \pm 78^{b,xy}$	–
125 FAO	$3.4 \pm 0.3^{a,x}$	$237 \pm 8^{ab,wx}$	$699 \pm 139^{a,wx}$	–
Rain-fed	$3.7 \pm 0.2^{a,y}$	$225 \pm 47^{a,wx}$	$1364 \pm 107^{c,x}$	$38.4 \pm 0.5^{d,x}$
Deficit irrigation	$3.8 \pm 0.3^{a,y}$	$242 \pm 44^{a,w}$	$1004 \pm 160^{b,x}$	$31.9 \pm 1.3^{c,w}$
FAO	$4.0 \pm 0.4^{a,y}$	$204 \pm 21^{a,w}$	$824 \pm 56^{ab,x}$	$30.1 \pm 1.3^{b,x}$
125 FAO	$3.9 \pm 0.1^{a,y}$	$227 \pm 25^{a,w}$	$651 \pm 124^{a,wx}$	$24.6 \pm 0.4^{a,w}$
Rain-fed	$5.7 \pm 0.4^{b,z}$	$193 \pm 32^{a,w}$	$905 \pm 189^{b,w}$	$34.4 \pm 0.3^{b,w}$
Deficit irrigation	$5.4 \pm 0.5^{ab,z}$	$226 \pm 31^{a,w}$	$757 \pm 12^{ab,w}$	$28.5 \pm 3.2^{ab,w}$
FAO	$5.5 \pm 0.3^{ab,z}$	$202 \pm 11^{a,w}$	$654 \pm 108^{a,w}$	$24.3 \pm 0.5^{a,x}$
125 FAO	$4.9 \pm 0.1^{a,z}$	$233 \pm 19^{a,w}$	$536 \pm 124^{a,w}$	$22.2 \pm 3.4^{a,w}$
2004/2005				
Rain-fed	$2.8 \pm 0.2^{b,w}$	$298 \pm 17^{b,w}$	$1019 \pm 216^{a,w}$	$29.8 \pm 2.2^{a,w}$
Deficit irrigation	$2.3 \pm 0.1^{a,w}$	$250 \pm 7^{a,w}$	$905 \pm 10^{a,x}$	$32.5 \pm 2.0^{a,w}$
FAO	$2.5 \pm 0.2^{ab,w}$	$272 \pm 10^{ab,x}$	$877 \pm 11^{a,x}$	$30.3 \pm 0.9^{a,x}$
125 FAO	$2.4 \pm 0.1^{a,w}$	$271 \pm 19^{ab,w}$	$724 \pm 38^{a,x}$	$28.7 \pm 1.0^{a,x}$
Rain-fed	$3.4 \pm 0.0^{a,x}$	$280 \pm 14^{b,w}$	$921 \pm 183^{b,w}$	$29.7 \pm 2.5^{a,w}$
Deficit irrigation	$3.4 \pm 0.0^{a,x}$	$238 \pm 11^{a,w}$	$691 \pm 11^{ab,w}$	$28.2 \pm 1.6^{a,w}$
FAO	$3.4 \pm 0.0^{a,x}$	$263 \pm 2^{b,wx}$	$724 \pm 57^{ab,w}$	$28.5 \pm 1.6^{a,wx}$
125 FAO	$3.5 \pm 0.1^{a,x}$	$238 \pm 3^{a,w}$	$551 \pm 14^{a,wx}$	$25.5 \pm 0.1^{a,x}$
Rain-fed	$4.1 \pm 0.1^{a,y}$	$269 \pm 12^{b,w}$	$818 \pm 224^{b,w}$	$27.2 \pm 3.4^{b,w}$
Deficit irrigation	$4.2 \pm 0.0^{a,y}$	$226 \pm 3^{a,w}$	$739 \pm 51^{b,w}$	$27.4 \pm 1.1^{b,w}$
FAO	$4.2 \pm 0.0^{a,y}$	$241 \pm 8^{ab,x}$	$679 \pm 19^{b,w}$	$23.9 \pm 1.8^{ab,w}$
125 FAO	$4.2 \pm 0.0^{a,y}$	$241 \pm 17^{ab,w}$	$423 \pm 102^{a,w}$	$18.3 \pm 3.6^{a,w}$

Different letters within a column (a–d) indicate significant differences ($p < 0.05$) with respect to irrigation treatment in each sampling. Different letters within a column (w–z) indicate significant differences ($p < 0.05$) with respect to ripeness index for each treatment.

stress conditions (Patumi et al., 1999; Tovar, Romero, & Girona, 2002).

As was previously mentioned, the concentration of phenolic compounds affects the sensory bitterness attribute with the beneficial and important consequences earlier discussed in the case of the Cornicabra olive oil variety, as well as oxidative stability. In terms of the latter, the observed decrease in the oxidative stability does not affect the Cornicabra virgin olive oil shelf-life or quality since this is a very stable and phenol-rich olive oil variety, but could significantly reduce the shelf-life of other varieties, such as Arbequina, due to its naturally poor phenol content.

3.3.4. Chlorophyll and carotenoid pigments

These contents of the oils was not influenced by irrigation (data not shown). However, as expected, an important decrease in pigment content during fruit ripening was observed, since at later stages of fruit ripening pigments were diminished to only a few ppm, as previously reported for the same variety (Salvador et al., 2001).

3.4. Discriminant analysis

Results obtained from Anova and principal component analyses were applied to stepwise discriminant analysis showing that total phenol content, oleic acid, linoleic acid and K_{232} were the most useful variables for classification of the virgin olive oils from the different treatments studied. The first two discriminant functions of the statistical analysis explained 96% of the variance (84% and 12%, respectively) for both crop seasons studied. The plotting of the discriminant functions is shown in Fig. 2, which shows that virgin olive oils obtained using rain-fed conditions were clearly separated from those obtained using the different irrigation treatments studied. Virgin olive oils from the FAO treatment were midway between those of

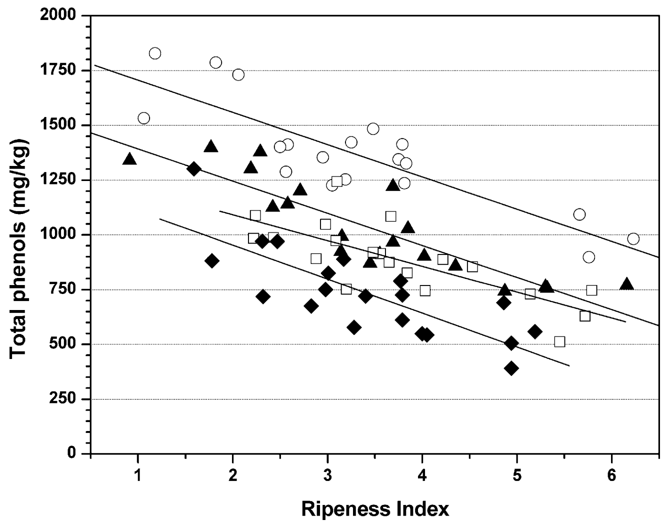

Fig. 1. Evolution of total phenol content throughout fruit maturation in the four treatments studied in crop season 2003/2004. ○, rain-fed; ▲, regulated deficit irrigation, RDI; □, FAO; ◆, 125 FAO.

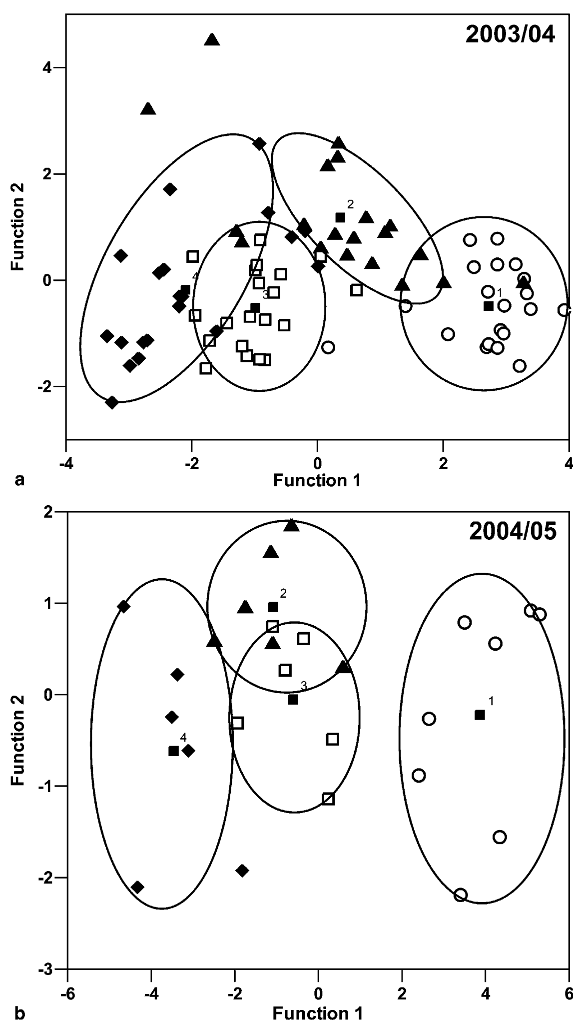

Fig. 2. Plotting of the discriminant functions of the virgin olive oils obtained from the four irrigation treatments studied in the two crop seasons. Variables: total phenol content, oleic acid, linoleic acid and K_{232} ○, rain-fed; ▲, regulated deficit irrigation, RDI; □, FAO; ◆, 125 FAO.

RDI and 125 FAO treatments in 2003/2004. Moreover, it is very important to note that the RDI strategy planned in the second crop season, where water was applied only from the beginning of August, produced olive oil more similar to that obtained by FAO conditions as far as its composition and quality is concerned, but with an important reduction in the amount of water used in the olive grove.

The selection of an optimal irrigation treatment for traditional olive orchards in Castilla-La Mancha, where water resources are scarce, calls for the establishment of a suitable compromise between olive production, quality of virgin olive oil and water consumption. Therefore, in terms of the results obtained in this two-year assay, the best irrigation treatment for this region is a regulated deficit irrigation (RDI), and apparently better results are obtained applying water only from the beginning of August, when the accumulation of oil begins in the fruit, since it is sufficient for the olive tree to recover from water stress and, moreover, similar results to FAO conditions are obtained.

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