Regulated and sustained deficit irrigation: impacts on yield components of olive trees

A. Fernandes-Silva[1,2,a], L. Canas[1,b], T. Brito[1,3] and P. Marques[1,2,c]

[1]Agronomy Department, University of Trás-os-Montes e Alto Douro, Quinta dos Prados, 5000-801 Vila Real, Portugal; [2]Centre for Research and Technology of Agro-Environment and Biological Sciences, University of Trás-os-Montes e Alto Douro, Quinta dos Prados, 5000-801 Vila Real, Portugal; [3]CEFAGE – Centre for Advanced Studies in Management and Economics, Évora, Portugal.

Abstract

Nowadays, to overcome the negative impact of climatic change, the irrigation of the land occupied by olive grove is increasing. So, deficit irrigations (DI) practices are important to reduce agricultural water use. In this experiment, mature olive ('Madural') trees for oil production received full irrigation (FI), sustained deficit irrigation (SDI) and regulated deficit irrigation (RDI) and were compared to commercial olive orchard (Northeast of Portugal) in 2019. In deficit irrigation treatments, the total amount of irrigation ranged from 30 to 60% of FI, which was equivalent to a water volume of 100% of estimated evapotranspiration. Water stress caused a significant reduction of both fresh and dry yield in all treatments except in RDI_{60}. Oil concentration was negatively affected in both, RDI and in SDI_{30}, irrigation treatments. The highest oil yield was attained in FI (560±72.9 kg ha^{-1}), the lowest yield - in SDI_{30} (355.7±30.6 kg ha^{-1}). The differences, which were observed between FI and DI treatments, were significant. Oil yield responded linearly to the seasonal irrigation water (r^2=0.92, p=0.01) with irrigation efficiency of 0.62 kg m^{-3} for oil production. Although the results are preliminary, they showed that RDI_{60} treatment could save 50% of water without strong effect on yield and with an economic profit similar to FI. Additionally, SDI_{30} seems to be a good DI strategy in a situation of very low water availability for irrigation in order to mitigate adverse climate change effects. With this strategy, the fruit and oil yields were reduced 30-37% but water savings were 70% compared to FI.

Keywords: economic profit, *Olea europaea* L., oil concentration water use efficiency

INTRODUCTION

Olive tree (*Olea europaea* L.) is one of the most important crops of the Mediterranean region, where the climate is typically characterized by highly potential evaporation, variable rainfall during the growing season, with recurring water shortages. It is well known that water availability is the major environmental factor that constrain olive production in many regions of the world.

The olive tree is well adapted to tolerate drought, and can survive and produce fruits with little available water (Fernandes-Silva et al., 2010; Girón et al., 2015), a trait that is associated with the species' ability to maintain photosynthesis and transpiration at low water potential (Sofo et al., 2008; Moriana et al., 2003; Fernandes-Silva et al., 2016). Despite the drought tolerance of olive, in the near future it will be exposed to longer summer shortages, associated with high intensity of solar radiation and air temperature, creating conditions under which water deficit might become critical even for drought adapted species. Thus, nowadays, the need to manage irrigation efficiently gains special attention.

When availability of water resources is scarce, the irrigation timing is crucial to ensure plant production and to minimize yield reduction. In fruit trees, regulated deficit irrigation

---

[a]E-mail: anaaf@utad.pt

[b]E-mail: al62695@utad.eu

[c]E-mail: pedro.marques@utad.pt

Acta Hortic. 1327. ISHS 2021. DOI 10.17660/ActaHortic.2021.1327.34
Proc. IV International Symposium on Horticulture in Europe – SHE2021
Eds.: J.N. Wünsche and A. Milyaev

(RDI), with periods when the irrigation can be stopped or reduced to a minimum level, based on physiological aspects of the response of plants to water deficit, has been proposed to save water without major effects on yield (Chalmers et al., 1981). However, the success of the adoption of this irrigation strategy requires a precise knowledge of phenological stages, which are sensitive to water deficit. In olive tree, it was proven that water stress early in the season may reduce the yield due to negative effects on flowering, fruit set and on the first phase of fruit growth with intensive cell division (Goldhamer, 1999). The second phase of fruit development, which correspond to pit hardening, is the less sensitive to water deficit (Goldhamer, 1999). Oil biosynthesis in fruits starts toward the end of pit hardening, in the third phase of fruit growth. At this stage, the fast growth of the fruit occurs due to cell expansion, in which water availability determines the size of the fruit and the accumulation of oil. Consequently, this phase is very sensitive to water deficit (Lavee and Wodner, 1991).

The aim of this study was to evaluate the effect of various sustained and regulated deficit irrigation strategies on different yield components of cultivar 'Madural', with comparison to fully irrigated olive trees.

MATERIALS AND METHODS

Experimental area

The experiment was conducted during the season of 2019 in a commercial olive orchard located in Mirandela (Lat. 41.40°, Long. -7.3°) at the North-East region of Portugal with a Csa climate by Köppen-Geiger classification (Peel et al., 2007). The experimental plot of 1.5 ha included 13-year-old olive trees of cultivar 'Madural' (7×7 m) for oil production. The amount of water applied by irrigation was scheduled based on mean daily evapotranspiration of the crop (ET), which was estimated from the reference evapotranspiration (ET_o) calculated with the Penman-Monteith methodology (Allen et al., 1998) and adjusted by a monthly local crop coefficient (K_c) according to Fernandes-Silva et al. (2010). The correction coefficient for ground cover (K_r) was done according to Fereres and Castel (1981).

Five irrigation treatments were tested: i) full irrigated trees (FI) that received an amount of water equivalent to 100% of estimated evapotranspiration (ET); ii) sustained deficit irrigation, irrigated with an amount of water corresponding to 60% of ET (SDI_{60}); iii) sustained deficit irrigation, irrigated with an amount of water corresponding to a 30% of ET (SDI_{30}) and hence, of FI; iv) regulated deficit irrigation(RDI_{100}), irrigated equally to FI except in the pit hardening period, in which irrigation was reduced to 10%, and v) regulated deficit irrigation, in which the trees were irrigated with 60% of ET (RDI_{60}) in the same period as the RDI_{100} with irrigation cut off in the pit hardening period (end of July to the third week of August), after that was irrigated equally to SDI_{60}. Irrigation started on July 4th and stopped on October 10th. Olive trees were irrigated with a drip line emitters (±4 L h^{-1}). In each plot of each irrigation treatment, a water counter was placed. The seasonal amount of irrigation applied was 47.9, 28.7, 14.4, 26.4 and 25.7 mm, in FI, SDI_{60}, SDI_{30}, RDI_{100} and RDI_{60} irrigation treatments, respectively.

Plant measurements

Plant water status was evaluated by measurements of midday shoot water potential (Ψ_{MD}) and relative water content (RWC) in the leaves on three olive trees per treatment with an interval of two weeks. The methodology used is described in Fernandes-Silva et al. (2016).

Plant height, as well as longitudinal and transverse crown diameters were measured by a large ruler, at 0.25 m intervals. These parameters were used for estimation of canopy volume (assuming an ellipsoid) and the fraction of ground cover. Leaf area density (LAD) was determined using measurements of diffuse radiation interception performed by a *Plant Canopy Analyzer* (LAI-2200; Li-Cor, Lincoln, NE, USA) by placing the instrument at the soil level in different points around the olive tree. Measurements of diffuse radiation was done either on cloudy days or just before sunrise to avoid direct radiation.

Olive trees were harvested at the end of November. The yield from seven trees per treatment was weighted in the field. A sub-sample of 500 g fresh fruit from each tree was taken to evaluate the following parameters: fresh fruit mass, dry matter, oil content, fruit volume, pulp: stone ratio and equatorial fruit diameter. Oil was quantified by near infrared analysis (NIR) (Correa et al., 2019).

Water use efficiency for irrigation applied (IA) for olive oil production (WUE_{Oil}) was obtained as the ratio between oil content in dry matter and seasonal irrigation intensity.

Statistical data analysis (ANOVA and Tukey HSD test) was performed with the SPSS program (IBM SPSS Statistics 26).

RESULTS AND DISCUSSION

During the irrigation season a maximum ET_o=6.9 mm was attained in middle of July (day of the year 198). Total precipitation was 106 mm, 25% of which occurred in the middle of September and 18% in the end of August. Maximum vapor pressure deficit was 2.3 kPa on 23 July (Figure 1). Maximum air temperature recorded was 39°C, whereas maximum mean air temperature was 29°C.

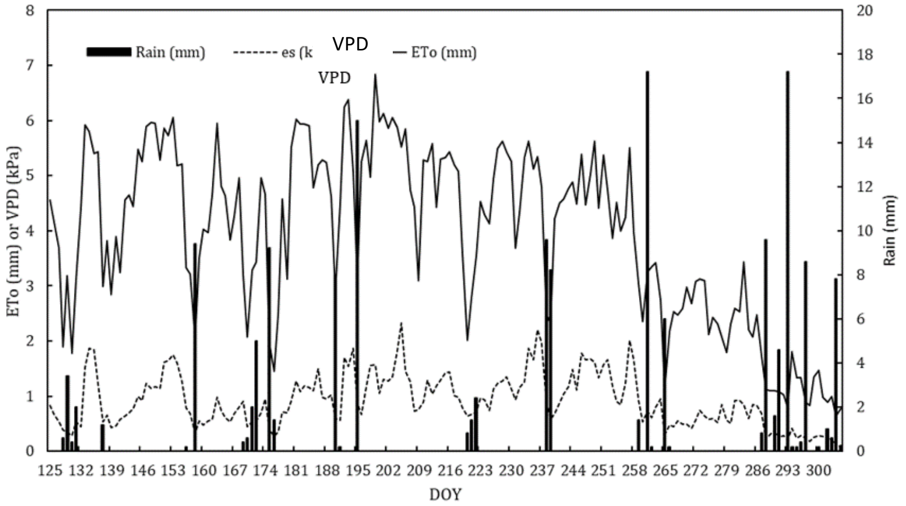

Figure 1. Seasonal evolution of daily reference evapotranspiration (ET_o), vapor pressure deficit (VPD) and rainfall during the experiment. DOY = day of the year.

Plant water status (Table 1) evaluated by midday shoot water potential (Ψ_{MD}) and relative water content (RWC) in the leaves showed that olives trees, which received FI, were well watered, whereas deficit irrigated olives plants in SDI_{30} were more stressed, as expected. However, these plants experienced a moderate water stress, according to the previous studies by Fernandes-Silva et al. (2016). Water status of the plants with SDI_{60} and RDI_{60} irrigation did not differ significantly. These trees experienced a slight water stress when compared to full irrigated trees. Plants of RDI_{100} had values of Ψ_{MD} similar to the SDI_{60} and RDI_{60} and were 25 to 33% lower than those of FI, although in RWC values of the same treatments no differences were detected.

Fruit fresh and fruit dry weight were higher in FI and RDI_{60} treatments, whereas the other deficit irrigation treatments caused smaller fruits (Table 2). These parameters showed statistical differences ($p<0.05$) comparing the fruit from SDI_{60} (3.26±0.17) and RDI_{60} (2.71±0.32). Although the trees with RDI_{100} produced fruits smaller than the trees from other treatments, differences were not statistically significant. Fruit size of the control treatment was larger than those of deficit irrigation treatments but was not statistically different from all irrigation treatments. No differences were observed for fruit volume, equatorial diameter and for to the relation pulp: stone among all the irrigations treatments. The lower biometric parameters described for RDI_{60} may be attributed to the large number of fruits per tree volume, which was the highest (1024±357) followed by FI, although differences between them were not significant ($p<0.05$). The lowest number of fruits was observed in SDI$_{60}$ treatment (555±112) with no differences compared to SDI$_{30}$ and RD$_{100}$.

Table 1. Mean values of shoot midday water potential (Ψ_{MD}) and relative water content (RWC) in the leaves of two representative days during irrigation season for full irrigated (FI), continuous deficit irrigation (SDI$_{60}$ and SDI$_{30}$) and regulated deficit irrigation (RDI$_{100}$ and RDI$_{60}$) treatments. Values of leaf area density (LAD) and canopy volume (V) are also presented.

Treatment	**August 1st**		**October 9th**		**LAD**	**V**
%ET	**Ψ_{MD} (MPa)**	**RWC (%)**	**Ψ_{MD} (MPa)**	**RWC (%)**	**(m^{-1})**	**(m^{-3})**
FI	-2.1±0.3^{a}	92.2±1.3^{a}	-2.2±0.1^{a}	94.2±3.9^{a}	1.7±0.22^{a}	5.3±1.0^{a}
SDI$_{60}$	-2.6±0.1^{ab}	90.2±1.5^{a}	-2.9±0.2^{ab}	89.3±10^{a}	1.5±0.22^{b}	6.5±1.7^{b}
SDI$_{30}$	-2.7±0.1^{b}	89.8±1.7^{a}	-3.8±0.1^{c}	84.7±1.8^{b}	1.7±0.40^{a}	4.7±1.3^{c}
RDI$_{100}$	-2.8±0.4^{b}	91.0±3.0^{a}	-3.3±0.7^{b}	89.7±2.4^{a}	1.4±0.27^{b}	5.5±1.8^{a}
RDI$_{60}$	-2.9±0.1^{b}	89.3±1.4^{a}	-3.2±1.0^{b}	90.9±1.4^{a}	1.6±0.27^{a}	5.5±1.4^{a}

Values followed by the same letter, within the same column, were not significantly different ($p<0.05$), according to Tukey's least significant difference test.

Table 2. Effects of irrigation treatment on the yield components for the full irrigated (FI), continuous deficit irrigation (SDI$_{60}$ and SDI$_{30}$) and regulated deficit irrigation (RDI$_{100}$ and RDI$_{60}$) treatments, for 'Madural' in 2019.

	Irrigation treatment (%ET)				
	FI	**SDI$_{60}$**	**SDI$_{30}$**	**RDI$_{100}$**	**RDI$_{60}$**
Fresh fruit yield (kg ha^{-1})	3,208.6±437.8^{a}	2,367.9±146.0^{c}	2,217.8±168.4^{c}	2,499.0±361.2^{bc}	2,981.3±357.3^{ab}
Fruit dry yield (kg ha^{-1})	1,656.1±215.8^{a}	1,1214.3±83.8^{b}	1,1158,7±98.9^{c}	1,288.1±220.0^{b}	1,511.3±207.3^{ab}
Yield/TCSA^{a} (kg m^{-2})	1,340.1±234.4^{a}	991.1±129.5^{b}	1,128.5±268.4^{c}	1,245.4±163.1^{a}	1,440.7±296.1^{a}
Oil content (% dry weight)	33.8±1.9^{a}	34.3±2.0^{a}	30.7±1.0^{b}	30.4±1.3^{bc}	28.8±1.0^{c}
Oil content (% fresh weight)	16.9±0.96^{a}	17.1±0.80^{a}	15.6±0.20^{b}	15.5±0.36^{bc}	14.6±0.58^{c}
Oil yield (kg ha^{-1})	560.0±72.9^{a}	416.5±28.8^{b}	355.7±30.6^{b}	391.6±66.9^{b}	435.3±59.7^{b}
Fruit fresh weight (g $fruit^{-1}$)	3.07±0.26^{ab}	3.26±0.17^{b}	2.69±0.28^{a}	2.87±0.23^{ab}	2.71±0.32^{a}
Fruit dry weight (g $fruit^{-1}$)	1.59±0.13^{ac}	1.67±0.06^{a}	1.40±0.13^{c}	1.47±0.09^{abc}	1.37±0.15^{bc}
Fruit volume (cm^3 $fruit^{-1}$)	2.98±0.24^{a}	3.17±0.13^{a}	2.52±0.29^{a}	2.74±0.32^{a}	2.60±0.44^{a}
Maximum diameter of fruits (mm $fruit^{-1}$)	15.39±0.65^{a}	15.75±0.39^{a}	14.62±0.87^{a}	15.14±0.44^{a}	14.63±0.49^{a}
Pulp/stone	4.68±0.41^{a}	4.91±0.16^{a}	4.10±0.40^{a}	4.34±0.44^{a}	3.90±0.25^{a}
Fruit number/canopy Volume (fruits m^{-3})	898±223^{abc}	555±122^{b}	828±235^{abc}	861±176^{abc}	1024±357^{c}

Values followed by the same letter, within the same row, were not significantly different ($p<0.05$), according to Tukey's least significant difference test.

^{a}TCSA: trunk cross sectional area.

The higher values for fresh and dry matter of fruit yield (kg ha^{-1}) was observed in FI, followed by RDI$_{60}$ (93% of FI), but no statistical differences were observed between them (Table 2). Although fruit yield of RDI$_{100}$ was lower than that of RDI$_{60}$, the differences were not statistically significant ($p>0.05$). Fruit yield of the RDI$_{100}$ was statistically similar ($p>0.05$) to that obtained for both sustained deficit irrigations treatments (SDI$_{60}$ and SDI$_{30}$), although it showed higher values than these treatments. Moreover, we observed highly significant differences ($p<0.01$) in fruit yield when compared FI and RDI$_{60}$, with SDI$_{60}$ and SDI$_{30}$. Yield reduction was 27% for SDI$_{60}$ and 30% for SDI$_{30}$. To eliminate the effect olive tree parameters on the differences (Table 2) in fruit yields, the latter were normalized (using dry matter values) to trunk cross sectional area. Again, the results indicated that fruit yield was higher in FI and RDI$_{60}$, followed by RDI$_{100}$, SDI$_{30}$, SDI$_{60}$. No statistical differences were found between RDI$_{100}$, RDI$_{60}$ and FI. The low yield obtained in SDI$_{60}$ can mainly be explained by low number of fruits per tree (3,455±301 compared to 4,670±497 in FI). The fruit weight was not negatively affected by water deficit. In SDI_{30} treatment, the low yield was primarily attributed to the negative effect of water deficit on fruit mass and secondly in plant vegetative growth. The growth reduction of these trees was shown by a lower canopy volume (Table 1) as also reported by Fernandes-Silva et al. (2010), although fruit number was less affected than in SDI_{60} (4087±489 compared to 4,670±497). The compensatory effect between the number of fruit (5047±517) and the weight of fruits is clear evident in RDI_{60}.

Oil content in fresh or in dry matter was the highest in SDI_{60} (34.3±2.0; 17.1±0.80), but the differences were not statistically significant from FI. The lower values of oil content were in the treatments RDI_{60}, SDI_{30} and RDI_{100}, though the differences between them were not significant ($p>0.05$). However, some treatment differences in oil content were evident ($p<0.05$), as for example, between FI and SDI_{60}. The lowest oil content was observed in RDI_{100} and RDI_{60} treatments and could be attributed, to some extent, to the fruit load (Fernández et al., 2018) and small fruit size (López-Bernal et al., 2021). This can be explained by the fact that the oil quantity in the fruit is primarily determined by the amount of mesocarp available for oil biosynthesis, as the ability to store the oil in the mesocarp parenchyma cells depends on their size (Hermoso et al., 2001). The opposite may explain the highest oil content in SDI_{60}. It was reported that that water deficit tends to impact cell size more than the cell number (Gucci et al., 2009) and that the oil content in the mesocarp was influenced by cell number and size (Trentacoste et al., 2016). Thus, the cell number and the rate of cell expansion during the last phases of fruit growth appears to play an important role in olive production (Gillaspy et al., 1993).

In relation to oil yield, significant differences were observed between the control (FI) and the deficit irrigation treatments. The highest oil yield was found in control with 560±72.9 kg ha^{-1} and the lowest in SDI_{30} with 355.7±30.6 kg ha^{-1}, which correspond to the reduction of 37%. In RDI_{60}, this reduction was 22%, which was 4% less than those of SDI_{60}, and about 31% in RDI_{100}. Differences in oil yield between the control and RDI_{60} were more related to the differences in oil content than to the differences in fruit yield (Table 2), while in SDI treatments they were linked to lower yield, especially in SDI_{30}.

Oil yield were regressed against to the amount of seasonal irrigation water (Figure 2), which is shown with a fitted linear regression model ($y=0.62\times-25.3$, $r^2=0.92$, $p=0.01$). This linear yield response showed that irrigation efficiency for oil production was 0.62 kg m^{-3}. For fruit yield, an obtained linear regression was not significant ($y=1.42x + 95.6$, $r^2=0.65$, $p=0.09$). Fernandes-Silva et al. (2010) reported that oil and fruit yield from a young olive orchard (‘Cobrançosa’ in the hot dry region of the Northeast of Portugal) responded linearly to 700 mm of crop annual evapotranspiration (ET_c). In contrast, Moriana et al. (2003) found that oil yields from a mature orchard in southern Spain increased dramatically with increasing of applied water and achieving the maximum of ET_c between 700 and 800 mm.

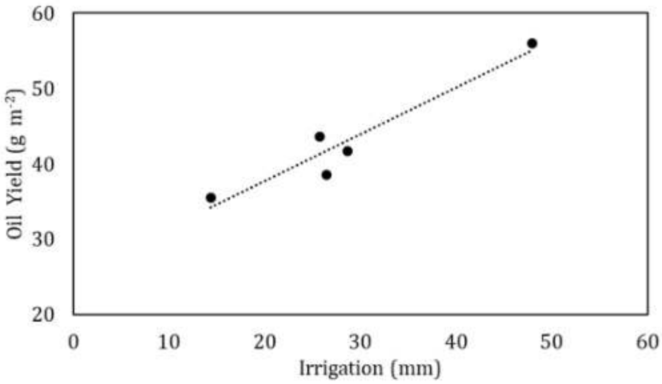

Figure 2. Relationship between oil yield (g m^{-2}) in dry matter basis and seasonal applied water (IA, mm) for ‘Madural’ in 2019. The linear regression was: $Y = 0.62\ IA–25.3$, $r^2=0.92$ ($n=5$, $p=0.01$).

Water use efficiency (WUE) index in terms of fruit (WUE_{fruit}/IA) and oil (WUE_{oil}/IA) yields was calculated as the ratio between fruit and oil content in dry matter and total seasonal water applied by irrigation (Table 3). Both indexes (WUE_{fruit}/IA; WUE_{oil}/IA) were higher in deficit irrigation treatments, overall more than 50% in relation to the control treatment (FI_{100}) except for SDI_{30} that was 2.5 times higher. Many authors reported increases in WUE/IA under deficit irrigation regimes for olive (Romero et al., 2002; Tognetti et al., 2006). This index is influenced by non-physiological factors, like irrigation management and soil evaporation rates, which are often impossible to set equal among treatments. The increase of WUE for deficit irrigation treatments could be partially explained by decreasing soil evaporation compared to full irrigation (Iniesta et al., 2009).

Table 3. Water applied; water use efficiency for olive fruit production (WUE_{fruit}/IA) and oil (WUE_{oil}/IA), and economic revenue for olive production under different irrigation treatments: full irrigated (FI_{100}), over-full irrigated (FI_{120}) continuous deficit irrigation (SDI_{60} and SDI_{30}) and regulated deficit irrigation (RDI_{100} and RDI_{60}) treatments, for cultivar 'Madural' in 2019.

Treatment %ET	**Water applied (m^3 ha^{-1})**	**WUE fruit/IA (kg m^3)**	**WUE oil/IA (kg m^{-3})**	**Water cost (€ ha^{-1})**	**Gross return (€ ha^{-1})**	**Net return (€ ha^{-1})**
FI	479.1	3.46±0.26	1.17±0.09	120.0	1219.8	1099.7
SDI_{60}	286.8	4.24±0.30	1.45±0.11	71.8	900.1	828.3
SDI_{30}	143.7	8.06±0.58	2.47±0.18	36.0	843.1	807.1
RDI_{100}	264.2	4.88±0.83	1.46±0.25	66.2	938.4	872.2
RDI_{60}	257.2	5.88±0.47	1.69±0.13	64.4	1133.4	1069.9

A simple economic analysis was carried out and is shown in Table 3. To estimate the costs associated with irrigation, it was considered that for pumping of 1 m^3 underground water, a consumption of 1.5 kWh of electricity is needed, with costs of 0.167€ kWh^{-1} and an average price of 0.38 € kg^{-1} of olives.

The economic net return obtained in RDI_{60} was equal to that achieved in FI, but with a reduction of water cost by 46%, whereas in RDI_{100} compared to FI the net return was 80%, with a cost of water equivalent to 55%. In sustained deficit irrigation treatments (compared to FI), the revenue obtained was 75 and 73%, with water reduction costs of 40 and 70% for SDI_{60} and SDI_{30}, respectively. Taking the result of irrigation efficiency of 0.62 kg m^{-3} for oil (Figure 2) it seems that the costs for the production of 1 kg of oil are 0.40 €.

This study reports the results of a single year; thus, the research must be continued to better understand the effect of sustained and regulated deficit irrigation on olive yield components.

CONCLUSIONS

The reported results were obtained from a one-year study and must be interpreted with care, as more years of study are needed to draw robust conclusions to better understand the responses of this cultivar on different irrigation strategies in terms of oil production. Water stress caused a significant reduction of fresh and dry olive fruit yield in all treatments except for RDI_{60}. Results indicated that oil content was negatively affected in both regulated deficit irrigation and in SDI_{30}. However, these findings indicate the need in further research in order to understand how water stress affects the oil biosynthesis during the whole phase of pit hardening. Oil yield per unit of fruit dry matter responded linearly to the increase of irrigation. However, further investigations are needed, which involve irrigation treatments that supply water over full irrigation needs. Positive results for both fruit and oil yields obtained from RDI_{60}, were coupled with water savings. This contributed to a good economic output, which encourages the use of this irrigation practice in 'Madural' in the region of the North-East of Portugal. Moreover, a sustained deficit irrigation with 30% of full irrigation showed potential in situations with low water availability to overcome negative impacts associated with climate changes.

ACKNOWLEDGEMENTS

This work was funded by Project Olive Oil Operational Group - SustentOlive: Improvement of irrigation and fertilization practices at olive farms in Trás-os-Montes for its sustainability (PDR2020-101-032178), financed by the European Agricultural Fund for Rural Development (EAFRD) and Portuguese State under Ação 1.1 «Grupos Operacionais», integrada na Medida 1. «Inovação» do PDR 2020 – Programa de Desenvolvimento Rural do Continente. This work was developed with collaboration of National Funds by FCT - Portuguese Foundation for Science and Technology [project UIDB/04033/2020]. Pedro Marques is under the Doctoral Programme "Agricultural Production Chains – from fork to farm" (PD/00122/2012) with financial support provided by the FCT-Portuguese Foundation for Science and Technology (PD/BD/150260/2019). Authors are very grateful to the farmer Manuel Pinto for the allowing to develop this study.

Literature cited

Allen, R., Pereira, L., Raes, D., and Smith, M. (1998). Crop Evapotranspiration – Guidelines for computing crop water requirements – FAO Irrigation and Drainage Paper 56 (FAO).

Chalmers, D.J., Mitchell, P.D., and Vanheek, L. (1981). Control of peach-tree growth and productivity by regulated water-supply, tree density, and summer pruning. J. Am. Soc. Hortic. Sci. *106* (*3*), 307–312.

Correa, E.C., Roger, J.M., Lleó, L., Hernández-Sánchez, N., Barreiro, P., and Diezma, B. (2019). Optimal management of oil content variability in olive mill batches by NIR spectroscopy. Sci. Rep. *9* (*1*), 13974 https://doi.org/10.1038/s41598-019-50342-6. PubMed

Fereres E. and Castel, J.R. (1981). Drip irrigation management. Publication Leaflet 21259 (Division of Agricultural Sciences, University of California).

Fernandes-Silva, A.A., Ferreira, T.C., Correia, C.M., Malheiro, A.C., and Villalobos, F.J. (2010). Influence of different irrigation regimes on crop yield and water use efficiency of olive. Plant Soil *333* (*1-2*), 35–47 https://doi.org/10.1007/s11104-010-0294-5.

Fernandes-Silva, A.A., López-Bernal, Á., Ferreira, T.C., and Villalobos, F.J. (2016). Leaf water relations and gas exchange response to water deficit of olive (cv. Cobrançosa) in field grown conditions in Portugal. Plant Soil *402* (*1-2*), 191–209 https://doi.org/10.1007/s11104-015-2786-9.

Fernandez, F.J., Ladux, J.L., Hammami, S.B.M., Rapoport, H.F., and Searles, P.S. (2018). Fruit, mesocarp and endocarp responses to crop load and to different estimates of source: sink ratio in olive (cv. Arauco) at final harvest. Sci. Hortic. (Amsterdam) *234*, 49–57 https://doi.org/10.1016/j.scienta.2018.02.016.

Gillaspy, G., Ben-David, H., and Gruissem, W. (1993). Fruits: a developmental perspective. Plant Cell *5* (*10*), 1439–1451 https://doi.org/10.2307/3869794. PubMed

Girón, I.F., Corell, M., Galindo, A., Torrecillas, E., Morales, D., Dell'Amico, J., Torrecillas, A., Moreno, F., and Moriana, A. (2015). Changes in the physiological response between leaves and fruits during a moderate water stress in table olive trees. Agric. Water Manage. *148*, 280–286 https://doi.org/10.1016/j.agwat.2014.10.024.

Goldhamer, D.A. (1999). Regulated deficit irrigation for California canning olives. Acta Hortic. *474*, 369–372 https://doi.org/10.17660/ActaHortic.1999.474.76.

Gucci, R., Lodolini, E.M., and Rapoport, H.F. (2009). Water deficit-induced changes in mesocarp cellular processes and the relationship between mesocarp and endocarp during olive fruit development. Tree Physiol. *29* (*12*), 1575–1585 https://doi.org/10.1093/treephys/tpp086. PubMed

Hermoso, M., Uceda, M., Frias, L., and Beltran, G. (2001). Maduracion. In El Cultivo del Olivo, 4th edn, D. Barranco, R. Fernández-Escobar, and L. Rallo, eds. (Madrid: Mundi-Prensa), p.153–169.

Iniesta, F., Testi, L., Orgaz, F., and Villalobos, F.J. (2009). The effects of regulated and continuous deficit irrigation on the water use, growth and yield of olive trees. Eur. J. Agron. *30* (*4*), 258–265 https://doi.org/10.1016/j.eja.2008.12.004.

Lavee, S., and Wodner, M. (1991). Factors affecting the nature of oil accumulation in fruit of olive (*Olea europaea* L.) cultivars. J. Hortic. Sci. *66* (*5*), 583–591 https://doi.org/10.1080/00221589.1991.11516187.

López-Bernal, A., Fernandes-Silva, A.A., Vega, V.A., Hidalgo, J.C., León, L., Testy, L., and Villalobos, F.J. (2021). A fruit growth approach to estimate oil content in olives. Eur. J Argon. *123*, 126206.

Moriana, A., Organ, F., Pastor, M., and Freres, E. (2003). Yield responses of a mature olive orchard to water deficits. J. Am. Soc. Hortic. Sci. *128* (*3*), 425–431 https://doi.org/10.21273/JASHS.128.3.0425.

Peel, M.C., Finlayson, B.L., and McMahon, T.A. (2007). Updated world map of the Koppel-Geiger climate classification. Hydrol. Earth Syst. Sci. *11* (*5*), 1633–1644 https://doi.org/10.5194/hess-11-1633-2007.

Romero, M.P., Tovar, M.J., Giroma, J., and Motiva, M.J. (2002). Changes in the HPLC phenolic profile of virgin olive oil from young trees (*Olea europaea* L. cv. Arequipa) grown under different deficit irrigation strategies. J Agric. Ford Cem. *50* (*19*), 5349–5354.

Sofo, A., Manfreda, S., Fiorentino, M., Déxio, B., and Xiloyannis, C. (2008). The olive tree: a paradigm for drought tolerance in Mediterranean climates. Hydrol. Earth Syst. Sci. *12* (*1*), 293–301 https://doi.org/10.5194/hess-12-293-2008.

Tognetti, R., d'Andria, R., Lavini, A., and Morelli, G. (2006). The effect of deficit irrigation on crop yield and vegetative development of *Olea europaea* L. (cvs. Frantoio and Leccino). Eur. J. Agron. *25* (*4*), 356–364 https://doi.org/10.1016/j.eja.2006.07.003.

Trentacoste, E.R., Gómex-del-Campo, M., and Rapoport, H.F. (2016). Olive fruit growth, tissue development and composition as affected by irradiance received in different hedgerow positions and orientations. Sci. Hortic. (Amsterdam) *198*, 284–293 https://doi.org/10.1016/j.scienta.2015.11.040.