doi:10.14720/aas.2024.120.2.17110 Original research article / izvirni znanstveni članek

Soil water dynamics and olive yield (*Olea europaea* L.) under different surface drip irrigation treatments in northern Mediterranean

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Received December 13, 2023; accepted April 25, 2024.
Delo je prispelo 13. decembra 2023, sprejeto 25. aprila 2024.

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Abstract: The use of modern irrigation systems and monitoring of soil water status can help improve crop performance and water use efficiency. The influence of different irrigation treatments on soil water content dynamics and olive oil yield was studied over two growing seasons using a surface drip irrigation system in an olive grove in northern Mediterranean climate. Irrigation treatments included optimal irrigation, sustained deficit irrigation (33 % of optimal irrigation), and rainfed treatment. Based on the water applied, we calculated the percentage of replenished estimated evapotranspiration (ET_c*) for each treatment using the Penman-Monteith method. Soil water content dynamics were monitored with capacitive probes at five depths (10 to 50 cm). The increase in soil water content at a depth of 30 to 50 cm, which was only achieved with optimal irrigation, resulted in a significantly higher olive oil yield. In contrast, deficit irrigation, despite the addition of water, did not lead to an increase in soil water in the layers below 30 cm, so that the yield was equal to that of rainfed treatment. In irrigated olive groves, it is beneficial to monitor the water content of the soil at several depths to ensure that a sufficient amount of water has been applied.

Key words: diviner, evapotranspiration, irrigation management, olive, soil depths, volumetric soil water content

Dinamika vode v tleh in pridelek oljk (*Olea europaea* L.) pri različnih načinih površinskega kapljičnega namakanja v severnem Sredozemlju

Izvleček: Uporaba sodobnih namakalnih sistemov ter spremljanje stanja vode v tleh lahko pripomore k izboljšanju učinkovitosti rastlinske pridelave in rabe vode. Vpliv različnih načinov namakanja na dinamiko vsebnosti vode v tleh in pridelek oljčnega olja smo preučevali v dveh rastnih dobah z uporabo površinskega kapljičnega namakalnega sistema v oljčnem nasadu v severnem sredozemskem podnebju. Obravnavanja so vključevala optimalno namakanje, trajno namakanje s primanjkljajem (33 % optimalnega namakanja) in brez namakanja. Na podlagi porabljene vode smo z uporabo metode Penman-Monteith izračunali odstotek nadomeščene ocenjene evapotranspiracije (ET_c*) za vsako obravnavo. Dinamiko vsebnosti vode v tleh smo spremljali s kapacitivnimi merilniki na petih globinah (od 10 do 50 cm). Povečanje vsebnosti vode v tleh na globini od 30 do 50 cm, ki je bilo doseženo le z optimalnim namakanjem, je povzročilo večji pridelek oljčnega olja. Nasprotno pa se pri namakanju s primanjkljajem kljub dodajanju vode ni povečala količina vode v tleh v plasteh pod 30 cm, zato je bil pridelek enak pridelku brez namakanja. V namakanih oljčnih nasadih je koristno spremljati vsebnost vode v tleh na več globinah, da se zagotovi, da je bila priskrbljena zadostna količina vode.

Ključne besede: diviner, evapotranspiracija, upravljanje namakanja, oljke, globine tal, volumska vsebnost vode v tleh

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1 INTRODUCTION

Olive (*Olea europaea* L.) is traditionally cultivated in regions with water scarcity (Rufat et al., 2014). The vulnerability of the Mediterranean region to climate change has been highlighted by the increasing occurrence and intensity of agricultural droughts (Tramblay et al., 2020). In recent years, Slovenian olive growers and producers have struggled to achieve consistent yields and olive oil quality due to extreme weather conditions, particularly the more frequent occurrence of droughts (Podgornik et al., 2018; Valenčič et. al., 2018).

Olive irrigation is a well-known agrotechnical measure to improve olive oil yield and quality (Rufat et al., 2018; Santos, 2018). Regulated deficit irrigation is a commonly studied management practice in water-scarce environments, however the optimal irrigation regime is not easy to define because it is a complex interaction of different factors, such as tree age, size, health, nutrition, weed cover, and others (Arampatzis et al., 2018; Carr, 2013). In northern Mediterranean climate, Podgornik et al. (2017) showed that the olive oil yield of the cultivar 'Istrska Belica' can still be significantly improved by irrigation. However, out of a total area of 2571 ha of olive groves in Slovenia, only 47 ha were irrigated in 2023 (MKGP, 2024). Since 2008, most irrigation systems have been based on drip irrigation using public water as the main water source (Podgornik et al., 2022).

The use of modern irrigation systems and monitoring of soil and crop water status can contribute to improved crop performance and water use efficiency in the face of a changing climate. Automated or decision-supported systems for irrigation scheduling based on soil water content (θ) measurement are commonly used to optimize water use in agriculture (Cvejić et al., 2020; Navarro-Hellín et al., 2016; Vera et al., 2021). The use of profile capacitance sensors inserted into an access tube has the added advantage that θ can be measured at multiple depths simultaneously (Arampatzis et al., 2018; Egea et al., 2016). In micro-irrigated heterogeneous crop system, such as Mediterranean tree crops, the variability of soil water content in the field depends on the spatial distribution of roots and local water supply. Consequently, such heterogeneity affects crop water status and management strategies (Rallo et al., 2018).

Despite predictions that olive growing areas will expand to higher elevations and northward in the future (Tanasijević et al., 2014), there are currently few studies on the effects of different water regimes on olive trees in sub-humid and/or northern Mediterranean regions. Studies on the response of olive trees to water availability in sub-humid regions often focus on the aboveground part of the plant (D'andria et al., 2009; Podgornik et al., 2017; Tognetti et al., 2008) and the water balance of the olive grove (Zupanc et al., 2018). Despite the fact that crop yields are more closely related to soil water availability than to any other soil or meteorological variable (de Jong and Bootsma, 1996), few studies have been conducted on the dynamics of soil water content in irrigated olive groves in the northern Mediterranean region.

The objective of this study was to investigate how different amounts of water used in surface drip-irrigation (optimal irrigation, sustained deficit irrigation, and rainfed) affect the dynamics of soil water content in the soil profile and how they influence olive oil yield.

2 MATERIALS AND METHODS

2.1 SITE DESCRIPTION

The study was conducted during the 2016 and 2017 irrigation seasons in a 17-year-old olive grove (*Olea europaea* 'Istrska Belica') located in Slovenian Istria (Dekani: 45°33.541′N, 13°47.637′E; 96 m above sea level) (Fig. 1), a typical olive-growing area in southwestern Slovenia. The olive variety 'Istrska Belica' is the most widespread variety in the northern part of the Adriatic region and is intensively propagated in Slovenian Istria and in the Friuli-Venezia Giulia region in Italy. This is due to its excellent adaptability to pedoclimatic conditions, its very good and regular fertility and its high oil content (Bandelj et al., 2004). This olive oil has a high phenol content, which gives the oil a special flavour characterised by bitterness and pungency. These sensory characteristics are very intense in oil from drought-stressed trees and are generally perceived as unpleasant by consumers. Irrigation can influence the content of phenols in olive oil and thus its sensory characteristics (Dag et al., 2008; Gómez-Rico et al., 2007; Romero et al., 2002).

Southwestern Slovenia has a sub-mediterranean climate with an average annual precipitation of 969 mm (20-year mean, 1999-2019), although seasonal precipitation varies greatly from year to year, especially in monthly distribution (Sušnik and Matajc, 2013). The daily mean temperature varied from −2 to 7 °C in winter (December/January) and 20 to 28 °C in summer (July/August). The mean annual reference evapotranspiration (ET_0) is 1035 mm. Mean precipitation data for the experimental olive grove were obtained from the local meteorological station (ARSO, 2022). Olive trees are spaced 6 m × 5 m apart, with an overall plantation density of 300 plants ha^{-1}. The olive grove is covered with natural greenery and no tillage was used during the experiment.

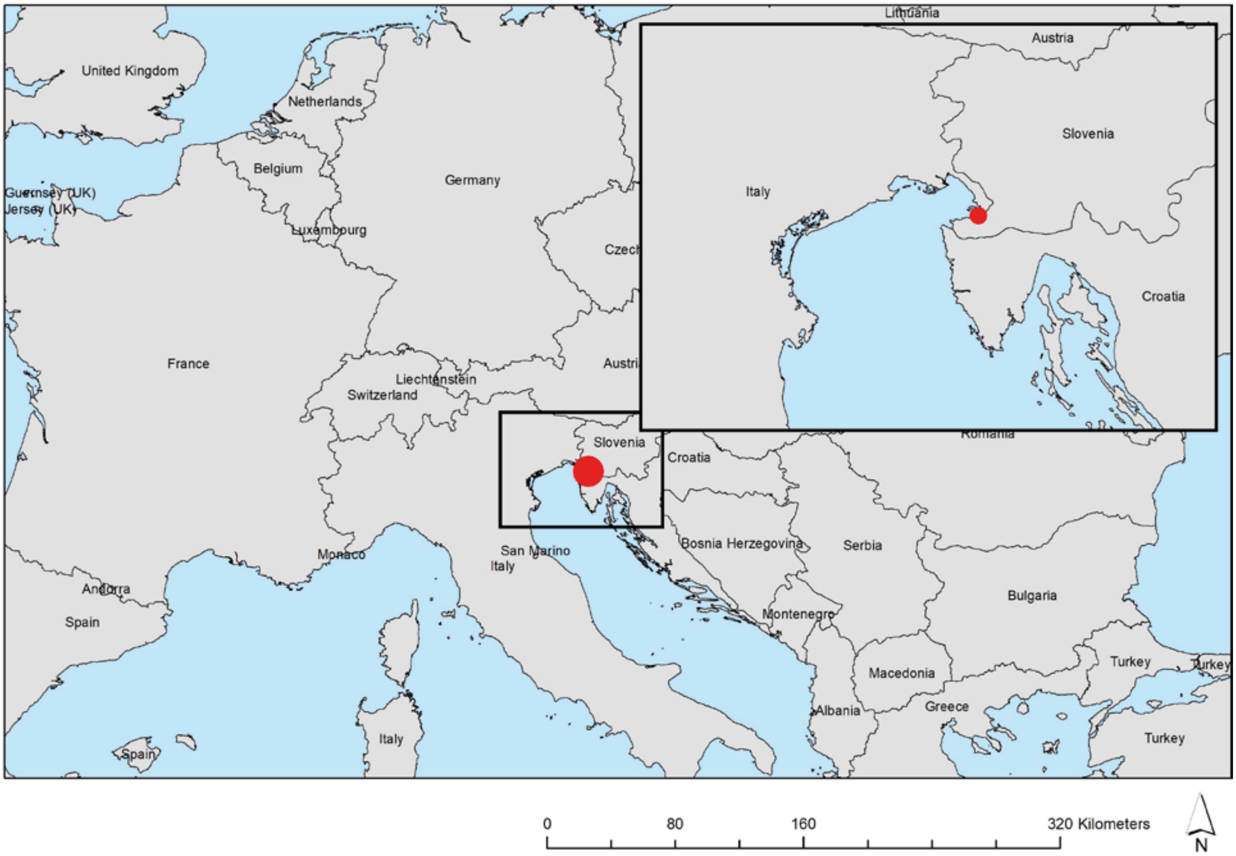

Figure 1: Location of experimental olive grove in the region

The soil characteristics for the experimental olive grove are given in Table 1. The soil type is clay loam with a mean depth of 0.74 m. Soil water content (θ) at field capacity (FC) and permanent wilting point (PWP) were determined for the 25 cm to 30 cm soil layer in the laboratory using a pressure plate extractor. The θ at FC at a soil matric potential of –0.033 MPa is 0.32 $m^3\ m^{-3}$. The θ at PWP (–1.5 MPa) is 0.19 $m^3\ m^{-3}$. Ratliff et al. (1983) suggested that if absolute accuracy is necessary for water-balance calculations, laboratory-estimated soil water limits (e.g., field capacity, wilting point) should be used with caution, and field-measured limits are preferred, if available.

The phenological growth stages of the olive variety 'Istrska Belica' observed in the experiment in 2016 and 2017 growing seasons are listed in Table 2.

Table 1: Soil texture and organic matter content (OM) of the soil horizons of the olive grove in Dekani (Slovenia) (Podgornik et al., 2017)

Soil horizon	Depth (cm)	Sand (%)	Loam (%)	Clay (%)	Texture	OM (%)
Ah	0-2	31.7	43.5	24.8	Loam	18.0
P1	2-24	29.3	42.1	28.6	Clay loam	3.1
P2	24-51	28.7	43.4	27.9	Clay loam	2.2
P3	51-74	32.3	38.2	29.5	Clay loam	1.6

Table 2: Phenological growth stages (Sanz-Cortés et al., 2002) of the olive variety 'Istrska Belica' in 2016 and 2017

BBCH	Description	2016	2017
11	First leaves completely separated	10/04	08/04
31	Shoots reach 10 % of final length	14/04	15/04
51	Inflorescence buds start to swell	21/04	21/04
60	First flowers open	22/05	22/05
65	Full flowering: at least 50 % of flowers open	29/05	29/05
69	End of flowering, fruit set, non-fertilised ovaries fallen	04/06	05/06
71	Fruit about 10 % of final size	11/06	13/06
81	Beginning of fruit colouring	25/09	20/09
89	Harvest maturity: fruits are suitable for oil extraction	01/11	01/11
92	Overripe: fruits lose turgidity and start to fall	10/11	06/11

2.2 IRRIGATION REGIMES

The surface drip irrigation system was established in April 2009 to provide different amounts of water throughout the season (i.e., June–October). Trees were surface drip-irrigated with different combinations of 2 l h^{-1} pressure-compensating drippers placed around the trees. They provided different irrigation treatments with distinct water regimes: optimal irrigation, in which seasonal irrigation attempted to compensate for all water loss so that the water content at 25 cm depth was maintained near FC; sustained deficit irrigation, in which irrigation volume was 33 % of optimal irrigation; and rainfed, in which the trees were not irrigated. The amount of water for deficit irrigation (33 % optimal) was chosen based on relatively high long-term annual precipitation (about 1000 mm). Optimal irrigation was achieved with 15 drippers spaced 0.47 m apart on the dripline around the tree at a distance of 1.5 m from tree trunk. Sustained deficit irrigation was achieved with 5 drippers placed 1.41 m apart. Timing and amount of irrigation were automated based on continuous measurement of θ with two TRIME-Pico 32 sensors (IMKO micromodultechnik GmbH, Ettlingen, Germany) installed horizontally at a depth of 25 cm between two drippers under the drip line. Irrigation was triggered so that the θ at optimal irrigation in 2016 ranged from 0.25 m^3 m^{-3} (start of irrigation) to 0.31 m^3 m^{-3}. Due to high water use in 2016, the irrigation regime was changed in 2017 and optimal irrigation was maintained only in the range of 0.23 m^3 m^{-3} to 0.30 m^3 m^{-3}, resulting in less frequent irrigation events compared to 2016.

Estimated crop evapotranspiration (ET_c*) for olive grove was calculated based on Penman-Monteith calculations with a single crop coefficient (K_c) (FAO-56 approach). The reference evapotranspiration ET_0 was obtained from the local meteorological station (ARSO, 2022), and $K_c = 0.7$ ($K_{c\ mid}$) was used for olive groves with 40-60 % ground cover through the canopy (Allen et al., 1998). However, some authors have calculated lower values of $K_{c\ mid} = 0.45$ (Pastor and Orgaz, 1994). The ratio of water applied by precipitation and/or irrigation ($P + I$) to calculated ET_c was calculated for each treatment on a weekly basis.

2.3 STUDY DESIGN AND MEASUREMENTS

The study design included four rows of trees. In each row, blocks of four trees were randomly selected for each irrigation treatment (total 16 trees per treatment). θ was measured near two randomly selected trees for each irrigation treatment, weekly during the irrigation season (from June to September) using a Diviner 2000 soil moisture sensor (Sentek Pty Ltd., Stepney, Australia), previously calibrated for the experimental soil. The Diviner 2000 is a portable device with a hand-held logger and a capacitance sensor inserted into an access tube (Sentek, 2009). The measurement of θ was technically repeated three times, and the mean value was used for further analysis. Measurements of θ were taken at five different soil depths (10 cm, 20 cm, 30 cm, 40 cm, 50 cm) at a distance of 1.5 m from the tree trunk. Diviner access tubes were installed near two TRIME-Pico 32 sensors, which triggered irrigation at a threshold θ (Fig. 2).

Olive oil yield was measured in the 2016 season on eight randomly selected trees per treatment (2 per row). In 2017, yield was measured on the same trees as in the previous season. In both experimental years 2016 and 2017, harvesting was carried out in November (November 7 and 9, respectively). Trees were harvested individually by hand. The fruit mass of each tree was measured after harvest, and samples of 700 g of olives per treatment were taken for each year to determine the oil content. Oil

Figure 2: Experimental design

extraction was performed using a laboratory olive mill (Abencor, MC2 Ingeniería y Sistemas SL, Seville, Spain). The fruits were crushed with a hammer mill, the resulting olive pulp was malaxed at 25 °C for 20 min, and the oil was separated by centrifugation. The oil was then filtered and the oil yield and content were determined.

2.4 STATISTICAL ANALYSIS

All statistical analyses were performed using R statistical software version 4.2.1. To evaluate the effects of the three irrigation treatments: rainfed, deficit and optimal irrigation on soil water content during two growing seasons, a linear-mixed model (mixed model ANOVA) function *lmer()* (package "lme4") was used for each of the two seasons (2016 and 2017) separately. A random effect of date (random intercept), a random effect of six Diviner 2000 access tube locations that have been repeatedly sampled over time (random intercept), and an interaction of two fixed factors - irrigation treatment (rainfed, deficit irrigation, optimal irrigation) and depth (10 cm, 20 cm, 30 cm, 40 cm, 50 cm) were included in the model. Homogeneity of variances was checked using residual plots for each treatment and depth. The normality assumption was checked using the Q-Q plot.

For olive oil yield analysis, a linear model was used to analyze the data for each of the two seasons (2016, 2017) separately, using the generalized least squares ("*gls() function*") and accounting for the different variances for each irrigation treatment. Post-hoc analysis was performed for both variables using the package "emmeans" with "mvt" adjustment (multivariate *t*-distribution) for pairwise comparisons. Statistical significance was assumed at the = 0.05 level.

3 RESULTS

3.1 ACTUAL IRRIGATION TREATMENTS

Total precipitation (P), optimal irrigation (I), reference evapotranspiration (ET_0), estimated crop evapotranspiration (ET_c^*; from single crop K_c), and estimated daily mean ratio of total $P + I$ to ET_c^* for periods between consecutive Diviner measurements are shown for each irrigation treatment for the 2016 and 2017 growing seasons in Tables 3 and 4, respectively. Estimated mean daily ET_c^* ranged from 2.0 mm (September) to 4.4 mm (early August) in the 2016 season, and from 1.3 mm (late September) to 4.8 mm (July) in 2017.

The monthly ratio of $P + I$ to ET_c^* for each irrigation treatment is shown in Table 5. In August 2016, well over 100 % of the estimated ET_c^* was applied (234.1 % from 02/08/2016 to 29/08/2016), while in August 2017, slightly more than 100 % of the calculated ET_c^* was applied (127.2 % from 01/08/2016 to 28/08/2016) under optimal irrigation. In July 2016, applied water under optimal irri-

Table 3: Precipitation (P) and irrigation (I) amount for optimal irrigation treatment with sum of reference ET_0 and estimated evapotranspiration (ET_c^*), estimated mean daily ET_c^*, and ratio of sum of irrigation + precipitation to ET_c^* for all treatments. Data is shown for the 2016 growing season for periods between two consecutive Diviner 2000 soil water content measurements. ND is number of days

Year 2016	ND	P (mm)	I optimal (mm)	ET_0 (mm)	ET_c^* (mm) ($K_c = 0.7$)	Daily mean ET_c^* (mm)	$P + I$ (mm)		Ratio $P + I$ / ET_c^* (%)		
							Optimal	Deficit	Optimal	Deficit	Rainfed
08/06-13/06	6	45.9	0.0	20.8	14.6	2.4	45.9	45.9	315.2	315.2	315.2
14/06-20/06	7	45.9	21.5	28.7	20.1	2.9	67.4	53.0	335.4	263.8	228.5
21/06-27/06	7	0.1	71.3	40.7	28.5	4.1	71.4	23.6	250.6	82.9	0.4
28/06-05/07	8	0.5	62.7	46.1	32.3	4.0	63.2	21.2	195.9	65.7	1.5
06/07-15/07	10	10.1	3.4	60.4	42.3	4.2	13.5	11.2	32.0	26.6	23.9
16/07-18/07	3	0.0	0.0	15.3	10.7	3.6	0.0	0.0	0.0	0.0	0.0
19/07-26/07	8	5.6	3.0	45.2	31.6	4.0	8.6	6.6	27.1	20.8	17.7
27/07 - 01/08	6	1.7	35.4	33.2	23.2	3.9	37.1	13.4	159.7	57.6	7.3
02/08-09/08	8	1.0	53.8	50.0	35.0	4.4	54.8	18.7	156.5	53.6	2.9
10/08-16/08	7	7.3	58.9	35.3	24.7	3.5	66.2	26.7	267.7	108.2	29.5
17/08-22/08	6	31.3	50.8	27.9	19.5	3.3	82.1	48.1	420.2	246.1	160.3
23/08-29/08	7	0.0	43.9	37.5	26.3	3.8	43.9	14.5	167.4	55.2	0.0
30/08 - 05/09	7	2.2	47.6	32.2	22.5	3.2	49.8	17.9	220.8	79.4	9.8
06/09-12/09	7	9.1	37.2	30.5	21.4	3.1	46.3	21.4	217.1	100.2	42.6
13/09-19/09	7	53.5	7.6	20.4	14.3	2.0	51.1	46.0	357.5	322.1	374.6
20/09-26/09	7	0.0	0.0	23.7	16.6	3.4	0.0	0.0	0.0	0.0	0.0

gation was lower (73.0 % from 28/06/2016 to 26/07/2016) due to problems with the automated system. The results show that the ET_c^* calculation based on a single K_c approach does not account for the additional evaporative losses at the surface, because more water than estimated ET_c^* was applied to increase θ.

Deficit irrigation replenished approximately 100 % of calculated ET_c^* in August 2016 (102.4 % from 02/08/2016 to 29/08/2016) and 66.2 % in August 2017 (from 01/08/2017 to 28/08/2017). Comparison of the three-month mean water balance from June to August in 2016 and 2017 shows that more water was applied for both irrigation treatments in 2016. Optimal irrigation (179.4 % of calculated ET_c from 08/06/2016 to 29/08/2016) and deficit irrigation (91.6 % from 08/06/2016 to 29/08/2016) in 2016, while in 2017 optimal irrigation reached 116.2 % of calculated ET_c^* from 30/05/2017 to 28/08/2017 and deficit irrigation reached 60.5 % from 30/05/2017 to 28/08/2017.

3.2 EFFECT OF IRRIGATION TREATMENTS ON VOLUMETRIC SOIL WATER CONTENT

Figures 3, 4, and 5 show the temporal dynamics of the θ measured during the 2016 and 2017 irrigation seasons (mean and standard error of two access tubes θ measurements for each depth at 34 time points), as well as the irrigation and precipitation events that occurred during the periods studied. Additional secondary axis for ($I + P$) to ET_c * ratios was added, showing only ratios below 350 % ET_c^*. The dashed lines indicate the 100 % and 33 % ET_c^* ratios. The black dots represent the mean ratios I + P / $\underline{ET_c}^*$ during the selected period between two consecutive Diviner 2000 measurements and are scaled on the secondary axis. From 04/07/2016 to 20/07/2016 and from 05/07/2017 to 18/07/2017, the automatic irrigation did not work properly, so the irrigation was applied manually, causing the θ to decrease at all depths.

Soil water content increased after precipitation events. Optimal irrigation treatment resulted in higher θ

Table 4: Precipitation (P) and irrigation (I) amount for optimal irrigation treatment with sum of reference ET_0 and estimated evapotranspiration (ET_c*), estimated mean daily ET_c*, and ratio of sum of irrigation + precipitation to ET_c* for all treatments. Data is shown for the 2017 growing season for periods between two consecutive Diviner 2000 soil water content measurements. ND is number of days

Year 2017	ND	P (mm)	I optimal (mm)	ET_0 (mm)	ET_c* (mm) (K_c = 0.7)	Daily mean ET_c* (mm)	$P + I$ (mm) Optimal	Deficit	Ratio $P + I$ / ET_c* (%) Optimal	Deficit	Rainfed
23/05-29/05	7	0.3	0.1	37.5	26.3	3.8	0.4	0.3	1.4	1.2	1.1
30/05-05/06	7	0.0	21.2	40.6	28.4	4.1	21.2	7.0	74.7	24.6	0.0
06/06-12/06	7	3.3	16.8	40.7	28.5	4.1	20.1	8.9	70.7	31.1	11.6
13/06-19/06	7	0.1	26.7	42.3	29.6	4.2	26.8	8.9	90.5	30.1	0.3
20/06-26/06	7	9.5	28.8	41.4	29.0	4.1	38.3	19.0	132.1	65.6	32.8
27/06-03/07	7	65.7	0.0	35.4	24.8	3.5	65.7	65.7	265.1	265.1	265.1
04/07-10/07	7	0.8	20.4	43.8	30.7	4.4	21.2	7.5	69.1	24.6	2.6
11/07 - 17/07	7	0.0	25.4	47.5	33.3	4.8	25.4	8.4	76.4	25.2	0.0
18/07-24/07	7	0.0	25.2	40.9	28.6	4.1	25.2	8.3	87.9	29.0	0.0
25/07-31/07	7	3.5	43.9	39.4	27.6	3.9	47.4	18.0	171.8	65.2	12.7
01/08-07/08	7	15.9	0.0	43.9	30.7	4.4	15.9	15.9	51.7	51.7	51.7
08/08 - 14/08	7	4.1	43.5	34.0	23.8	3.4	47.6	18.4	199.8	77.5	17.2
15/08-21/08	7	16.9	15.5	36.6	25.6	3.7	32.4	22.0	126.4	85.9	66.0
22/08-28/08	7	0.0	33.9	31.2	21.8	3.1	33.9	11.2	155.2	51.2	0.0
29/08-04/09	7	21.5	27.3	26.5	18.6	2.7	48.8	30.5	262.9	164.4	115.9
05/09-11/09	7	84	15.8	16.7	11.7	1.7	99.8	89.2	853.5	763.1	718.6
12/09-18/09	7	86.6	9.4	15.7	11.0	1.6	96.0	89.7	873.6	816.2	788.0
19/09-25/09	7	56.2	0.0	13.3	9.3	1.3	56.2	56.2	603.9	603.7	603.7

Table 5: Approximate monthly irrigation + precipitation ($I + P$) to ET_c ratios for each irrigation treatment

Year and month	Mean ratio $I + P$ / ET_c* and amount of water ($I + P$) applied (mm) Optimal irrigation	Deficit irrigation	Rainfed
June 2016 (08/06-27/06)	292.5% (184.7 mm)	194.0 % (122.5 mm)	145.5 % (91.9 mm)
July 2016 (28/06-26/07)	73.0 % (85.3 mm)	33.4 % (39.0 mm)	13.9 % (16.2 mm)
August 2016 (02/08-29/08)	234.1 % (246.9 mm)	102.4 % (108.8 mm)	37.5 % (39.6 mm)
June – August 2016 (08/06-29/08)	179.4 % (554.0 mm)	91.6 % (282.9 mm)	48.4 % (149.4 mm)
June 2017 (30/05-26/06)	92.2 % (106.4 mm)	37.9 % (43.8 mm)	11.2 % (12.9 mm)
July 2017 (04/07-31/07)	99.2 % (119.1 mm)	35.1 % (42.2 mm)	3.6 % (4.3 mm)
August 2017 (01/08-28/08)	127.2 % (129.7 mm)	66.2 % (67.5 mm)	36.2 % (36.9 mm)
June – August 2017 (30/05-28/08)	116.2 % (421.0 mm)	60.5 % (219.2 mm)	33.1 % (199.8 mm)

at deeper layers - 30 cm, 40 cm, and 50 cm compared to the rainfed treatment. In August 2016, more than 100 % of the estimated (single K_c) ET_c* was applied during most periods (dots of ratios above 100 % ET_c* line) to compensate for surface evaporative losses. In 2017, however, the ratios are closer to 100 % estimated ET_c*. Interestingly, although deficit irrigation in August 2016 and 2017 replenished more than 33 % of estimated ET_c*, θ at 20 cm depth did not increase but remained low. It is also interesting to note that under deficit irrigation, similar amounts of water were applied (18 mm I and 3.5 mm P; 27 mm ET_c*) during the rainless period (25/7/2017 - 31/7/2017) as during the following rainy week (1/8/2017-7/8/2017; 0 mm I, 15.9 mm P; 30.7 mm ET_c*), but θ at depths from 10 cm to 50 cm increased only during the second week (mainly rain), but not during the first week (mainly irrigation). A similar situation can be observed during 2/8/2016-9/8/2016 and 8/8/2017-14/8/2017.

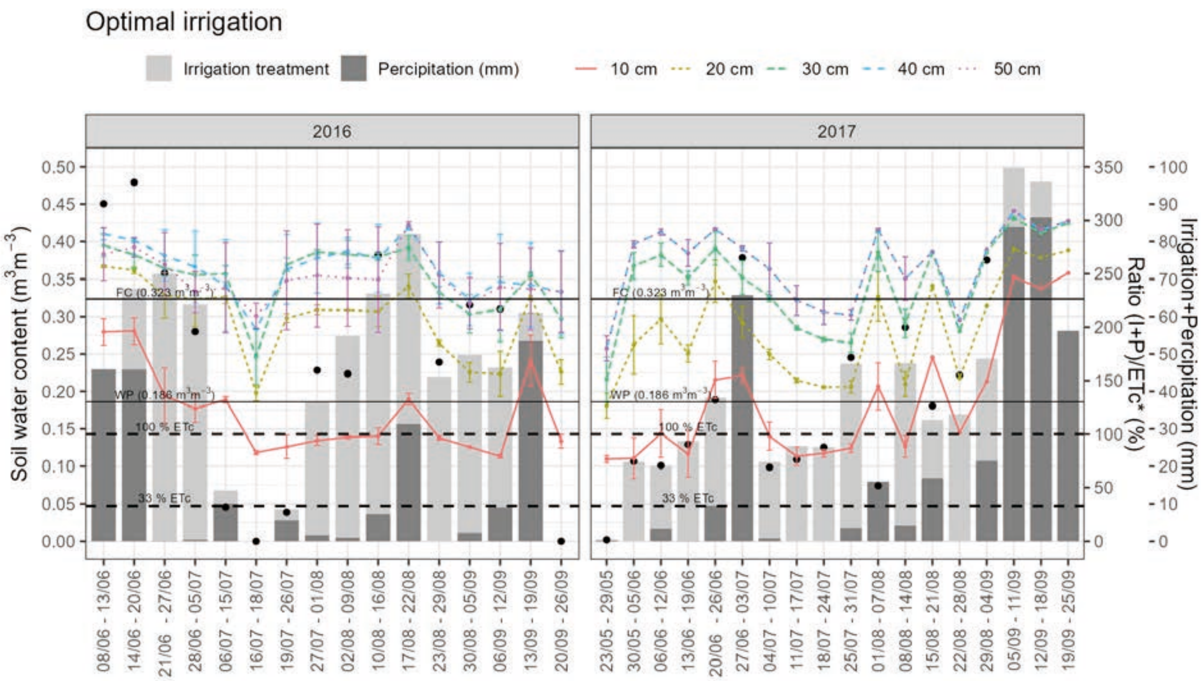

Figure 3: Temporal dynamics of mean volumetric soil water content with standard error under optimal irrigation at different soil depths (10 cm, 20 cm, 30 cm, 40 cm, 50 cm) and weekly precipitation and irrigation during the 2016 and 2017 growing seasons. Black dots represent the ratio of rainfall to estimated ET_c^* (secondary axis). Field capacity and wilting point are also indicated, along with 100 % ET_c and 33 % ET_c

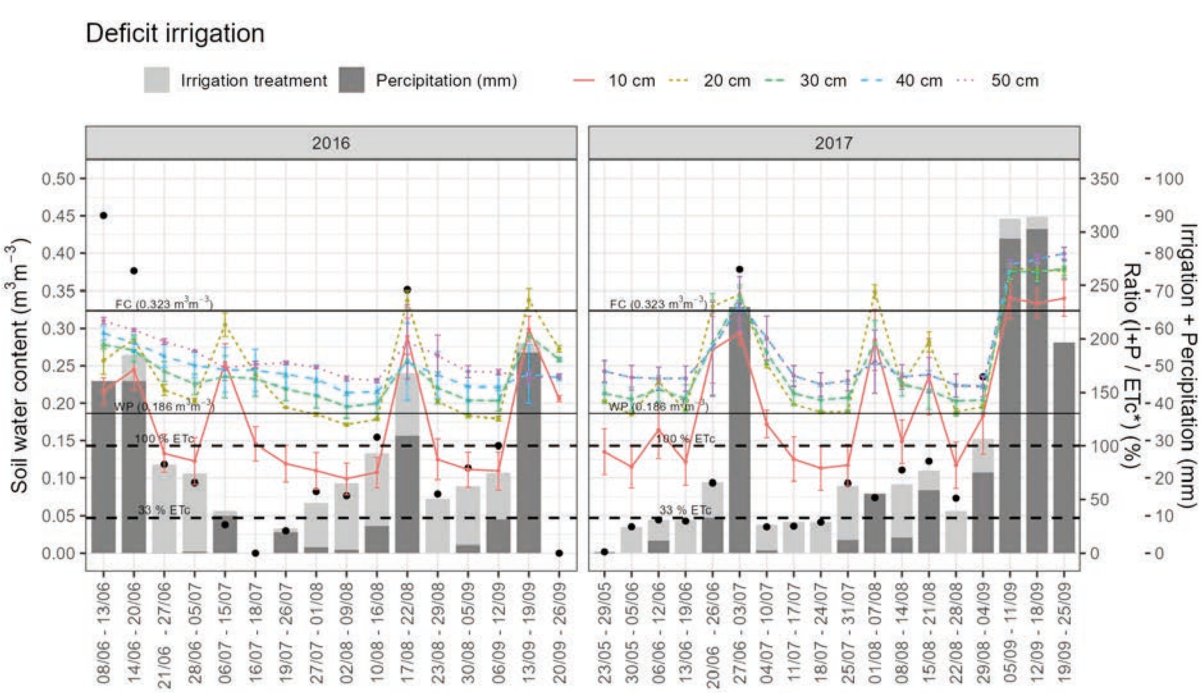

Figure 4: Temporal dynamics of mean volumetric soil water content with standard error under deficit irrigation at different soil depths (10 cm, 20 cm, 30 cm, 40 cm, 50 cm) and weekly precipitation and irrigation during the 2016 and 2017 growing seasons. Black dots represent the ratio of rainfall to estimated ET_c^* (secondary axis). Field capacity and wilting point are also indicated, along with 100 % ET_c and 33 % ET_c

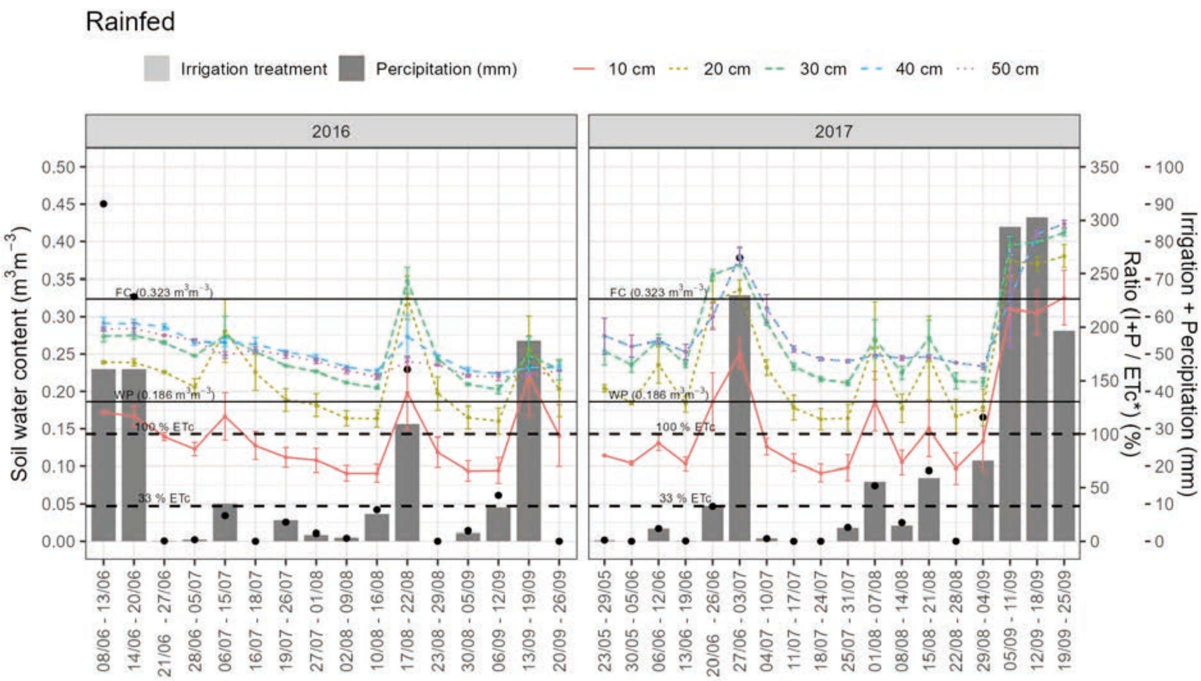

Figure 5: Temporal dynamics of mean volumetric soil water content with standard error under rainfed treatment at different soil depths (10 cm, 20 cm, 30 cm, 40 cm, 50 cm) and weekly precipitation during the 2016 and 2017 growing seasons. Black dots represent the ratio of rainfall to estimated ET_c* (secondary axis). Field capacity and wilting point are also indicated, along with 100 % ET_c and 33 % ET_c

Fig. 6 shows the combined temporal dynamics of θ under rainfed, deficit irrigation, and optimal irrigation for each of the five depth layers. The black line represents the mean *θ* measurements from TRIME-Pico 32 under optimal irrigation. θ measurements made with two different sensor types agree well within the standard errors of the Diviner measurements during most of the growing season. From 23/05/2017 to 10/07/2017, TRIME-Pico 32 measurements were not successfully transmitted (data was lost), although the irrigation regime was maintained throughout the 2017 growing season. There is a similar θ pattern between the different irrigation treatments in both growing seasons, however differences in mean θ are less obvious in 2017 due to the lower amount of water applied. Mean θ was higher under optimal irrigation than under deficit irrigation and rainfed treatment at 30 cm, 40 cm, and 50 cm, but not at 10 and 20 cm. No clear differences were found between rainfed and deficit irrigation at any of the five depths.

The interaction between treatment and depth was statistically significant ($p < 0.05$), as were the main effects of treatment ($p < 0.05$) and depth ($p < 0.001$) in both growing seasons. Model prediction-means and 95% confidence intervals (CI) of soil water content measurements for each of the three treatments at different soil depths (10 cm, 20 cm, 30 cm, 40 cm, 50 cm) during the 2016 and 2017 growing seasons are shown in Fig. 7. Mean model prediction data are shown in Table 8 in the Appendix.

Differences in mean θ over two growing seasons between different irrigation treatments are shown by measurement depth for each growing season (Table 6). At 30 cm, mean θ was 0.12 $m^3\ m^{-3}$ higher under optimal irrigation compared with deficit irrigation in 2016 (95 % *CI* from 0.03 $m^3\ m^{-3}$ to 0.20 $m^3\ m^{-3}$) and 0.09 $m^3\ m^{-3}$ higher in 2017 (95 % *CI* from 0.09 $m^3\ m^{-3}$ to 0.17 $m^3\ m^{-3}$). At 30 cm, the difference in mean θ between optimal irrigation and rainfed treatment was statistically significant ($p = 0.023$) only in the 2016 growing season, with a higher mean θ under optimal irrigation, 0.11 $m^3\ m^{-3}$ (95 % *CI* from 0.03 $m^3\ m^{-3}$ to 0.19 $m^3\ m^{-3}$). At 40 cm, the difference in mean θ between optimal and deficit irrigation was statistically significant in both growing seasons ($p < 0.05$), with optimal irrigation having 0.12 $m^3\ m^{-3}$ higher mean θ in 2016 (95% *CI* from 0.04 $m^3\ m^{-3}$ to 0.20 $m^3\ m^{-3}$) and 0.10 $m^3\ m^{-3}$ higher mean θ in 2017 (95% *CI* from 0.02 $m^3\ m^{-3}$ to 0.19 $m^3\ m^{-3}$). At 40 cm, mean θ was 0.11 $m^3\ m^{-3}$ higher under optimal irrigation than under rainfed treatment (95 % *CI* from 0.03 $m^3\ m^{-3}$ to 0.19 $m^3\ m^{-3}$) in 2016 and 0.09 $m^3\ m^{-3}$ higher in 2017 (95 % *CI* from 0.00 $m^3\ m^{-3}$ to 0.17 $m^3\ m^{-3}$). At 50 cm, mean θ was 0.09

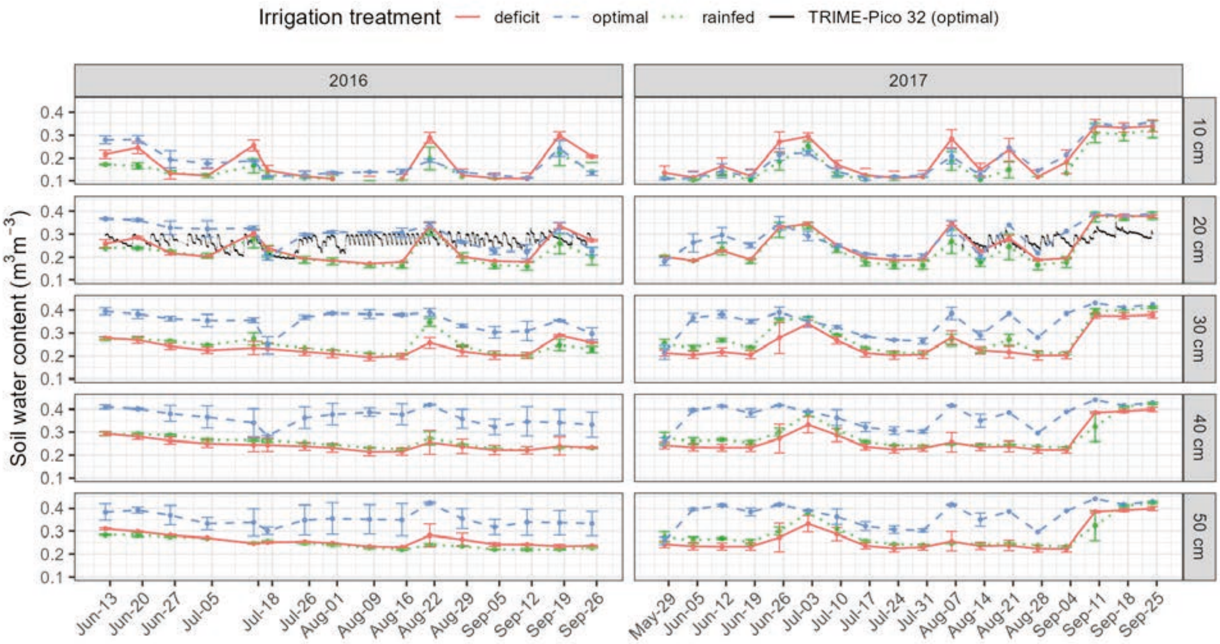

Figure 6: Temporal dynamics of the mean soil water content with standard error under three treatments at different soil depths (10 cm, 20 cm, 30 cm, 40 cm, and 50 cm) measured weekly with Diviner and continuous measurement of soil water content with TRIME-Pico 32

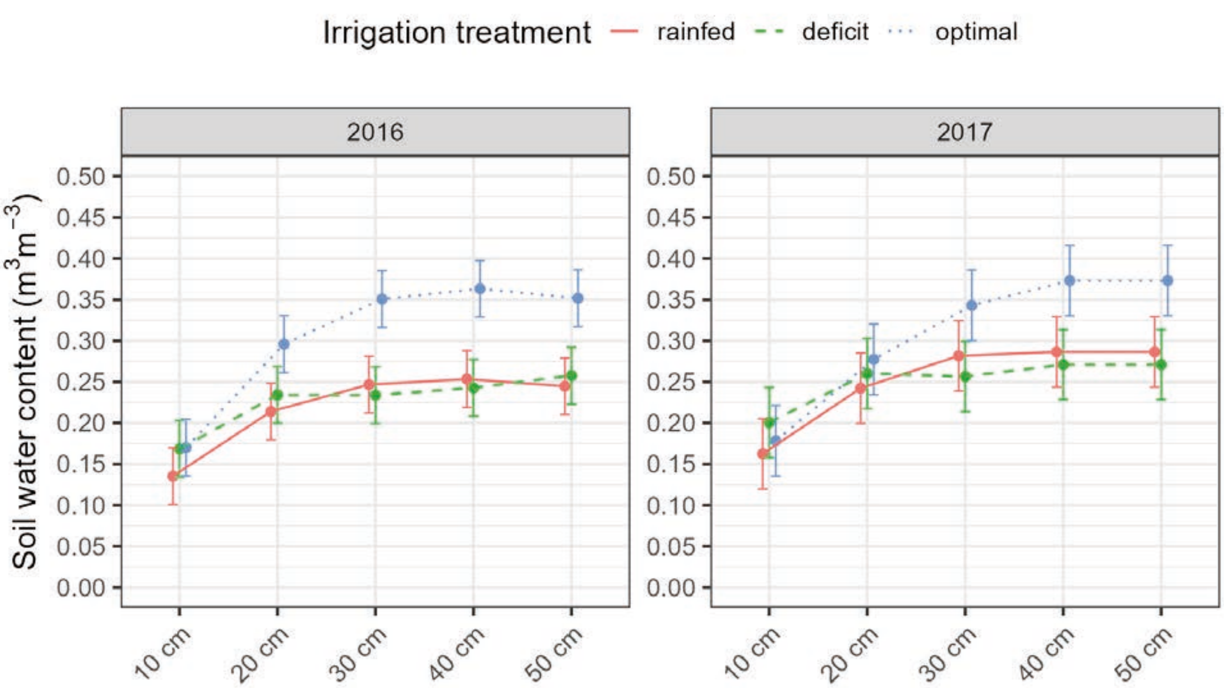

Figure 7: Model predictions of mean values and 95% confidence intervals of volumetric soil water content measurements for each of three treatments at different soil depths (10 cm, 20 cm, 30 cm, 40 cm, 50 cm) for the 2016 and 2017 growing seasons

$m^3\ m^{-3}$ higher under optimal irrigation than under deficit irrigation (95% *CI* from 0.01 $m^3\ m^{-3}$ to 0.18 $m^3\ m^{-3}$) in 2016 and 0.10 $m^3\ m^{-3}$ higher in 2017 (95 % *CI* from 0.02 $m^3\ m^{-3}$ to 0.19 $m^3\ m^{-3}$). At 50 cm in both growing seasons, mean θ was higher under optimal irrigation than under rainfed treatment.

Thus, the θ under the optimal irrigation treatment was higher compared to deficit irrigation and rainfed treatments in both growing seasons. Mean differences are higher in growing season 2016. The level of soil water content under the optimal irrigation treatment reflected the amount of water applied in each growing season. However, this was not the case in the deficit irrigation and rainfed treatments, between which no significant differences in θ were found at any depth, although more water was applied in the deficit irrigation treatment (Figures 4 and 5).

Table 6: Pairwise comparisons of differences in mean soil water content between irrigation treatments for each depth of monitoring for the 2016 and 2017 growing seasons

Year	Depth	Pairwise comparison	2.5 % percentile ($m^3\ m^{-3}$)	Mean differences ($m^3\ m^{-3}$)	97.5 % percentile ($m^3\ m^{-3}$)	*p*-value
2016	10 cm	optimal - deficit	−0.08	0.00	0.08	1.000
		optimal - rainfed	−0.05	0.03	0.12	0.455
		deficit - rainfed	−0.05	0.03	0.12	0.493
	20 cm	optimal - deficit	−0.02	0.06	0.14	0.122
		optimal - rainfed	−0.00	0.08	0.16	0.051
		deficit - rainfed	−0.06	0.02	0.10	0.826
	30 cm	optimal - deficit	0.03	0.12	0.20	0.015
		optimal - rainfed	0.02	0.10	0.19	0.023
		deficit - rainfed	−0.10	−0.01	0.07	0.968
	40 cm	optimal - deficit	0.04	0.12	0.20	0.013
		optimal - rainfed	0.03	0.11	0.19	0.019
		deficit - rainfed	−0.09	−0.01	0.07	0.987
	50 cm	optimal - deficit	0.01	0.09	0.18	0.032
		optimal - rainfed	0.02	0.11	0.19	0.021
		deficit - rainfed	−0.07	0.01	0.10	0.966
2017	10 cm	optimal - deficit	−0.11	−0.02	0.06	0.770
		optimal - rainfed	−0.07	0.02	0.10	0.918
		deficit - rainfed	−0.05	0.04	0.12	0.384
	20 cm	optimal - deficit	−0.07	0.02	0.10	0.892
		optimal - rainfed	−0.05	0.04	0.12	0.455
		deficit - rainfed	−0.07	0.02	0.10	0.876
	30 cm	optimal - deficit	0.00	0.09	0.17	0.045
		optimal - rainfed	−0.02	0.06	0.15	0.131
		deficit - rainfed	−0.11	−0.03	0.06	0.692
	40 cm	optimal - deficit	0.02	0.10	0.19	0.026
		optimal - rainfed	0.00	0.09	0.17	0.045
		deficit - rainfed	−0.10	−0.02	0.07	0.923
	50 cm	optimal - deficit	0.02	0.10	0.19	0.026
		optimal - rainfed	0.00	0.09	0.17	0.045
		deficit - rainfed	−0.10	−0.02	0.07	0.924

3.3 EFFECT OF IRRIGATION TREATMENTS ON OLIVE OIL YIELD

Mean fruit yield, oil content and olive oil yield are shown in Fig. 8. Fruit yield and olive oil yield of the different irrigation treatments in each of the two growing seasons reflect the observed differences in θ. However, mean oil content is the highest under deficit irrigation treatment in 2016. In 2017 mean values of oil content appear higher under rainfed and deficit than under optimal irrigation treatment.

The mean olive oil yield with 95 % percentiles for the studied trees is shown in Table 9 in the Appendix. Pairwise comparisons of differences in mean olive oil yield between different irrigation treatments for two growing seasons are shown in Table 7. A linear model accounting for different variances for each treatment was used for each growing season, and statistically significant differences in olive oil yield between treatments were observed ($p = 0.022$). Pairwise comparisons between treatments in the 2016 season showed statistically significant differences in mean yield between optimal and deficit irrigation treatment ($p = 0.045$) with a 2.24 l tree^{-1} higher olive oil yield under optimal irrigation compared to deficit (95 % *CI* from 0.06 l tree^{-1} to 4.43 l tree^{-1}). Differences between optimal and rainfed treatment in 2016 season ($p = 0.084$) were not statistically significant, although olive oil yield has been 1.95 l tree^{-1} 0.53 l tree^{-1} higher under optimal irrigation (Table 7).

A similar pattern was observed in the 2017 growing season. Differences in mean olive oil yield between optimal irrigation and rainfed treatment were statistically significant ($p = 0.048$), with mean olive oil yield under optimal irrigation being 1.56 l tree^{-1} higher (95 % *CI* from 0.01 l tree^{-1} to 3.31 l tree^{-1}). Differences in mean olive oil yield between optimal and deficit irrigation were nearly statistically significant ($p = 0.058$), with mean olive oil yield higher under optimal irrigation by 1.50 l tree^{-1} (±0.57 l tree^{-1}).

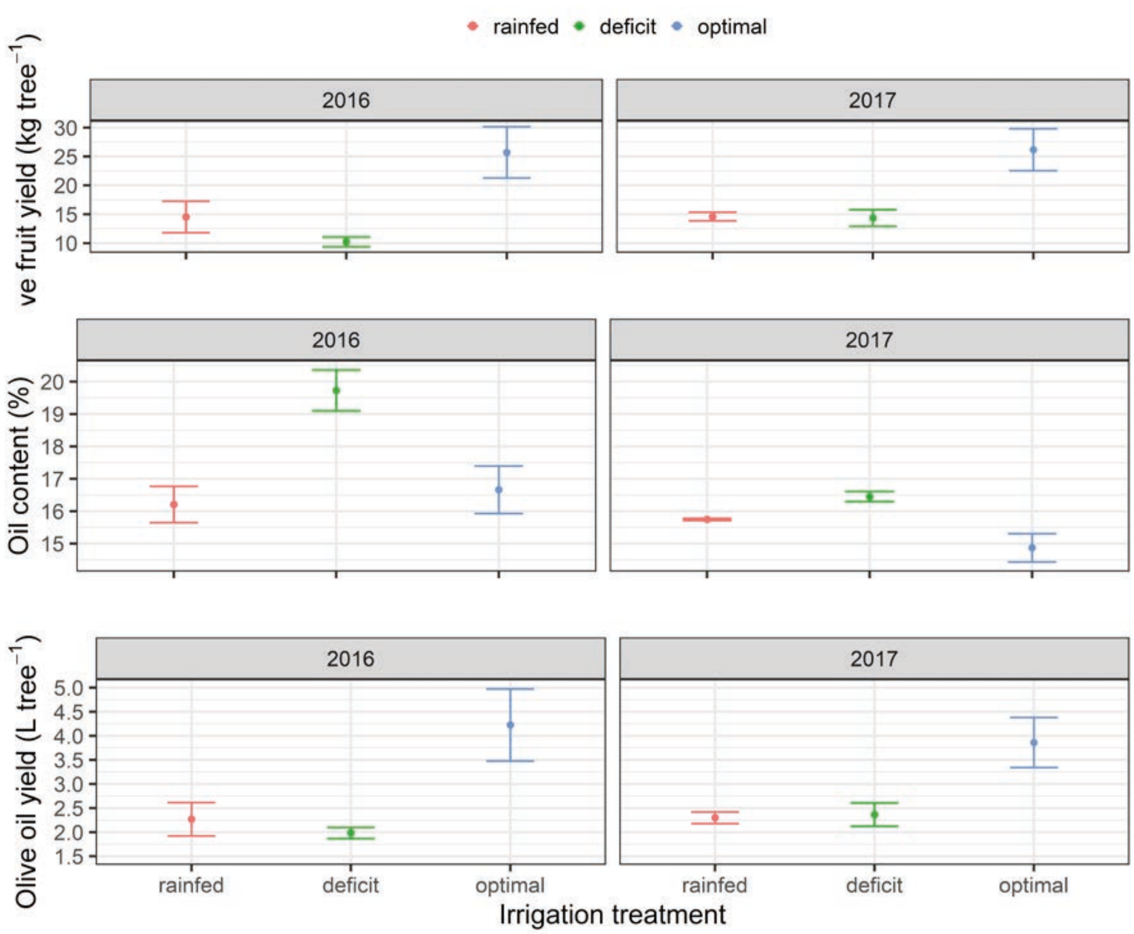

Figure 8: Mean olive fruit yield, oil content and olive oil yield per tree with standard errors for eight olive trees per treatment for the 2016 and 2017 growing seasons

Table 7: Pairwise comparisons of yield (litres of olive oil) between rainfed, deficit irrigation, and optimal irrigation treatment for the 2016 and 2017 growing seasons

Growing season	Contrast	2.5 % percentile ($l\ tree^{-1}$)	Mean differences ($l\ tree^{-1}$)	97.5 % percentile ($l\ tree^{-1}$)	p-value
2016	optimal - deficit	0.1	2.2	4.4	0.045
	optimal - rainfed	−0.3	2.0	4.2	0.084
	deficit - rainfed	−1.3	−0.3	0.7	0.709
2017	optimal - deficit	−0.1	1.5	3.1	0.058
	optimal - rainfed	0.01	1.6	3.1	0.048
	deficit - rainfed	−0.7	0.06	0.8	0.967

4 DISCUSSION

Although deficit irrigation is often advantageous compared to rainfed olive groves (Fereres and Soriano, 2007; Fernandes-Silva et al., 2010), it was not superior to rainfed treatment in terms of θ and olive oil yield in the present study. However, a surface drip irrigation system was used in the present study, which, according to Martínez and Reca (2014), results in lower olive oil yields compared to the subsurface irrigation system due to water loss through soil evaporation. A similar observation regarding water evaporation was made for citrus irrigation in Mediterranean climate (Martínez-Gimeno et al., 2018). Caruso et al. (2013), using subsurface drip irrigation, obtained 82 % of olive oil yield with deficit irrigated olives (46–52 % of water supply) compared to optimal irrigation. Potential water savings from switching from surface to subsurface drip irrigation were also described by Bonachela et al. (2001).

Since θ did not differ at any depth under rainfed treatment and deficit irrigation in either growing season (Fig. 4), this raises the question of the effectiveness of such sustained deficit irrigation with a surface drip system. Similar soil water content values between rainfed and deficit irrigation can be explained by advective heat transfer from the dry soil surface surrounding the small wet surface around the surface emitters (Matthias et al., 1986). Bonachela et al. (2001) measured evaporation with microlysimeters and found that it can be as high as 8 mm day^{-1} near the wetter surface (0.2 m from the emitter) and 6 mm day^{-1} at a distance of 0.2 to 0.35 m from the emitter. This is much higher than our maximum estimated daily ET_c^* calculated from the reference ET_0 using Penman-Monteith method and single crop coefficient $K_{c\ mid}$ for olive orchard, a method that assumes complete and uniform soil wetting. An irrigation study conducted on a 9-year-old olive orchard ('Coregiolo') in Australia showed that evapotranspiration during the irrigation was higher in irrigated than in rainfed trees because evapotranspiration was limited in rainfed trees due to low water content in the soil during summer (Zeleke, 2014).

Measured olive oil yields and θ at depths of 10 to 50 cm in two growing seasons, indicate that it is important to measure θ at different depths to assess whether the irrigation system achieves an increase in θ at the root depth (Datta et al., 2017). In our case, it was critical to increase the water content at a depth of 30 to 50 cm to increase the olive oil yield. Relying only on replenishing the estimated ET_c^* with a single crop coefficient and the reference ET_0 value of the previous day or week does not necessarily guarantee an increase in soil water content and thus yield. Estimation of the true ET_c value may be erroneous due to non-uniform soil wetting during surface drip irrigation (Matthias et al., 1986; Bonachela et al., 2001), errors in estimating K_c values when calculating ET_c (Allen et al., 2005), and the distance between the weather station and the location of the irrigated area (Fernández García et al., 2020). The irrigation water used could be wasted, as in our case of surface deficit irrigation. A better estimate of ET_c could be obtained with the double crop coefficient approach, which includes a separate prediction of soil evaporation (Allen et al., 1998). However, this approach could not be used in the present study because daily irrigation data were not available. Dual crop coefficient approach is also more complicated and more computationally intensive, especially because of the determination of daily K_e values for surface evaporation. The total K_c for non-uniformly wetted surfaces can be as high as $K_c = 1.3$ (Allen et al., 1998), which in our case would better correspond to evapotranspiration losses.

Conesa et al. (2021) compared an automated surface drip irrigation system, based on management allowed depletion threshold to trigger irrigation using θ values obtained with multi-depth capacitance sensors, with a conventional irrigation scheduling using estimated ET_c for nectarine trees grown in the Mediterranean region under two water availability scenarios. Similar to our study, irrigation dose based on the 100 % ET_c method did not necessarily increase θ close to FC at a depth of 0.5

m from May to July (unlike an automated system with a threshold trigger). The 100 % ET_c method supplied water only to the upper soil layer.

By measuring soil water content at relevant depths (the main root water uptake zone) with properly installed θ sensors to maintain adequate soil water content during the critical period, we can ensure that the irrigation system replenishes sufficient water, even without knowing and calculating the estimation of the true ET_c values.

5 CONCLUSIONS

This research addresses the influence of different irrigation treatments on the dynamics of soil water content and olive oil yield. A surface drip irrigation system was used in an olive grove in a northern Mediterranean climate, an olive growing area that has not been yet well studied. An increase in soil water content at a depth of 30 to 50 cm, achieved only with optimal irrigation, resulted in significantly higher olive oil yield. In contrast, sustained deficit irrigation did not increase soil water in the layers below 30 cm, despite the addition of water, so the yield was equal to that of rainfed treatment. Therefore it is advisable for olive oil producers to monitor soil water content in layers deeper than 30 cm to verify that enough water was applied to compensate for evapotranspiration losses. Policymakers and legislators should also be aware of the benefits of monitoring soil water content in a given soil layer, especially when deficit surface irrigation is used, as water is wasted if it does not reach the roots at the desired depth. Irrigation scheduling based on estimated ET_c using a single K_c approach can be problematic when using surface drip irrigation systems. In addition, the placement of drip emitters can also be an important contributor to water allocation. The shortcomings of this study are that the experiment was conducted in a single olive grove, with a single olive tree variety, with a specific soil type and a specific configuration of the surface drip irrigation system. Therefore, it is not necessarily transferable to sites with other characteristics. Under different growing conditions, further studies are needed to more accurately determine best irrigation practices, including irrigation system, timing, frequency, water quantity, and to evaluate the effects of different deficit irrigation strategies on olive tree growth, olive oil quantity and quality. Future work should also investigate deficit subsurface drip irrigation in olive groves in the northern Mediterranean climate.

5.1 ACKNOWLEDGMENTS

We would like to thank the Hlaj family for allowing us to perform our study in their olive grove in Dekani. We are grateful to Peter Korpar and our colleagues from the Science and Research Centre Koper, the Institute for Oliveculture for their technical assistance. We would like to thank dr. Miha Curk for his help in creating the map of the experimental site.

5.2 FUNDING

This study was supported by the Ministry of Agriculture, Forestry and Food of the Republic of Slovenia and the Slovenian Research Agency, Project No. V4-1609 and Research Programme P40085.

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7 APPENDIX

Table 8: Model predictions of mean values and 95 % confidence intervals of soil water content of irrigated treatments at different depths for the 2016 and 2017 growing seasons

Growing season	Depth	Treatment	2.5 % percentile (m^3 m^{-3})	Mean θ (m^3 m^{-3})	97.5 % percentile (m^3 m^{-3})
2016	10 cm	rainfed	0.10	0.14	0.17
		deficit	0.13	0.17	0.20
		optimal	0.14	0.17	0.20
	20 cm	rainfed	0.18	0.21	0.25
		deficit	0.20	0.23	0.27
		optimal	0.26	0.30	0.33
	30 cm	rainfed	0.21	0.25	0.28
		deficit	0.20	0.23	0.27
		optimal	0.32	0.35	0.39
	40 cm	rainfed	0.22	0.25	0.29
		deficit	0.21	0.24	0.28
		optimal	0.33	0.36	0.40
	50 cm	rainfed	0.21	0.24	0.28
		deficit	0.22	0.26	0.29
		optimal	0.32	0.35	0.39
2017	10 cm	rainfed	0.16	0.12	0.21
		deficit	0.20	0.16	0.24
		optimal	0.18	0.14	0.22
	20 cm	rainfed	0.24	0.20	0.29
		deficit	0.26	0.22	0.30
		optimal	0.28	0.23	0.32
	30 cm	rainfed	0.28	0.24	0.32
		deficit	0.26	0.21	0.30
		optimal	0.34	0.30	0.39
	40 cm	rainfed	0.29	0.24	0.33
		deficit	0.27	0.23	0.31
		optimal	0.37	0.33	0.42
	50 cm	rainfed	0.29	0.24	0.33
		deficit	0.27	0.23	0.31
		optimal	0.37	0.33	0.42

Table 9: Mean olive oil yield with 95 % percentiles for eight olive trees per treatment for the 2016 and 2017 growing seasons

Growing season	Treatment	2.5% percentile (l $tree^{-1}$)	Mean (l $tree^{-1}$)	97.5 % percentile (l $tree^{-1}$)
2016	optimal	2.5	4.2	6.0
	deficit	1.7	2.0	2.3
	rainfed	1.5	2.3	3.1
2017	optimal	2.6	3.9	5.1
	deficit	1.8	2.4	2.9
	rainfed	2.0	2.3	2.6