FRUITS

ORIGINAL ARTICLE

Influence of irrigation strategies on productivity, fruit quality and soil-plant water status of subsurface drip-irrigated apple trees

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Abstract – Introduction. The aim of this work was to study the effects of regulated deficit irrigation (RDI) on fruit yield, fruit weight and fruit quality parameters, as well as soil-plant water relations, in apple orchards under high-frequency subsurface drip irrigation in a region with a continental climate. **Materials and methods.** Four irrigation treatments were applied in 2010 and 2011 to apple trees cv. 'Gala': T1, no irrigation; T2, optimal irrigation except during summer; T3, optimal irrigation except during summer when RDI with a threshold for irrigation at -1.2 MPa midday stem water potential (Ψstem) was utilised; T4, optimal irrigation. The soil water status and plant water status were followed over two growing seasons. **Results and discussion.** The irrigation treatments had no significant impact on fruit yield. However, compared with optimal irrigation (T4) and RDI (T3), the absence of irrigation in summer (T1, T2) induced low Ψstem (< -1.2 MPa), decreased fruit size and slightly increased the soluble solid, vitamin C and polyphenol contents of the fruits. The RDI (T3) during summer allowed a water-use reduction of 47% without loss in fruit yield, fruit weight and fruit quality compared with the optimal irrigation (T4). **Conclusion.** The RDI treatment saved 47% water compared with optimal irrigation without negative impacts on yield and fruit quality. In the temperate conditions of Switzerland, Ψstem, as well as Ψsoil, are well adapted for scheduling RDI in apple orchards.

Keywords: Switzerland / apple / *Malus domestica* / irrigation scheduling / regulated deficit irrigation / water stress / phenolics / vitamin C

Résumé – Influence de stratégies d'irrigation sur la productivité, la qualité des fruits et le statut hydrique sol-plante de pommiers arrosés en goutte à goutte enterré. Introduction. Le but de cette étude a été d'analyser les effets de la régulation déficitaire de l'irrigation (RDI), avec des applications d'eau en goutte à goutte enterré à fréquence élevée, sur le rendement en fruits, le poids des fruits, et la qualité des fruits, ainsi que sur les relations hydriques entre sol et plante sur des vergers de pommier sous un climat continental. **Matériel et méthodes.** Quatre procédés d'irrigation ont été appliqués aux pommiers (cv. 'Gala') en 2010 et 2011 : T1, témoin non irrigué ; T2, irrigation optimal à l'exception d'absence d'irrigation durant l'été ; T3, irrigation optimal à l'exception une restriction d'irrigation induisant un stress modéré durant l'été, avec un seuil fixé à –1.2 MPa de Ψstem (irrigation déficitaire régulée, RDI) ; T4, irrigation optimale. L'impact de ces régimes sur le potentiel hydrique du sol (Ψsoil) et le potentiel hydrique du tronc (Ψstem) a été suivi pendant deux saisons. **Résultats et discussion.** Les régimes d'irrigation n'ont eu aucun impact significatif sur le rendement en fruits. Toutefois, par rapport à l'irrigation optimale (T4) et RDI (T3), l'absence d'irrigation en été (T1, T2) induit des potentiels de tronc bas (Ψstem < –1,2 MPa) et une diminution du poids des fruits. Par contre, les teneurs en sucre, en vitamine C et en polyphénols des fruits sont tendanciellement augmentées. Le procédé RDI (T3) au cours de l'été, a permis une réduction de la consommation d'eau de 47 % sans perte de rendement en fruits, de poids et de la qualité des fruits par rapport à l'irrigation optimale (T4). **Conclusion.** Le procédé RDI (T3) a économisé 47 % d'eau par rapport à l'irrigation optimale (T4), sans effets négatifs sur le rendement et la qualité des fruits. Dans les conditions environnementales de la Suisse, le potentiel hydrique du tronc (Ψstem)

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ainsi que le potentiel hydrique du sol (*Ψsoil*) sont bien adaptés pour gérer l'irrigation déficitaire dans des vergers de pommiers.

Mots clés : Suisse / pomme / *Malus domestica* / gestion de l'irrigation / irrigation déficitaire régulée (RDI) / stress hydrique / composés phénoliques / vitamine C

1 Introduction

Considering the increasing world population and climate change, water can become a limiting factor for agriculture [1]. In this context, increasing water-use efficiency is a vital issue for socio-economic development in many regions. More efficient water use is possible with improvements in plant breeding to enable crops to grow successfully in drought environments and in irrigation management, as well as in irrigation systems such as subsurface drip irrigation [1, 2]. This system delivers water directly to the root zone and minimises soil surface evaporation, runoff and deep percolation [2–5]. Another promising approach, especially for fruit crops, is regulated deficit irrigation (RDI), which aims to reduce irrigation during specific phenological stages without risk of loss to yield and fruit quality [6–13]. The concept of RDI was first proposed to control vegetative growth in peach orchards without influencing fruit yield [14, 15]. Studies on peach and apricot revealed that yield, fruit size and fruit quality can be maintained under conditions of mild to moderate plant stress when applied during some phenological stages [6–8]. RDI was also successfully applied to apple [9–13], citrus [16], almond [17] and loquat [18].

Moderate water stress with RDI can influence fruit quality parameters. Studies on peaches and apples showed that moderate water stress induced higher fruit sugar contents [19, 20]. The contribution of apple products, possessing a wide range of biological activities with beneficial protective effects for health against cardiovascular disease, asthma and pulmonary dysfunction, diabetes, obesity, and cancer, has been reviewed [21] and confirmed by epidemiological observations, indicating that regular consumption of one or more apples per day may reduce the risk of certain cancers [22]. However, there is little information on the effects of different irrigation treatments on the nutritional parameters of apple fruit.

To manage irrigation, different methods have been used to monitor soil humidity and identify the actual plant water status, including tensiometers [23], granular matrix sensors [24] and capacitance probes [25]. Soil water status has long been used for scheduling irrigation [26], and is one of the most useful scheduling methods available, due to its practicability and low cost [27]. Using soil-based measurements for RDI presupposes the existence of a reliable plant-based indicator and a threshold that can be used to predict the absence of impact on yield and fruit quality. The relationship of the midday stem water potential (*Ψstem*) and fruit size has been analysed for apple by Naor [28]. It appears that the proportion of fruits larger than 65 mm measured at harvest significantly decreases with −1.2 to −1.3 MPa *Ψstem*. This was confirmed in a Spanish trial, in which none of the deficit treatments ranging from −1.1 to −1.2 MPa throughout the season differed from the control in yield and fruit size at harvest, while those reaching values

Table I. Soil characteristics of the experimental site at four different depths measured at the beginning of the experiment in 2010.

Soil Depth (m)	Organic matter (%)	pH	Soil granulometry		
			Clay (%)	Silt (%)	Sand (%)
0.00–0.25	3.7	8.0	24.2	40.4	35.3
0.25–0.50	3.3	8.1	23.5	41.6	35.0
0.50–0.75	2.0	8.2	22.4	43.5	34.1
0.75–0.10	2.4	8.2	23.9	43.2	32.9

lower than −1.4 MPa from mid-July showed a significant decrease in both parameters [29]. *Ψstem* has been successfully used in dominant anisohydric species or cultivars such as fruit trees [30], prune [31, 32], apple [33], almond [34] and citrus trees [35], as well as vineyards [36]. However, it has been shown that for species or cultivars with dominant isohydric behaviour, this indicator is replaced by leaf water potential measured at predawn (*Ψpd*) [37].

This study specifically addresses subsurface drip irrigation and will evaluate the impact of different irrigation strategies – no irrigation, RDI and comfort irrigation – on fruit yield, fruit weight and fruit quality, including vitamin C, total polyphenol content (TPC) and antioxidative potential. Furthermore, information is scant about soil and plant water status with high-frequency subsurface drip irrigation. The relationship between the plant and soil water status at different soil depths was assessed in order to define accurate measurement methods with their corresponding threshold values for scheduling RDI in orchards.

2 Materials and methods

2.1 Experimental site, plant material

The experiment was conducted in an experimental orchard located at Agroscope in Conthey, Switzerland (latitude 46°12′ N, longitude 7°18′ E, altitude 500 m). The climate is continental, with high daily and seasonal variations in temperature. The average temperature from 1978 to 2007 was 9.9 °C, the average annual rainfall was 630 mm and the calculated water deficit during the vegetation period for apple trees was 275 mm.

Soil analyses were carried out from 15 samples randomly taken in March 2010 at four different depths (*table I*). According to the American Unified Soil Classification System (USCS) standard, the soil is a loam, with pH ranging from 8.0 (soil) to 8.2 (subsoil) and organic matter decreasing from 3.7% at 25 cm depth to 2.4% at 100 cm depth. Gravel does not exceed 10%. Soil fertility is at an optimal level for phosphorus and above the optimum for potassium and magnesium.
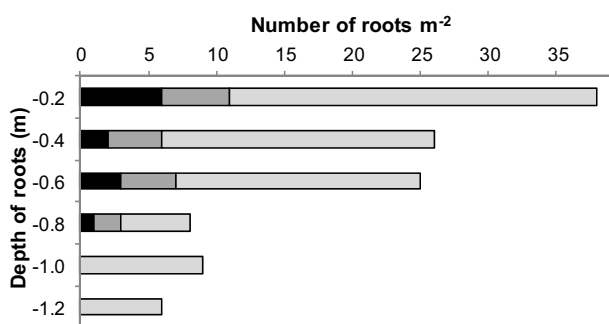
Figure 1. Distribution of roots of Gala apple trees grafted on M9 at the beginning of the experiment in 2010 in different soil layers of 0.20 m according to their diameters: ■ thick roots (> 5 mm), ■ medium roots (> 1 to < 5 mm), ■ fine roots (< 1 mm), observed on a soil profile 1.2 m deep and 3.0 m wide.

The experimental orchard was planted in 2002 with cv. Royal Gala® on M9 rootstock, clone FL 56. Trees are trained in two different systems: a three-axis V-shape system, 2.8 m high, and a vertical two-axis hedge system, 3.5 m high. Planting density was 4.0 m × 1.4 m (1,800 trees ha^{-1}) for both systems, and the rows are north-south oriented. The orchard was fertilised with 60 kg N, 10 kg P and 40 kg K according to guidelines for integrated production [38]. The full bloom of Gala was on April 26th in 2010 and April 18th in 2011, and fruits were harvested on August 24th in 2010 and August 19th in 2011. The root distribution of the Gala apple trees is shown in *figure 1*, indicating that most roots were found between 20 and 60 cm depth. Some fine roots were found down to 1.2 m.

Subsurface drip irrigation was carried out with two dripper lines (CNL Uniram, 30 cm, 1.6 L h^{-1}, Netafim Ltd., Tel Aviv, Israel) installed 0.5 m from the tree row and at a soil depth of 0.25 m. The dripper flow rate of 1.6 L h^{-1} and dripper spacing of 0.3 m was chosen for homogeneous water distribution achieved with a pressure compensating system (1.0−4.0 bar). Irrigation was automatically set to 2−4 pulses day^{-1} with duration of 3 to 12 min per pulse depending on the season and the total water volume to be distributed every day. Adjustments were made once a week to keep soil humidity as constant as possible at −0.03 MPa for the treatments and periods when optimal irrigation had to be applied.

2.2 Irrigation treatments and experimental design

The soil of the experimental orchard was completely covered by a transparent plastic foil to avoid penetration of the rainwater to the roots. Furthermore, the plastic foil was covered by green plastic to limit the influence of solar radiation on the soil temperature. The slight inclination of the field by 1−2% allowed rainwater to flow superficially out of the orchard.

The irrigation treatment experiments were based on three fruit-growing periods according to the recommendation of the Food and Agriculture Organization (FAO) [39]: P1, from full bloom to the end of fruit cell division (about 60 days for apples); P2, corresponding to the fruit cell growing period (from the beginning of July to the beginning of August); and P3, about 3 to 4 weeks before harvest.

The following four irrigation treatments were applied: T1, no irrigation from full bloom to harvest (P1 to P3); T2, optimal irrigation during P1 and P3, no irrigation during P2; T3, optimal irrigation during P1 and P3, application of deficit irrigation (as a way to maintain $\Psi stem$ at about −1.2 MPa during P2; this threshold is supposed to ensure sufficient water supply to the plants and avoid negative impacts on the yield and quality of fruit [40]); and T4, optimal irrigation from full bloom to harvest. The trees were irrigated according to soil water potential ($\Psi soil$) at the threshold value of −0.03 MPa (measured with sensors at a soil depth of 0.3 m), except the T3 treatment with RDI during P2.

The experimental design is a split plot with three replications and four irrigation treatments. Each plot contained 18 trees, with two subplots of 9 trees per tree shape (the three-axis V-shape system and vertical two-axis system). Plant water status and fruit yield and quality were measured separately on two individuals per subplot. However, the results of both shapes were pooled, because there were no significant interactions between irrigation treatments and tree shapes for the parameters analysed.

2.3 Yield, fruit weight and stem development

The fruits from each of the two reference trees of every subplot were individually harvested at the end of August in 2010 and 2011. Total yield (in kg) and number of fruits, as well as the individual fruit weight and colour, were obtained with a sorting machine (Greefa, Tricht, The Netherlands), dividing Class A fruits (fruit diameter of 65 to 80 mm) from the other fruits. The trunk circumference was measured at 0.2 m above the grafting point at the end of the vegetation period in autumn.

2.4 Fruit quality parameters

Tests for soluble solid contents (SSC, °Brix), acidity (malic acid, g L^{-1}) and firmness (kg cm^{-2}) were performed on a random sample of 20 fruits per tree at harvest using the semi-automatic Pimprenelle robotic machine (Setop Giraud Technology, France) [41]. This instrument consists of three measuring units: a penetrometer, optical refractometer and titrator.

Sampling and sample treatment for the quantification of the total phenolic content (TPC) and antioxidative potential by ferric reducing antioxidant power (FRAP) were done as described in other studies [42, 43]. At harvest, 20 fruits out of the whole production per tree were randomly chosen and pooled in one sample. The 20 fruits were sliced with an apple divider (Divisorex, Famos-Westmark GmbH, Lennestadt-Elspe, Germany) into 10 pieces plus the core area. The core area was discarded. Two opposite slices of each fruit were randomly chosen and immediately frozen in liquid nitrogen, and all 40 frozen slices were pooled as a representative sample. The frozen apple pieces were crushed in a dry ice mill (Meidinger AG, Kaiseraugst, Switzerland) and ground to fine powder with a cutter (La Moulinette DPA 1, Moulinex, Germany). Afterwards, the samples were stored at −20 °C until extraction. Extraction was carried out by mixing 2.5 g frozen powder with 50 mL methanol containing 1% formic acid (v/v) and

Table II. Water applied, fruit yield, class A fruits, fruit weight and trunk diameter in 2010 and 2011 in relation to the different irrigation strategies: no irrigation (T1); optimal irrigation except no irrigation during July to the beginning of August (T2); optimal irrigation except regulated deficit irrigation (RDI) during July to the beginning of August (T3); optimal irrigation (T4). Each value of the agronomic parameters corresponds to the mean (± standard deviation) of 2 training systems and 3 replications. Different letters indicate significant differences among the treatments (Tukey, $P < 0.05$).

Years	Treatments		Agronomic parameters			
	Water applied		Total yield	Class A	Fruit weight	Trunk diameter
	(L m^{-2})		(kg tree^{-1})	fruits (%)	(g)	(mm)
2010	T1	0	19.5 ± 7.0	58 ± 14	121 ± 16 b	54.0 ± 4.4 b
	T2	72	17.6 ± 8.2	65 ± 12	129 ± 8 ab	58.9 ± 7.0 a
	T3	82	24.4 ± 10.1	76 ± 11	140 ± 9 a	59.7 ± 6.9 a
	T4	149	21.7 ± 10.7	76 ± 8	138 ± 15 a	57.0 ± 6.7 ab
2011	T1	0	31.9 ± 7.4	74 ± 13	134 ± 12 b	56.9 ± 3.7 b
	T2	42	37.0 ± 13.1	79 ± 10	141 ± 11 ab	62.1 ± 7.9 a
	T3	69	37.2 ± 8.5	85 ± 7	149 ± 14 a	64.0 ± 6.6 a
	T4	135	38.0 ± 11.1	84 ± 8	147 ± 11 a	62.7 ± 6.8 a

homogenisation. Extracts were allowed to stand at room temperature for 1 h to sediment, before an aliquot of the supernatant was directly used for the analysis of TPC by the Folin-Ciocalteu method [42] and the FRAP method [43]. Both tests were carried out on a Konelab Arena 20XT analyser (Thermo Fisher Scientific Oy, Vantaa, Finland). An external catechin standard calibration was used for quantification, and the results were expressed as mg catechin equivalents (CE) 100 g^{-1} edible fruit (FM) [42, 43].

Vitamin C, ascorbic acid and dehydroascorbic acid were quantified after extracting 5.0 g of the above-mentioned frozen powder with 50 mL phosphate buffer containing 1 g L^{-1} DL-dithiothreitol. After 2 h at room temperature in order to reduce the dehydroascorbic acid, the extracts were filtered through a 0.45-μm filter, measured by HPLC-UV, and quantified with an external ascorbic acid standard calibration [44]. All extractions were done in duplicate and analysed twice.

2.5 Measurements of soil water status

To determine the soil water status, granular matrix probes (Watermark® probes, IRROMETER Company, Inc., Riverside, CA, USA) were installed at 0.30 and 0.60 m depths to get the $\Psi soil$, approximately vertically under the dripper line. The median value of three repeated probe values at each depth in each subplot was considered in order to schedule optimal irrigation.

Capacitance measurements were obtained from access tubes (Aquapro Sensors, Reno, NV, USA) at six soil depths from 0.15 to 0.90 m, at a distance from the tree row of 0.25 m. The measurement scale is in %Aquapro, and according the manufacturer's instructions the 100% value is considered as field capacity and values around 40% correspond to the lowest limit for water availability by the plant in a loam soil. Two Aquapro tubes were installed in each subplot. For both measurement systems, probes and tubes were located only in one replication.

2.6 Measurements of plant water status

$\Psi stem$ and predawn leaf water potential (Ψpd) were used for assessing plant water status. They were determined us-

ing a Scholander pressure chamber (Model 600; PMS Instrument Company, Albany, OR, USA) [45]. Measurements were made on one leaf per reference tree, *i.e.*, 12 measurements per irrigation treatment including both subplots. $\Psi stem$ monitoring was done every 3−4 days from early June to several days before harvest at solar noon, leaving the leaves covered in an aluminium foil before measurement. The duration for leaf sampling and measurements was 60 to 90 min. Ψpd was measured 5 times during the growing season in total darkness, between 03:00 and 04:00 am (solar time).

2.7 Data analysis

All statistical analyses were carried out using XLSTAT 2010. To compare the influence of the different treatments, data were subjected to an analysis of variance (ANOVA), and the significant differences were analysed with Tukey's test at a level of 95% ($P < 0.05$). The two tree shape systems were pooled, because no significant interactions were found between them and the irrigation treatments (data not shown). Relationships between factors were analysed by simple linear regression and by the coefficient of determination (R^2).

3 Results and discussion

### 3.1 Water application, fruit yield, fruit weight and stem development

Irrigation water differed sharply according to the irrigation treatment. The 2010 and 2011 average amount for T4 was 142 mm during the season (*table II*). For T3 (RDI) and T2, it was limited to 75 and 57 mm, which means water saving of 47% and 60%, respectively. The treatments did not induce any significant difference in yields. The treatments without irrigation during all or part of the season (T1, T2) produced the smallest fruits and lowest Class A percentage. The trunk diameter measured at the end of 2010 and 2011 showed clearly less trunk growth on these water-stressed trees, especially for the treatment with no irrigation, compared with full-irrigated and RDI trees. These plants were less vigorous and in the long term might produce less fruits.

Table III. Soluble solid and malic acid contents, firmness, total phenolic compounds (TPC), and vitamin C contents of the apple fruits in 2010 in relation to the different irrigation strategies: no irrigation (T1); optimal irrigation except no irrigation during July to the beginning of August (T2); optimal irrigation except regulated deficit irrigation (RDI) during July to the beginning of August (T3); optimal irrigation (T4). Each data value corresponds to the mean (± standard deviation) of 2 training systems and 3 replications. Different letters indicate significant differences among the treatments (Tukey, $P < 0.05$).

| Treatments	Soluble solids (°Brix)	Malic acid g kg^{-1}	Firmness kg cm^{-2}	TPC Me CE[a] 100 g^{-1}	Vitamin C mg 100 g^{-1}	FRAP mg CE[a] 100 g^{-1}
T1	12.6 ± 0.8	4.7 ± 0.4	9.5 ± 1.2	99 ± 15	4.7 ± 0.8	115 ± 10
T2	12.4 ± 0.9	4.8 ± 0.4	9.6 ± 0.9	91 ± 16	4.8 ± 0.5	106 ± 7
T3	12.0 ± 1.0	4.5 ± 0.2	9.2 ± 1.0	92 ± 16	4.2 ± 0.7	104 ± 9
T4	12.1 ± 0.8	4.6 ± 1.2	9.1 ± 0.7	92 ± 19	4.2 ± 0.4	104 ± 16

[a] CE = catechin equivalent.
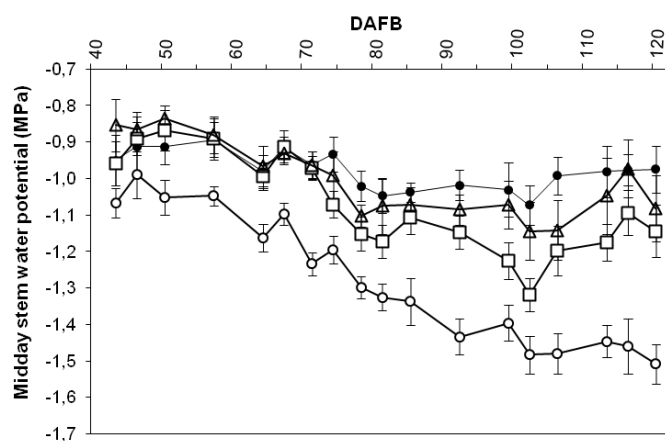
Figure 2. Midday stem water potential ($\Psi stem$) in 2010 in relation to the different irrigation strategies: T1, no irrigation (○); T2, optimal irrigation except no irrigation during July to the beginning of August (□); T3, optimal irrigation except regulated deficit irrigation (RDI) during July to the beginning of August (△); T4, optimal irrigation (●). Each point corresponds to the mean of 12 measurements (vertical bars indicate standard deviations). Days after full bloom (DAFB): 6–36 corresponded to May, 37–66 to June, 67–97 to July and 98–128 to August.

No significant impact of RDI was found on any agronomic parameter (*table II*). This confirms results found in pear [46,47], almond [48] and loquat [18]. However, some authors suggested that a moderate water deficit during the fruit growth stage decreased apple yield [9]. In this study, $\Psi stem$ lower than −1.2 MPa during summer had a negative impact on fruit size compared with optimal irrigation. These results on fruit size confirm similar effects obtained in semi-arid climates with apples [11]. A threshold of $\Psi stem$ at −1.2 MPa was suitable for RDI for both experimental years (*figure 2*).

3.2 Fruit quality

One of the goals in this study was to evaluate the possible influence of irrigation on commercial quality parameters and nutritional parameters. The results showed a slight tendency toward higher SSC, fruit firmness, vitamin C contents and TPC with increasing plant stress (*table III*). Smaller fruit size on stressed trees (T1 and T2) could explain this result through a
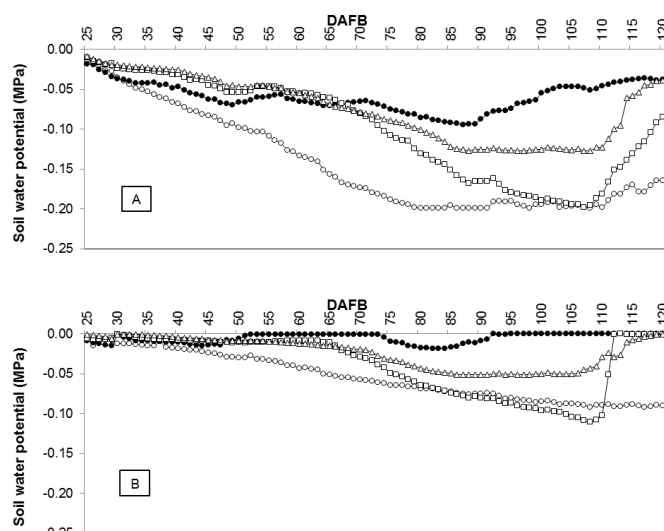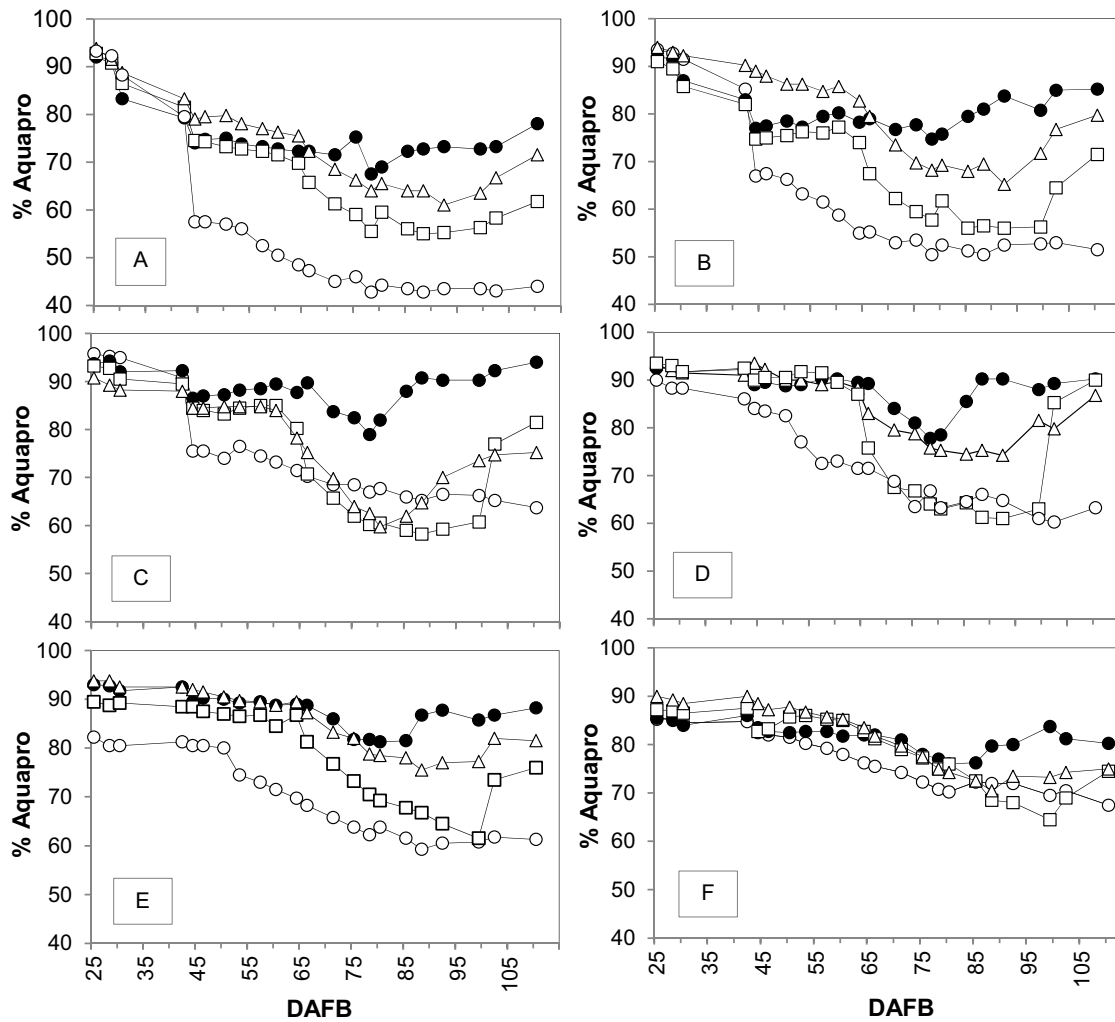

Figure 3. Soil water potential ($\Psi soil$) at 0.3 m (A) and 0.6 m (B) soil depth in 2010 in relation to the different irrigation strategies: T1, no irrigation (○); T2, optimal irrigation except no irrigation during July to the beginning of August (□); T3, optimal irrigation except regulated deficit irrigation (RDI) during July to the beginning of August (△); T4, optimal irrigation (●). Each point corresponds to the mean of six measurements. Days after full bloom (DAFB): 6–36 corresponded to May, 37–66 to June, 67–97 to July and 98–128 to August.

concentration effect. Similar results confirm the effect of water stress on phytochemical compounds in apples [49,50]. However, this influence is very moderate compared with that of cultivars. In a study comparing 104 cultivars, the range of TPC was between 52 and 379 mg CE 100 g^{-1} and the range of antioxidant potential was between 42 and 429 mg CE 100 g^{-1} of edible fresh matter [39], while the TPC increase as a consequence of the irrigation regime does not exceed 7% in this study.

3.3 Soil water status

During the experiment, $\Psi soil$ measured with Watermark® probes decreased to about −0.20 MPa at 0.30 m depth without irrigation in 2010 (*figure 3*), whereas at 0.60 m the decrease was less significant, about −0.10 MPa. This difference was
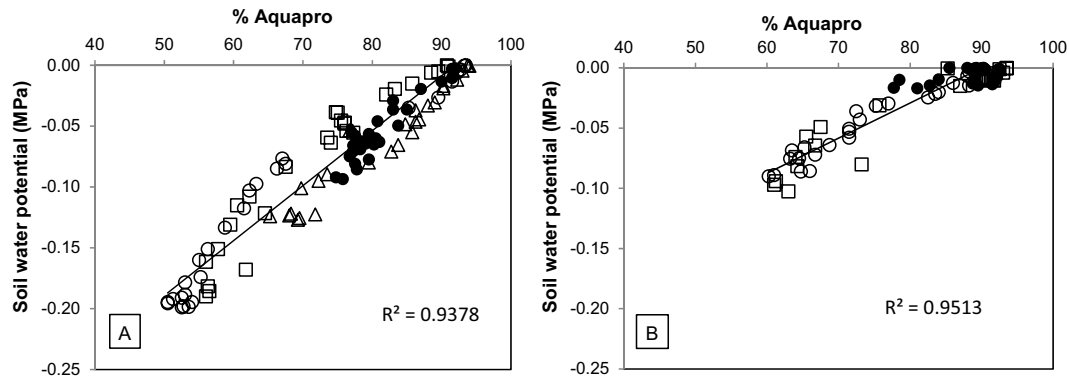
Figure 4. Capacitance measurements, expressed in %Aquapro (with a 100% value considered as field capacity and values around 40% as the lowest limit for water availability by the plant in a loam soil) at different soil depths (A: 0.15, B: 0.30, C: 0.45, D: 0.60, E: 0.75 and F: 0.90 m) in 2010 in relation to the different irrigation strategies: T1, no irrigation (○); T2, optimal irrigation except no irrigation during July to the beginning of August (□); T3, optimal irrigation except regulated deficit irrigation (RDI) during July to the beginning of August (△); T4, optimal irrigation (●). Each point is the mean of four measurements. Days after full bloom (DAFB): 6-36 corresponded to May, 37-66 to June, 67-97 to July and 98-128 to August.

due to higher root density at 0.30 m than at 0.60 m (*figure 1*). In contrast, with optimal irrigation, $\Psi soil$ decreased only to −0.08 MPa at 0.30 m below ground level and −0.02 MPa at 0.60 m. The treatments with no irrigation (T2) and RDI (T3) during July to the beginning of August showed an intermediate evolution. In T3, $\Psi soil$ reached −0.12 and −0.05 MPa at 0.30 m and 0.60 m soil depth, respectively. Restoring optimal irrigation in August for these two treatments induced a quick rise in $\Psi soil$ values, up to optimal water availability, as expected [8,51].

Capacitance measurements in the Aquapro access tubes showed fewer differences among irrigation treatments with increasing soil depth (*figure 4*). At a given soil depth, a change in the curve slope may indicate a decrease in water availability. In general, a significant decrease in soil water content (SWC), indicating easy water uptake, was followed by a flattening of the curve, suggesting that water availability was becoming

critical at this level. For the no-irrigation control treatment (T1), such a signal appeared successively with increasing soil depth. For the upper soil layers (15−45 cm) where the root density is highest, the flattening of the curve was detectable at 30 to 35 DAFB. Most of the tree water supply was then covered by available water at 0.60 and 0.75 m soil depth until critical depletion, occurring four weeks later (about 65 DAFB). The critical threshold of the non-limiting water range seemed to be different according to soil depth: 55% at 0.30 m and 65−75% at 0.45 to 0.75 m. Values at 0.90 m are rather stable throughout the season, indicating that this soil layer has a lower direct contribution to tree water uptake due to weak root colonisation.

Capacitance measurements in the Aquapro access tubes showed a close evolution at 0.3 and 0.6 m (*figure 4*) compared with $\Psi soil$, meaning that the relationship between SWC and $\Psi soil$ was strong at both soil depths (*figure 5*). This indicates

Figure 5. Relationships between soil water potential ($\Psi soil$) and capacitance measurements, expressed in %Aquapro (with a 100% value considered as field capacity and values around 40% as the lowest limit for water availability by the plant in a loam soil) at 0.3 m soil depth (A) and at 0.6 m (B) in 2010 considering the different irrigation strategies: T1, no irrigation (○); T2, optimal irrigation except no irrigation during July to the beginning of August (□); T3, optimal irrigation except regulated deficit irrigation (RDI) during July to the beginning of August (△); T4, optimal irrigation (●).
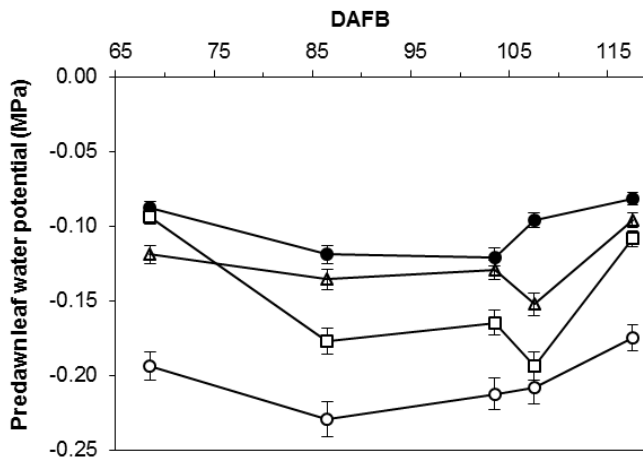
Figure 6. Predawn plant water potential (Ψpd) in 2010 for the different irrigation strategies: T1, no irrigation (○); T2, optimal irrigation except no irrigation during July to the beginning of August (□); T3; optimal irrigation except regulated deficit irrigation (RDI) during July to the beginning of August (△); T4; optimal irrigation (●). Each point corresponds to the mean of 12 measurements (vertical bars indicate standard deviations). Days after full bloom (DAFB): 6−36 corresponded to May, 37−66 to June, 67−97 to July and 98−128 to August.

3.4 Plant water status

The data range of Ψpd in this study was between −0.08 and −0.23 MPa during summer (*figure 6*). Such small differences that both measurement methods give reliable results in the range of 0.0 to −0.2 MPa $\Psi soil$. However, the slopes of the regression curve between the two depths were quite different, which confirms that limiting water availability may occur at different SWC according to soil depth. In fact, the correspondence between SWC and $\Psi soil$ depends on soil composition; even if the granulometry seems to be similar in all the layers observed, there are differences in organic matter between soil layers (*table I*) that can explain the differences between the two soil layers.

between irrigated and non-irrigated plants could be explained by the fact that the root systems of the trees were partially supplied by a restricted humid zone such as groundwater [52]. Plants submitted to drought of the whole root depth reached much lower values of Ψpd. In T1 and T2, which received no irrigation during summer, available water was probably supplied by lower root layers, as indicated in *figure 4F*. However, the SWC remained very stable in these soil layers throughout the season, indicating that this water cannot be considered a water reserve for this treatment due to low root density (*figure 1*). The low water uptake might be sufficient for night plant rehydration, thereby avoiding a strong decrease in Ψpd during the season without irrigation. Nevertheless, a high coefficient of determination (R^2) between Ψpd and $\Psi soil$ was observed in this study (*figure 7*) as well as in other studies; for example, a study on grapevine [53]. This can be explained by the large range of $\Psi soil$, between −0.04 and −0.20 MPa during the season, with different values for stressed and non-stressed apple trees according to the irrigation management. However, studies on this topic suggested that predawn plant water potentials were not a consistent measurement for managing irrigation, especially under well-watered conditions [52, 54]. Further to such limitation, for managing irrigation, $\Psi stem$ should be preferred in case of anisohydric behaviour [55]. Apple trees display in general anisohydric characteristics [56].

$\Psi stem$ very clearly separated the four irrigation treatments in this experiment (*figure 2*). The suitability of the −1.2 MPa $\Psi stem$ as an adequate threshold for deficit irrigation scheduling, despite experiments in very different climatic and soil conditions (*i.e.*, Israel and Spain), confirms its wide suitability for cultivars with the specified behaviour [28, 29]. However, the measurement of $\Psi stem$ is very time-consuming and until now there has been no system available to measure leaf water potential electronically. Since the relationship between $\Psi stem$ and $\Psi soil$ was well established, especially at the 0.3 m soil depth (*table IV, figure 8*), this study pointed out that with high-frequency subsurface irrigation at 0.25 m below ground level, the measurement of soil water status with Watermark® probes is accurate at a soil depth of 0.30 m. For scheduling
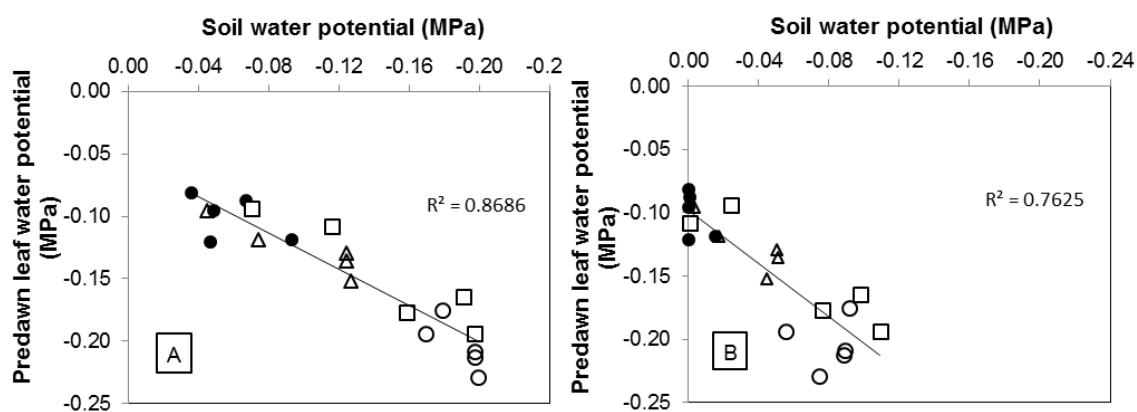
Figure 7. Relationships between predawn water potential (Ψpd) and soil water potential ($\Psi soil$) at 0.3 m soil depth (A) and at 0.6 m (B) in 2010 considering different irrigation strategies: T1, no irrigation (O); T2, optimal irrigation except no irrigation during July to the beginning of August (□); T3, optimal irrigation except regulated deficit irrigation (RDI) during July to the beginning of August (△); T4, optimal irrigation (●).
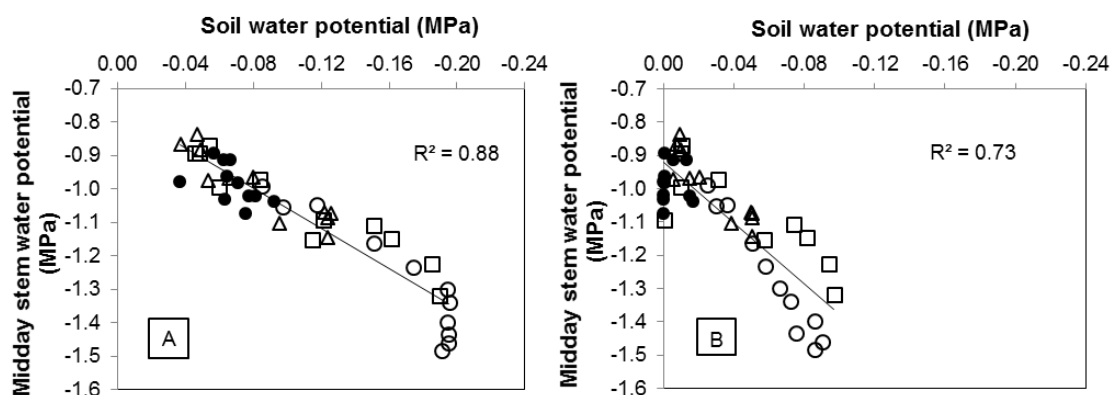
Figure 8. Relationships between midday stem water potential ($\Psi stem$) and soil water potential ($\Psi soil$) at 0.30 m soil depth (A) and 0.60 m (B) in 2010 considering different irrigation strategies: T1, no irrigation (O); T2, optimal irrigation except no irrigation during July to the beginning of August (□); T3, optimal irrigation except regulated deficit irrigation (RDI) during July to the beginning of August (△); T4, optimal irrigation (●).

Table IV. Relation between soil water potential ($\Psi soil$) and midday stem potential ($\Psi stem$) for two soil depths, as well as capacitance measurements, expressed in %Aquapro and midday stem potential ($\Psi stem$) at six different soil depths in 2010. The values correspond to the coefficient of determination (R^2) of the respective relationships.

Soil depth	$\Psi soil$ to $\Psi stem$ relationship			Capacitance measurements to $\Psi stem$ relationship						
(m)	0.3	0.6	Mean	0.15	0.30	0.45	0.60	0.75	0.90	Mean
R^2	0.88	0.73	0.85	0.82	0.73	0.47	0.69	0.86	0.64	0.81

RDI in the experimental orchard with Watermark sensors, the calculated $\Psi soil$ threshold values of −0.15 and −0.08 MPa, respectively, for 0.30 m and 0.60 m depth turned out to be adequate for RDI. Compared with on-surface drip irrigation, subsurface irrigation, especially with high-frequency water application, avoided risky situations such as when water supplies lower than 1 mm day^{-1} (as in T4) would probably have wetted a very shallow soil layer, poorly colonised by roots and more exposed to a higher evaporation rate. With subsurface irrigation, water is injected into the most efficient root layer. This might also be a reason for the high coefficient of determination (R^2) between $\Psi soil$ and $\Psi stem$, and why the −1.2 MPa $\Psi stem$ threshold could be detected in a $\Psi soil$ threshold, which

was confirmed to be suitable for this particular orchard in subsequent seasons (data not shown).

4 Conclusion

For the apple orchard under study with high-frequency subsurface irrigation, the optimal irrigation did not significantly impact fruit yields for two consecutive years compared with absence of irrigation. However, fruit weight was significantly increased compared with the non-irrigated treatments inducing a $\Psi stem$ value considerably lower than −1.2 MPa during the summer period. In contrast, fruit quality responded

slightly negatively to optimal watering, suggesting a dilution phenomenon. Moderate water stress, not lower than −1.2 MPa $\Psi stem$, did not influence fruit size, commercial quality or nutritional quality (SSC, total phenolic compounds and vitamin C) compared with optimal irrigation. However, this moderate stress saved approximately 50% of water compared with the optimal irrigation.

$\Psi soil$ proved to be an adequate and easily measurable indicator for RDI scheduling. In this experiment there was a strong relationship between $\Psi soil$ and $\Psi stem$ (R^2 = 0.91). The calculated $\Psi soil$ threshold values of −0.15 and −0.08 MPa for 0.30 m and 0.60 m soil depth, respectively, turned out to be suitable for scheduling RDI.

These results contribute to improving the use of tools measuring $\Psi soil$ and $\Psi stem$ for irrigation scheduling of apple orchards, allowing deficit irrigation, and saving water without reducing yield and fruit quality.

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