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Financial assessment of adopting irrigation technology for plant-based regulated deficit irrigation scheduling in super high-density olive orchards

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Abstract

Hedgerow orchards with high plant densities, or super high-density (SHD) orchards, are considered to be amongst the most profitable management systems for most fruit-tree species. Regulated deficit irrigation (RDI) strategies are recommended for SHD olive orchards, especially when scheduled from automatic and continuous measurements of plant water stress. There is a lack of information, however, on the profitability of this approach. In this work we analysed the financial feasibility of using three different systems for monitoring water stress in an ‘Arbequina’ SHD olive orchard under a RDI strategy recommended for the experimental area (SW Spain). The systems were based on sap flow (SF), trunk diameter variation (TDV) and leaf turgor pressure (TP) related measurements. We first compared their equivalent annual cost (EAC), resulting the TP based technology as that with the greatest potential to be adopted by farmers. We then used Discounted Cash Flow Analysis (DCFA) to compare the financial feasibility of an RDI treatment scheduled from TP related measurements and providing 45% of the crop water needs ($45RDI_{TP}$) with both a similar treatment but scheduled with the crop coefficient approach ($45RDI_{CC}$) and a fully irrigated (FI) treatment. Our results from two irrigation seasons demonstrated that the 45RDI strategy guarantees the profitability of SHD olive orchards in the long-term, with both $45RDI_{CC}$ and $45RDI_{TP}$ showing positive Net Present Value and Internal Rate of Return above the interest on capital. All the financial indicators suggested higher financial performance of $45RDI_{TP}$ as compared to $45RDI_{CC}$, but differences were not significant, likely because of the high variability among replicates. The financial impact of Common Agricultural Policy payments as well as varying olive oil and irrigation water prices on the irrigation treatments was discussed.

Keywords: hedgerow olive orchard, *Olea europaea*, precision irrigation, water economy, water productivity

1. Introduction

Water is becoming increasingly scarce around the world, being the sustainable use of water resources a major water policy challenge. In water-scarce areas, such as the Mediterranean region where most of the water resources available are allocated to agriculture, the challenge is even greater as limited water resources must be allocated to the various productive uses of water while preserving the environment and ecosystems (Falkenmark, 2000). To accomplish this, policy initiatives oriented towards the sustainable use of water from both the supply and demand perspectives should be promoted (Alcon et al., 2014a). While supply initiatives have been focused on increasing water resources availability (i.e. water regulation, alternative water resources), the demand alternatives aim to fostering better resource management practices through, for instance, the adoption of technologies or techniques to reduce water use.

In agriculture, water saving approaches such as drip irritation, have been widely adopted in arid and drought-prone areas (Alcon et al., 2011), with the resulting water use efficiency enhancement and irrigation input reduction while maintaining production levels (Skaggs, 2001). Drip irrigation systems have been extensively adopted in water-scarce regions because they reduce water losses by deep percolation, soil evaporation and runoff, as compared to other irrigation systems, and because their ease to control irrigation doses and frequencies. In addition to these advantages, research has demonstrated that the combination of drip irrigation systems with appropriate irrigation strategies and efficient irrigation scheduling methods substantially reduce irrigation supply while achieving the production target (Fereres and Soriano, 2007; Ruiz-Sanchez et al., 2010). Common irrigation strategies include full irrigation and a variety of deficit irrigation (DI) strategies, with regulated deficit irrigation, sustained deficit irrigation and supplemental irrigation among the most widely used (English, 1990). All those DI strategies have received much attention by researchers as a measure to reduce agricultural water use in regions with limited water availability (Centritto et al., 2005; Egea et al., 2009; Fernández et al., 2013; Girona et al., 2004; Marra et al., 2016; Marsal et al., 2002). Regulated deficit irrigation (RDI), in fact, has a high potential for woody species. With RDI, irrigation amounts close to the crop water needs are applied on the phenological stages most sensitive to the lack of water, while irrigation is reduced, or even interrupted, for the rest of the growing season (Conejero et al., 2011; Dichio et al., 2007; Fernández et al., 2013; Goldhamer et al., 2002; Marsal et al., 2000). With sustained deficit irrigation (SDI), a fixed fraction of the crop water needs is supplied all throughout the whole irrigation season (Fereres and Soriano, 2007; Laribi et al., 2013; Moriana et al., 2003; Peña et al., 2013). In addition to saving water, there are other advantages that can be attained with DI, such as increased crop quality (Buendía et al., 2008), earlier harvests (Fernández et al., 2010) and the control of excessive vegetative vigour (Fernández et al., 2013).

For hedgerow olive orchards with high plant density, also called super-high-density (SHD) orchards, RDI has been reported to be one of the best irrigation strategies in terms of orchard productivity under semi-arid conditions (Fernández et al., 2013; Gómez del Campo, 2013). However, achieving the expected agronomic targets in SHD olive orchards under RDI is challenging, since the targeted water savings must be achieved at the same time that episodes of excessive water stress are avoided when the crop is most sensitive to drought (Chalmers et al., 1981). Thus, the success of the RDI strategy in SHD olive orchards depends largely on proper monitoring of crop water status throughout the irrigation season. With that purpose, efforts have focused on the use of plant-based sensors for collecting records on physiological variables related to plant water status (Fernández, 2014a). In this sense, measurements related to sap flow (Fernández et al., 2008b; Rousseaux et al., 2009), trunk diameter (Cuevas et al., 2010; Moriana et al., 2010) and leaf turgor (Fernández et al., 2011; Padilla-Díaz et al., 2016) have been successfully used to monitor water stress in a variety of species. Systems have been developed for the continuous and automatic monitoring of those variables, robust enough for working under field conditions for long periods of time, and a number of user-friendly water stress indices have been derived and tested (Fernández, 2014a).

There is little information, however, on to what extent the use of new DI strategies and new irrigation technologies for plant-based regulated deficit irrigation scheduling is profitable in commercial fruit-tree orchards.

When water is the limiting factor for cropping, implementation of DI strategies is usually more profitable than full irrigation (Alcon et al., 2014b; García et al., 2004; Pérez-Pérez et al., 2010; Romero et al., 2006). Moreover, when DI is correctly scheduled, yields and farm incomes are stabilized, which help farmers and orchardists on planning economic decisions (Geerts and Raes, 2009). In addition, the adoption of DI becomes more interesting when other water saving technologies are in place, at conveyance and farm level, and becomes compulsory when water is scarce (Alcon et al., 2014b). Still, and for the case of RDI adoption in SHD orchards, there is no evidence on its financial suitability. The financial feasibility of SHD olive orchards has been previously evaluated (AEMO, 2010; Ait Hmida, 2010; Arbonés Florensa et al., 2014; Freixa et al., 2011; IOC, 2015), but without considering the impact of different irrigation management strategies. Therefore, studies aiming to assess the profitability of implementing RDI together with water stress monitoring tools in SHD orchards are needed to ease the process of adoption by farmers.

In this context, this study aims to evaluate the financial feasibility of a super-high-density (SHD) olive orchard grown for olive oil production in a water-scarcity context that has been managed following the recommended RDI strategy for this production system and supported by emerging water stress monitoring technologies. We considered three different stress monitoring technologies with potential for scheduling irrigation based on measurements related to sap flow (SF), trunk diameter variation (TDV) and leaf turgor pressure (TP), respectively. They were firstly analysed through their equivalent annual cost (EAC) to select the decision support technology for RDI scheduling most likely to be adopted by farmers. The selected technology was then implemented in a commercial SHD olive orchard, to schedule the RDI strategy recommend by Fernández (2014b) for this type of orchards, and compared through Discounted Cash Flow Analysis (DCFA) to conventional RDI (i.e. without plant-based water stress monitoring) and full irrigation strategies. The main contributions of this work are, therefore, to increase existing financial evidences on the adoption of RDI by farmers in the SHD management system for olive, and to evaluate the financial impact of adopting farm-level technology (i.e. plant-based sensors) to support RDI scheduling in this type of orchards.

2. Materials and Methods

2.1. Orchard description and irrigation treatments

The experiment was conducted at a commercial SHD olive orchard near Seville, Spain (37.248979, -5.796538) representative of those in the area. The olive trees (*Olea europaea* L., cv. Arbequina) were planted in 2007 at 4 m x 1.5 m tree spacing (1667 trees ha^{-1}). The trees were drip irrigated with one drip line per tree row and three 2 L h^{-1} pressure compensating drippers per tree. One flow meter was installed in each irrigation treatment to record the irrigation supply. Trees were fertilized to cover the crop needs and no weeds were allowed to grow in the inter-row spacing over the spring-summer season. The climate of the region is Mediterranean, characterized by a mean annual reference evapotranspiration (ET_o) and precipitation of 1528 mm and 540 mm, respectively (period 2002-2014). The soil has a sandy loam layer in the top 0.4 m and a sandy clay layer underneath. The electrical conductivity of the saturated soil-paste, pH and organic matter content determined in the top soil layer (0-0.4 m) were 2.5 dS m^{-1}, 6.34 and 0.28%, respectively.

Three irrigation treatments were established in the orchard during the growing cycles of 2014 and 2015: (i) full irrigation (FI) that supplied the irrigation needs (IN), calculated as ET_c-P_e (ET_c = crop evapotranpiration; P_e = effective precititation), for the whole irrigation season; (ii) regulated deficit irrigation aimed to replace 45% of IN, scheduled on the basis of the crop coefficient approach ($45RDI_{CC}$); (iii) regulated deficit irrigation aimed to replace 45% of IN, scheduled on the basis of leaf turgor related measurements ($45RDI_{TP}$) made with TP probes (Zimmermann et al., 2008). The 45RDI trees were irrigated with enough water to replace IN in three periods of the year when olive is most sensitive to water stress (Fernández, 2014b). For the rest of the year just one or two irrigation events per week were applied. The crop coefficient method was applied for scheduling irrigation in both the FI and $45RDI_{CC}$ treatments, with crop coefficients adjusted for the orchard conditions by Fernández et al. (Fernández et al., 2013). For the $45RDI_{TP}$ treatment, irrigation scheduling for the three periods mentioned above was adjusted using the shape of the daily curves provided by the TP probes and 3-day weather forecast, as it has been described by Padilla-Díaz et al. (2016). The irrigation amounts applied during these three periods were close or equal to IN, whereas the crop coefficient approach was used to schedule irrigation during the rest of the season and according to the 45RDI strategy described by Fernández (2014b). The fundamentals of the adopted 45RDI strategy are given in Fernández et al. (2013) and Fernández (2014b). The TP probes used in $45RDI_{TP}$ were selected among three irrigation scheduling technologies that were previously assessed from a technical and financial perspective (Sections 2.3 and 2.4.1). More details on the irrigation management can be found in Padilla-Díaz et al. (2016). Four 16 m x 12 m plots per treatment were used in a randomized block design. The plots had 32 trees, of which only the central 8 trees were sampled, to avoid border effects.

2.2. Crop measurements

Yield was determined annually in four trees per plot and four plots (replicates) per treatment (n=16). The trees were manually harvested and total fruits per plot were weighed separately. Samples of olives of each harvested tree were used to extract virgin olive oil (VOO) with an Abencor analyzer (Commercial Abengoa S.A., Seville, Spain). Irrigation water productivity (WP), defined as the number of VOO kilograms per cubic meter of water supplied and per hectare, was calculated for each treatment (Table 1). Further details on the agronomic and physiological variables controlled throughout the experiment can be found in Padilla-Díaz et al. (2016).

‘Table 1 about here’

2.3. Irrigation scheduling technologies

Three technologies with potential to be used for decision support of 45RDI scheduling and available in the market for farmers, were evaluated before establishing the irrigation treatments in 2014 (Fernández, 2014a). These were based on Sap Flow (SF), trunk diameter variation (TDV), and leaf turgor pressure (TP) related measurements. Table 2 shows the estimated average investment and operational costs for the three irrigation technologies assessed. The costs were standardized for a commercial SHD olive orchard of 10 ha requiring six sampling locations, i.e. six instrumented trees, to assess the orchard irrigation needs. For TDV measurements we used Verdtech stations with Plantsens radial dendrometers (Verdtech Nuevo Campo S.A., Spain). Each Verdtech station had remote telemetry unit (Adcon Telemetry, Austria) for data storage and transmission and solar panels to power all the electronic devices. Equipment rental is the option offered by Verdtech to customers, who have to pay a regular fee for data management and processing service (Cuevas et al., 2013, 2010).

For the SF measurements we used heat-pulse velocity (HPV) probes (Tranzflo NZ Ltd., Palmerston North, New Zealand), validated for olive by Fernández et al. (2006). Two sets of probes were installed in the trunk of each instrumented tree (Cuevas et al., 2013). In addition to the HPV probes, the system requires dataloggers and multiplexers, heat-pulse controllers, batteries, solar panels and data transmission modules (Fernández et al., 2008a). For the TP measurements we used ZIM probes (YARA ZIM Plant Technology, Hennigsdorf, Germany) and the related system. The probes are clamped in leaves and the outputs sent via radio to a datalogger with a GPRS modem for data transfer to a server owned by the manufacturer, who provides access to the customer via Internet. The customer must acquire all the required equipment (probes, dataloggers, transmission module, batteries, solar panels, masts, etc.) and pay the costs derived from the phone card for data transmission and renewal of the silicon of the TP probes. More details on the use of this technology in the experimental orchard can be found elsewhere (Fernández et al., 2011; Padilla-Díaz et al., 2016).

‘Table 2 about here’

2.4. Financial analysis

2.4.1. Equivalent annual cost

The Equivalent Annual Cost (EAC) was used to determine the financial cost and motivate the selection of one of the three technologies analysed in Section 2.3 to support 45RDI scheduling (i.e. 45RDI$_{TP}$ treatment). The EAC is used to quantify the annual cost of owning and operating an asset over its entire lifespan. The information provided in Table 2, which corresponds to a commercial 10 ha orchard that hypothetically requires six sampling locations, has been used for EAC calculation.

The EAC was estimated as follows, for each irrigation support technology:

$$\mathrm{EAC} = \mathrm{NPC}\frac{(1+i)^n \cdot i}{(1+i)^n - 1}$$

being *i* the discount rate, *n* the period analysis (years) and NPC the net present cost that discounts all costs to a single base year. NPC was defined as:

$$\mathrm{NPC} = k + \sum_{n=1}^{n} \frac{C_{\mathrm{n}}}{(1+i)^n}$$

where C_{n} denotes the operational expected costs in the time period assessed and *k* is the investment costs in the year zero.

2.4.2. Discounted Cash Flow Analysis

The financial performance of the three irrigation treatments assessed in this study (FI, $45\mathrm{RDI}_{\mathrm{CC}}$ and $45\mathrm{RDI}_{\mathrm{TP}}$) was performed through Discounted Cash Flow Analysis (DCFA). DCFA is a decision-making method that compares the expected benefits and costs of a given initiative or investment considering the lifespan of the investment and the opportunity cost of investing in an alternative of similar risk profile (IFAC, 2008). DCFA considers cash paid and received along the life of the initiative and may therefore be a suitable tool to evaluate the long-term financial feasibility of SHD olive orchards under various irrigation strategies.

For the financial comparison of the three irrigation treatments we identified the investment costs and all the cash flows along the life of the investment, established the time horizon of the evaluation and fixed the discount rate that reflects the time value of money. This information was then used to determine the Net Present Value (NPV), the Internal Rate of Return (IRR) and the Payback Period (PB). NPV was calculated as follows: aggregates all Cash Flows (CF_{n}) given in a certain period of time (*n*), applied to a discount rate (*i*), minus the investment costs (*k*).

$$\mathrm{NPV} = -k + \sum_{n=1}^{n} \frac{CF_{\mathrm{n}}}{(1+i)^{n}}$$

where CF_{n} are the expected Cash Flows in the time period assessed (n), i.e. the inflow minus the outflow (I_{n} - O_{n}), and (i) is the discount rate, which denotes the return an investor would expect from an alternative investment with similar risk or the interest rate on debt. The IRR, which is commonly used to evaluate the desirability of investments, is the interest rate at which discounted cash outflows equals discounted cash inflows of the investment. The PB period in DCFA refers to the period of time required for the return on an investment to 'repay' the amount corresponding to the original investment. Finally, a sensitivity analysis of the financial indicators to the variables of the most uncertain value was performed in order to conduct a reasoned judgement.

2.4.2.1 Outflow analysis

Outflow analysis comprises investment and operational costs. Investment costs refer to the capital required to establish a SHD olive orchard, including, in our case, the irrigation technology adopted. The operational costs correspond to the cash flow needed to properly run and develop the activity, including management and maintenance of the system. In this case study, an initial investment of €107,694 (2010 prices) was estimated for an average farm area of 10 ha. Investment costs comprise land preparation, trellis system, trees and tree wraps, planting, complete equipment for drip irrigation technology and a groundwater pumping system.

The operational costs include all the expenses associated with the annual productive process. They have been estimated in the experimental orchard for the 2014 and 2015 growing seasons. Thus, this category comprises aspects associated with the use of raw materials (i.e. energy, fertilizers and pesticides), farmer labour, external labour for operations such as pruning and harvest, machinery, insurance, maintenance and olive milling costs.

Among the operational costs, some remain constant among the irrigation strategies whereas others depend on the selected irrigation strategy and technology to schedule irrigation. The latter can be grouped into two categories: (i) those directly related to the irrigation strategy and technology (i.e. time for data processing, interpretation and irrigation scheduling; technology maintenance; energy consumption), and (ii) those indirectly related to irrigation management through its impact on the agronomic tree performance (i.e. manpower related to harvesting and pruning activities; olive milling cost). Measured differences in pruning time (pruner's wage considered = 60 € day^{-1}) and in olive milling, directly related with production, were considered in the analysis. Pruning costs were determined annually for each irrigation treatment, from the time invested by pruners in each irrigation plot. The cost of mechanical harvesting, shredding of pruning, phytosanitary treatments and ploughing was considered to be constant among irrigation strategies as no differences in the operation time were observed between treatments. The cost of irrigation water was not included into the analysis since the experimental orchard uses groundwater pumped from its wells. Therefore, the cost of water has been assumed to be that of the energy required for water pumping, estimated as 0.08 € m^{-3} for the experimental orchard. Estimated costs come from the 10 ha commercial farm where the experimental orchard is located.

2.4.2.2 Inflow analysis

Total incomes were determined from Virgin Olive Oil (VOO) production and sale prices, the VOO production being modulated by the irrigation strategy. The sale prices used in the analysis are those officially published by the Andalusian Government (OPM, 2016). Average prices of the period 2007-2015 years where deflated with the Oil Implicit Price Deflator, to avoid the effect of price volatility and inflation. The VOO average price in the year of plantation (2007) was 2.39 € kg^{-1}. Differences in VOO quality between treatments were also analysed but these were not different enough to guarantee a higher market price. For the DCFA, no yield was considered during the first two years after planting and this increased progressively up to the year 2012, from which maximum productions were considered until an orchard age of 17 years. From this time onwards, yield was considered to decline progressively down to 30% of the full production (orchard age of 20 years). Additionally, a residual income was accounted for the end-year to reflect the remaining service potential of orchard and irrigation scheduling technology assets.

Most of the olive growers in the European countries are entitled with the Common Agricultural Policy (CAP) payments. More specifically, in the study area the average CAP single payment for irrigated olive groves was 766 € ha^{-1} year^{-1} (Villanueva et al., 2015). Due to the fact that not all farmers are entitled to receive CAP payments, the results are shown both considering and excluding this additional income from the analysis.

2.3. Statistical analysis

The data derived during the trials were analysed for each irrigation strategy and irrigation scheduling method. Analysis of variance (ANOVA) was used to test the hypothesis of equal means of the costs, incomes and financial indicators for the different irrigation treatments. Four replicates per treatment were used in the ANOVA. In those cases with several measurements per replicate (e.g. yield), an average value per replicate (plot) was derived.

3. Results

3.1. Selection of decision support technology for RDI scheduling

The three technologies considered (TDV, SF and TP) were evaluated through the EAC value (Table 3), whose estimations were performed as described in Section 2.4.1, considering a 3% discount rate and a time period of 10 years. The results indicate that TDV and SF technologies have the highest EAC (531 and 440 € ha^{-1} year^{-1}, respectively), whereas TP presented a substantially lower EAC value (204 € ha^{-1} year^{-1}). The considerably lower EAC value derived for TP technology motivated the selection of this technology for the field experiments conducted over the two seasons of 2014 and 2015.

‘Table 3 about here’

3.2. Financial assessment of the irrigation strategy

The cash flow estimations for the three considered treatments are shown in Table 4 by using data from 2014 and 2015 experimental years (€$_{2015}$). Both 45RDI$_{CC}$ and 45RDI$_{TP}$ showed less ($p < 0.05$) annual total operational costs (TOC) than FI (Table 4). The highest TOC found in FI is due to the higher cost of energy, pruning and olive milling. In terms of the cost associated to irrigation scheduling (i.e. labour requirements), 45RDI$_{TP}$ showed higher cost ($p<0.05$) than FI and 45RDI$_{CC}$, mainly due to the longer time required to process and interpret the information derived from the ZIM (TP) records.

Nevertheless, when inflow and outflow were jointly compared, no significant differences were found between both 45RDI treatments in terms of cash flow, which indicates that the adoption of the TP technology would imply additional costs with no impact on the final cash flows perceived by the farmers. Significant differences in cash flow were found between FI and $45RDI_{CC}$, indicating that less financial margin was achieved with $45RDI_{CC}$. Between FI and $45RDI_{TP}$, however, no differences were found, suggesting that the reduction of costs when a $45RDI_{TP}$ strategy is adopted is offset by the loss of yield.

‘Table 4 about here’

Neither the Economic Productivity (EP) nor the Economic Water Productivity (EWP) showed any significant difference between treatments, although EWP tended to be higher in the 45RDI treatments than in FI (Table 4). The Unitary Production Cost (UPC) was also similar ($p > 0.05$) between the three irrigation strategies, indicating that no differences were found in terms of cost per kilogram of VOO produced.

Nevertheless, evaluating the financial feasibility of the irrigation treatments with short-term cost analysis can produce biased results, being the long-term cost analysis more suitable to this end. In this regards, a DCFA was carried out to analyse the profitability of the three irrigation treatments over the estimated productive life of the SHD olive orchard, i.e. 20 years, and a 3% discount rate. Yearly Cash Flows estimated during the study period were normalized to a reference year (2007) by using the average values derived over the experimental period and a discount rate of 3%. The profitability indicators (NPV, IRR and PB period) derived from the DCFA are shown in Table 5. Our results show that, under the experimental conditions of this case study, FI provided the highest returns in the long-term as denoted by a NPV of 16,328 €, an IRR of 13.29 % and a PB period of 9 years.

‘Table 5 about here’

When the CAP payment was excluded, the profitability of $45RDI_{CC}$ was significantly lower ($p < 0.05$) than that of FI, whereas no significant differences were observed between FI and 45RDI$_{TP}$. Although the differences observed in the profitability indicators between both 45RDI treatments were not significant, the adoption of TP technology to support RDI scheduling seems to enhance orchard profitability, as no significant differences were found between 45RDI$_{TP}$ and FI and 45RDI$_{TP}$ yielded a NPV increase of 3,109 € ha^{-1}, an IRR increment of 1.69% and a PB reduction of nearly 4.5 years, as compared to 45RDI$_{CC}$. When CAP payments are taken into account the profitability indicators improve considerably, rising the NPV and the IRR indicators by 9,282 € ha^{-1} and ca. 5%, respectively.

Figure 1 depicts a sensitivity analysis of NPV to water price, both considering and excluding the CAP payment. When CAP payment was excluded from the analysis, the results show that the adoption of 45RDI$_{TP}$ throughout the orchard lifecycle is still more profitable than 45RDI$_{CC}$ irrespective of water price. As compared to FI, the results show that FI is more profitable than 45RDI$_{TP}$ up to a water price of 0.30 € m^{-3}, above which 45RDI$_{TP}$ shows higher NPV. Regarding the water price above which NPV is negative and therefore the investment is not feasible, both 45RDI$_{TP}$ and FI presents the highest value (0.35 € m^{-3}), whereas 45RDIcc reaches the null NPV at a water price of 0.23 € m^{-3}. These findings indicate that, at water prices lower than 0.30 € m^{-3} and under non-limited water resources, the adoption of FI would be the preferred option from an financial perspective.

When the CAP payment is considered (Figure 1, right panel) the profitability of FI is higher than that of 45RDI$_{TP}$ at water prices lower than 0.30 € m^{-3}, whereas 45RDI$_{TP}$ becomes more profitable than FI at higher water prices. Regarding the water price above which NPV is null and the investment becomes unfeasible, 45RDI$_{TP}$ shows the highest value (0.71 € m^{-3}), followed by 45RDIcc (0.59 € m^{-3}) and FI (0.51 € m^{-3}), i.e. FI shows the lowest NPV water price. These results indicate that the use of FI would compromise the feasibility of the investment at water prices higher than 0.51 € m^{-3}. The results also show that, at water prices higher than 0.42 € m^{-3}, 45RDI$_{CC}$ would be more profitable than FI.

'Figure 1 about here'

Similarly to water price, a sensitivity analysis of NPV to VOO market prices was also made (Figure 2). The results indicate that FI has a break-even point at 1.68 €$_{2007}$ kg^{-1} (2.23 €$_{2015}$ kg^{-1}). From this price downward, therefore, no financial profitability is expected for this irrigation strategy. Similarly, the break-even points for 45RDI$_{TP}$ and 45RDI$_{CC}$ were found to be higher than the value obtained for FI, and somewhat higher in 45RDI$_{CC}$ (2.05 €$_{2007}$ kg^{-1}) as compared to 45RDI$_{TP}$ (1.93 €$_{2007}$ kg^{-1}). When the CAP payment was considered (Figure 2b), the minimum VOO price that should be perceived by farmers to obtain profitability is 1.28 €$_{2015}$ kg^{-1} for FI, 1.45 €$_{2015}$ kg^{-1} for 45RDI$_{TP}$ and 1.51 €$_{2015}$ kg^{-1} for 45RDC$_{CC}$.

'Figure 2 about here'

4. Discussion

As mentioned in the Introduction, the adoption of RDI strategies for olive production (Moriana et al., 2007; Ramos and Santos, 2010), including SHD olive orchards (Fernández et al., 2013; Gómez Del Campo and García, 2013), has been widely recommended in drought-prone areas based on their excellent agronomic performance. However, financial assessments required to support farmers in the adoption process of this irrigation strategy are scarce and mainly focused on other fruit tree species such as almond (Alcon et al., 2013; García et al., 2004; Romero et al., 2006), citrus (Pérez-Pérez et al., 2010) or grapevine (García García et al., 2012).

Several reports on the financial feasibility of SHD olive orchards have already been published (AEMO, 2010; Ait Hmida, 2010; Arbonés Florensa et al., 2014; Freixa et al., 2011; IOC, 2015). None of them, however, includes the long-term financial suitability of implementing deficit irrigation strategies in SHD olive orchards. The operational costs reported in those publications are in agreement with our estimations for the experimental conditions of this study (Table 4). However, considering only the TOC as a tool for decision on the most suitable production system or management strategy is not appropriate. Our results show, in fact, that an irrigation strategy selection based solely on TOC would have suggested $45RDI_{CC}$ as the most suitable strategy (Table 4), while the long term financial indicators, such that NPV or IRR, demonstrate that both FI and $45RDI_{TP}$ are the most profitable strategies for SHD olive orchards, at least for those of similar characteristics that our experimental orchard. Whether the best option is FI or $45RDI_{TP}$ would depend on water availability.

Despite the financial superiority of FI against $45RDI_{CC}$, FI will hardly be adopted by olive growers of drought-prone areas, where water allocations are often below the crop water requirements. In these cases farmers are forced to adopt deficit irrigation strategies (Expósito and Berbel, 2016). In the study area (Guadalquivir River Basin), for instance, the average water allocation for olive is 2,780 m^3 ha^{-1} (Borrego-Marín et al., 2016), far below the estimated irrigation requirements, which for SHD olive orchards amount to ca. 5,000 m^3 ha^{-1} $year^{-1}$ (Fernández et al., 2013; Padilla-Díaz et al., 2016). Consequently, the way olive growers use irrigation water throughout the whole irrigation season will certainly determine their orchard profitability. Our results demonstrate that the deficit irrigation strategy envisaged by Fernández et al. (Fernández et al., 2013) and optimized later (Fernández, 2014a), i.e. the 45RDI strategy, guarantees the profitability of SHD olive orchards in the long-term. Thus, both $45RDI_{CC}$ and

45RDI$_{TP}$ showed positive NPV and IRR values above the interest on capital (Table 5). Although all the financial indicators suggested higher financial performance of 45RDI$_{TP}$, i.e. when scheduled from TP probe outputs, as compared to 45RDI$_{CC}$, i.e. when the crop coefficient approach was used to schedule irrigation, differences were not significant (Table 5). Likely the high variability among replicates within the same treatment curtailed our financial assessment. On the other hand, differences between FI and 45RDI$_{TP}$ were also not significant, suggesting that similar profitability can be obtained with both irrigation approaches. Consequently, our findings suggest that the use of technology to assist RDI scheduling tends to increase the orchard profitability, although further research is needed to validate if this trend stands under different locations and experimental conditions.

Water prices are highly variable depending on the irrigation water source (Maestre-Valero et al., 2016) and so among irrigation areas. Whatever the conditions, the price of water for irrigation has generally increased in the last decade due to the energy cost increment and, also, the EU Water Framework Directive that establish, among other aspects, the cost recovery principle and that all water costs should be paid by the users. Both the rising of water prices and the decreasing water availability are main concerns for farmers, and justify sensitivity analysis of the orchard profitability to water prices, as those shown in Fig. 1.

It is important to stress that, although in our case study water cost is based on energy requirements to pump groundwater, about 80% of the Andalusian irrigated land uses surface water resources. In these cases, water withdrawal is usually collective and users have to pay a water price that covers all the irrigation district expenses (e.g. water conveyance, energy cost, personnel, maintenance, etc.). The energy requirements needed for operating these irrigation schemes are frequently high (Rodríguez Díaz et al., 2011), such that the irrigation cost is strongly linked to the energy cost. Consequently, profitability analyses should be made for scenarios of rising energy prices. In this regard, our sensitivity analysis in Fig. 1 shows that the maximum water price that break-even the irrigation treatments, i.e. total inflow equals total outflow in the long term, is 0.32 $€_{2007}$ m^{-3} (0.43 $€_{2015}$ m^{-3}) for FI and 0.46 $€_{2015}$ m^{-3} for $45RDI_{TP}$. These values are over the marginal value of irrigation water estimated in the study area by Mesa-Jurado et al. (2012) for traditional olive groves with enhanced guarantee of water supply. These findings also indicate the higher profitability of SHD olive orchards as compared to traditional, low density, olive production systems. Therefore, if water supply above 5,000 m^3 is guaranteed and water price is below 0.30 $€_{2007}$ m^{-3}, the adoption of RDI in SHD olive orchards would be unlikely.

Fluctuation of VOO prices from year to year is another factor that may compromise orchard profitability. The VOO price in the last nine years, using 2015 as reference year, ranged from 2.22 € kg^{-1} to 3.57 € kg^{-1}, with an average value of 2.72 € kg^{-1}. This yearly fluctuation in VOO price represents an additional risk for the financial sustainability of SHD olive orchards, which justifies the sensitivity analysis of treatment profitability to VOO prices shown in Fig. 2. The production cost analysis depicted in Table 4 provided the minimum VOO market price needed to cover all operational costs, i.e. the UPC values. These values, however, do not take into account the investment costs associated with the agricultural production, whereas the break-even VOO prices derived in the sensitivity analysis of Fig. 2 represent the real VOO market prices required to cover all the expenses, i.e. investment plus operational costs. Unlike what was observed in the sensitivity analysis to water price (Fig. 1), where FI and $45RDI_{TP}$ showed similar break-even points, the sensitivity analysis to VOO price ranked FI as the irrigation strategy that can withstand lower market VOO prices. It also showed that

$45RDI_{TP}$ and $45RDI_{CC}$ require around 0.25 and 0.37 € kg^{-1} higher VOO market prices, respectively, to reach the break-even point. However, when CAP payment was considered, these differences decreased to 0.16 and 0.22 € kg^{-1} for $45RDI_{TP}$ and $45RDI_{CC}$, respectively. As shown in Fig. 2, the financial feasibility of all three irrigation treatments is largely influenced by the market VOO prices. However, to assess which of the three irrigation strategies is most sensitive to the fluctuations of VOO prices, a second sensitivity analysis was conducted to show the marginal variation of NPV to the percent variation of VOO (Fig. 3). Results indicate that FI (slope of 3.4) is the less sensitive irrigation strategy to prices variation, being $45RDI_{CC}$ (slope of 7.1) the most. The high sensitivity of $45RDI_{CC}$ to VOO price (3.7-fold and 1.9-fold higher than those of FI and $45RDI_{TP}$, respectively) is also a risk factor that may affect the investment profitability, as it has been previously suggested (Arbonés Florensa et al., 2014; Santos et al., 2009). When CAP payment was taken into account the sensitivity to price variation decreased in absolute terms and between irrigation strategies (Fig. 3b).

‘Figure 3 about here’

Another important factor that can determine long-term SHD olive orchard profitability is lifespan. Previous studies have highlighted that the sustainability of SHD productive systems may be questioned due to the usually observed decline in production from seven or eight years after planting. This applies mainly to orchards where excessive vegetative vigour has not been properly controlled and problems derived from competency among trees appear (Pastor et al., 2007). In fact, until recently it was assumed that the lifespan of SHD olive orchards was around 12-14 years. However, a recent study carried out in the study area over a 14 year period (all previously published studies were conducted during 4-7 years after planting), has proven that SHD olive orchards may still be fully productive 14 years after planting (Diez et al., 2016), hence contradicting previous assessments. Diez et al. (2016) argued that the early decline in production observed by Pastor et al. (2007), as a consequence of an uncontrolled tree vigour, was probably due to excessive irrigation dosage, which tripled the amount of water applied by Diez et al. (2016) (600 vs. 200 mm year^{-1}). Although in the DCFA performed in this study the same orchard lifespan of 20 years was considered irrespective of the irrigation strategy, our findings suggest that FI could have a negative impact on the orchard lifespan. That could revert the conclusions drawn earlier (Table 5). In this regard, if an orchard lifespan of 14 years after planting is assumed for FI and the same estimated cash flows are used (Table 4), the $45RDI_{TP}$ strategy would need an orchard lifespan of 20 years to equal the NPV of the FI strategy. Therefore, these results suggest that $45RDI_{TP}$ may become more profitable than FI if the orchard lifespan under 45RDI exceeds 20 years without losing yield potential. Long-term agronomic assessments are needed, however, to confirm those suggestions.

5. Conclusions

Among the three studied treatments, our financial analysis suggests that both full irrigation (FI) and the regulated deficit irrigation strategy suggested for the orchard conditions and scheduled from leaf turgor related measurements ($45RDI_{TP}$) are the most profitable. If enough water is available at prices of up to 0.30 € m^{-3}, FI could be the best option, although it will likely cause competency problems among trees due to excess of vigour, which could shorten the productive life of the orchard. Our results suggest that $45RDI_{TP}$ would need an orchard lifespan of 20 years to equal the Net Present value of FI. The high variability found in the orchard did not allow us to establish whether $45RDI_{TP}$ or $45RDI_{CC}$ is the best option, although it is clear that $45RDI_{CC}$ can be applied in those orchards for which the values of the crop coefficient are known. Our results also show that 45RDI$_{CC}$ is the approach most sensitive to year-to-year variations in the price of virgin olive oil. It seems, therefore, that for the studied conditions the best approach to manage irrigation in SHD olive orchards will be 45RDI$_{TP}$.

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Tables:

Table 1. Mean virgin olive oil yield (VOO), irrigation supply (IW) and irrigation water productivity (WP) for the three water strategies (i.e. FI, $45RDI_{CC}$, $45RDI_{TP}$) in the 2014-2015 period.

Variable	**FI**		**$45RDI_{CC}$**		**$45RDI_{TP}$**	
VOO (kg ha^{-1})	1,916.62	a	1,402.17	b	1,588.00	ab
IW (m^3)	5,242.00		2,626.00		2,631.00	
WP (kg m^{-3})	0.37	a	0.57	b	0.61	b

FI: fully irrigated treatment scheduled from the crop coefficient approach, in which the trees received 100% of the crop water needs; $45RDI_{CC}$ and $45RDI_{TP}$ were regulated deficit irrigation (RDI) treatments in which the trees received 45% of the crop water needs, but the first was scheduled with the crop coefficient approach and the second from leaf turgor pressure related measurements. Irrigation water productivity (WP) was determined as the ratio VOO/IW. In each row, mean values followed by different letters indicate significant differences following Duncan's Multiple Range test ($p < 0.05$).

Table 2. Investment and operational costs* of the three technologies analysed for RDI decision support**.

	Investment concept	**Cost (€)**	**Lifespan (year)*****	**Operational concept**	**Cost (€ yr^{-1})**
Trunk Diameter Variation (TDV)				Equipment rent, data management & processing, annual installation & uninstallation, equipment maintenance.	5,314
Sap Flow (SF)	Probes, heat-pulse units, batteries, waterproof outdoor boxes, solar panels, DC regulators, battery chargers, data loggers, multiplexers, cable, and transmission modules.	18,174	3-10*	Annual installation & uninstallation, maintenance, data processing.	1,868
Leaf Turgor Pressure (TP)	Probes, data loggers, transmission modules, batteries, solar panels, waterproof outdoor boxes.	5,465	5-10*	Data management & processing, maintenance, annual installation & uninstallation.	1,437

*Average values for a standard 10 ha farm.

**Some costs, practices or materials may not be applicable to other locations. Additional practices not indicated in this table may be needed since some establishment and cultural practices may vary among growers and regions.

*** Lifespan range of the required equipment.

Table 3. Total annual costs for each decision support technology.

	Irrigation Technology		
	TDV	SF	TP
EAC (€ year^{-1} ha^{-1})	531	440	204

TDV: Trunk Diameter Variation; SF: Sap Flow; TP: Leaf Turgor Pressure.

Table 4. Mean operational costs, revenues, and cash flows for the SHD olive orchard under the three applied treatments, from orchard plantation (€$_{2015}$).

Variable	**FI**	**45RDI$_{CC}$**	**45RDI$_{TP}$**
***Raw material costs* (€ ha^{-1})**			
Fertilizers	116.98	116.98	116.98
Phytosanitary products	319.02	319.02	319.02
Electric energy	431.82	216.21	216.67
O&M TP costs			63.72
Total raw materials	867.85 a	652.24 b	716.42 c
***Labour costs* (€ ha^{-1})**			
Irrigation programming	157.13	157.13	211.42
Pruning	460.58 a	391.61 b	391.61 b
Phytosanitary treatments	70.83	70.83	70.83
Harvesting	73.59	73.59	73.59
Wood disposal	12.88	12.88	12.88
Ploughing	12.88	12.88	12.88
Total labour	787.88 a	718.91 b	773.19 c
***Machinery costs* (€ ha^{-1})**			
Phytosanitary treatments	305.92	305.92	305.92
Harvesting	76.13	76.13	76.13
Shredding of pruning	326.25	326.25	326.25
Ploughing	59.48	59.48	59.48
Total Machinery	767.78	767.78	767.78
***Other costs* (€ ha^{-1})**			
Insurance and tax	100.00	100.00	100.00
Investment maintenance	10.77	10.7	10.77
Olive milling	585.12 a	427.75 b	463.37 ab
Total other costs	695.89 a	538.52 b	574.14 ab
***TOTAL OPERATIONAL COSTS* (€ ha^{-1})**	3,119.35 a	2,677.42 b	2,831.50 b
TOTAL REVENUES (€ ha^{-1})	5,242.34 a	4,076.65 b	4,616.92 ab
***CASH FLOW* (€ ha^{-1})**	2,452.99 a	1,399.24 b	1,785.43 ab
EP (€ kg^{-1}) $^{+}$	1.21	0.96	1.09
EWP (€ m^{-3})$^{++}$	0.47	0.54	0.69
UPC (€ kg^{-1})$^{+++}$	1.70	1.94	1.82
***Subsidise CASH FLOW* (€ ha^{-1})**	3,219	2,165	2,551
Subsidise EP (€ kg^{-1})	1.63	1.52	1.58
Subsidise EWP (€ m^{-3})$^{+}$	0.62	0.84	0.99

FI: fully irrigated treatment scheduled from the crop coefficient approach, in which the trees received 100% of the crop water needs; 45RDI$_{CC}$ and 45RDI$_{TP}$ were regulated deficit irrigation (RDI) treatments in which the trees received 45% of the crop water needs, but the first was scheduled with the crop coefficient approach and the second from leaf turgor pressure related measurements. $^{+}$Economic Productivity (EP) = Gross margin / Total yield, where Gross Margin is the difference between total revenues and total operational costs; $^{++}$Economic Water Productivity (EWP) = Gross margin / Irrigation water used, $^{+++}$Unitary Production Cost (UPC) = Total operational costs/Total yield; Mean values followed by different letters within the same row indicate significant differences at 95% confidence level following Tukey test.

Table 5. Net present value (NPV), internal rate of return (IRR) and Pay Back period (PB) derived for each irrigation strategy over a simulated period of 20 years excluding and including Common Agricultural Policy (CAP) payment.

	Excluding CAP payment			Including CAP payment		
Indicator	**FI**	**45RDI$_{CC}$**	**45RDI$_{TP}$**	**FI**	**45RDI$_{CC}$**	**45RDI$_{TP}$**
NPV (€ ha^{-1})	16,328 a	5,698 b	8,807 ab	25,610 a	14,980 b	18,089 ab
IRR (%)	13.29 a	7.48 b	9.17 ab	17,20 a	12,72 b	13,78 ab
PB (years)	9.00 a	14.50 b	10.00 ab	7.00 a	9.00 b	8.00 ab

FI: fully irrigated treatment; 45RDI$_{CC}$; RDI treatment scheduled with the crop coefficient approach; 45RDI$_{TP}$: RDI treatment scheduled with leaf turgor pressure (TP).

Mean values followed by different letters within the same row and CAP payment option indicate significant differences at 95% confidence level following Tukey test.

Figures:

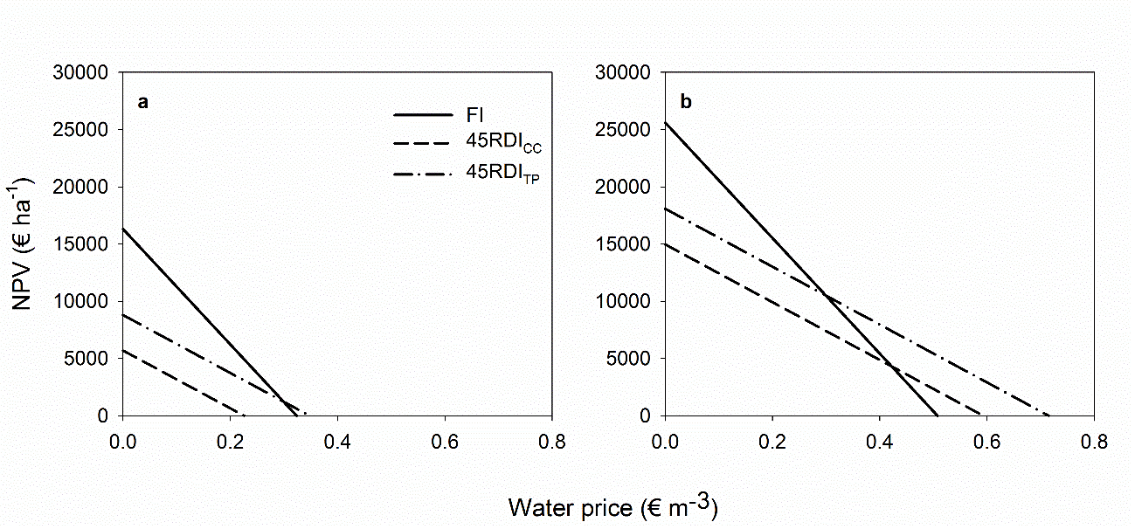

Figure 1. Sensitivity analysis, for the considered irrigation strategies, of Net Present Value (NPV) to irrigation water price, excluding (a) and including (b) Common Agricultural Policy payment (€$_{2007}$). FI: fully irrigated treatment scheduled from the crop coefficient approach, in which the trees received 100% of the crop water needs; 45RDI$_{CC}$ and 45RDI$_{TP}$ were regulated deficit irrigation (RDI) treatments in which the trees received 45% of the crop water needs, but the first was scheduled with the crop coefficient approach and the second from leaf turgor pressure related measurements.

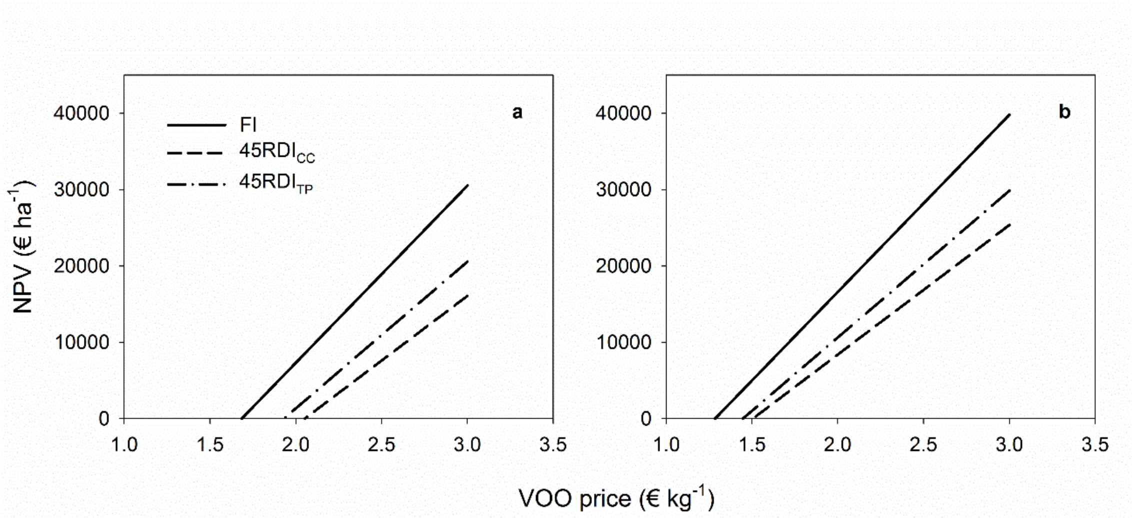

Figure 2. Sensitivity analysis of Net Present Value (NPV) of irrigation strategies to Virgin Olive Oil price excluding (a) and including (b) Common Agricultural Policy payment (€$_{2007}$). See Fig. 1 for details on the irrigation treatments.

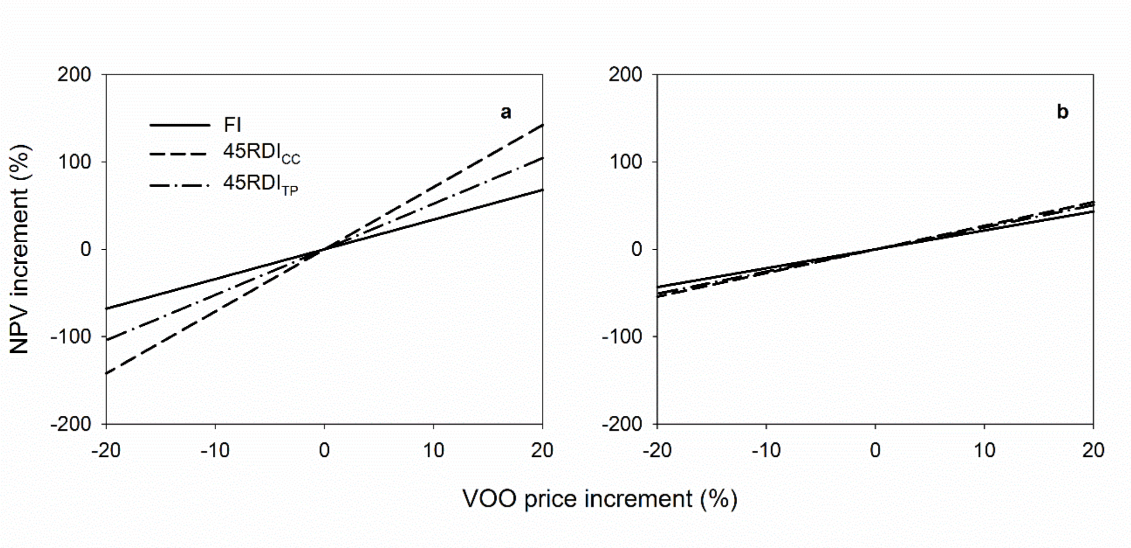

Figure 3. Net Present Value *(*NPV*)* percent variation as a consequence of the Virgin Olive Oil price percent variation in the three irrigation strategies assessed including (b) and excluding (a) Common Agricultural Policy payment. See Fig. 1 for details on the irrigation treatments.

Tables:

Table 1. Mean virgin olive oil yield (VOO), irrigation supply (IW) and irrigation water productivity (WP) for the three water strategies (i.e. FI, 45RDI$_{CC}$, 45RDI$_{TP}$) in the 2014-2015 period.

Variable	**FI**		**45RDI$_{CC}$**		**45RDI$_{TP}$**	
VOO (kg ha^{-1})	1,916.62	a	1,402.17	b	1,588.00	ab
IW (m^{3})	5,242.00		2,626.00		2,631.00	
WP (kg m^{-3})	0.37	a	0.57	b	0.61	b

FI: fully irrigated treatment scheduled from the crop coefficient approach, in which the trees received 100% of the crop water needs; 45RDI$_{CC}$ and 45RDI$_{TP}$ were regulated deficit irrigation (RDI) treatments in which the trees received 45% of the crop water needs, but the first was scheduled with the crop coefficient approach and the second from leaf turgor pressure related measurements. Irrigation water productivity (WP) was determined as the ratio VOO/IW. In each row, mean values followed by different letters indicate significant differences following Duncan's Multiple Range test ($p < 0.05$).

Table 2. Investment and operational costs* of the three technologies analysed for RDI decision support**.

	Investment concept	**Cost (€)**	**Lifespan (year)*****	**Operational concept**	**Cost (€ yr^{-1})**
Trunk Diameter Variation (TDV)				Equipment rent, data management & processing, annual installation & uninstallation, equipment maintenance.	5,314
Sap Flow (SF)	Probes, heat-pulse units, batteries, waterproof outdoor boxes, solar panels, DC regulators, battery chargers, data loggers, multiplexers, cable, and transmission modules.	18,174	3-10*	Annual installation & uninstallation, maintenance, data processing.	1,868
Leaf Turgor Pressure (TP)	Probes, data loggers, transmission modules, batteries, solar panels, waterproof outdoor boxes.	5,465	5-10*	Data management & processing, maintenance, annual installation & uninstallation.	1,437

*Average values for a standard 10 ha farm.

**Some costs, practices or materials may not be applicable to other locations. Additional practices not indicated in this table may be needed since some establishment and cultural practices may vary among growers and regions.

*** Lifespan range of the required equipment.

Table 3. Total annual costs for each decision support technology.

	Irrigation Technology		
	TDV	SF	TP
EAC (€ $year^{-1}$ ha^{-1})	531	440	204

TDV: Trunk Diameter Variation; SF: Sap Flow; TP: Leaf Turgor Pressure.

Table 4. Mean operational costs, revenues, and cash flows for the SHD olive orchard under the three applied treatments, from orchard plantation (€$_{2015}$).

Variable	**FI**	**45RDI$_{CC}$**	**45RDI$_{TP}$**
***Raw material costs* (€ ha^{-1})**			
Fertilizers	116.98	116.98	116.98
Phytosanitary products	319.02	319.02	319.02
Electric energy	431.82	216.21	216.67
O&M TP costs			63.72
Total raw materials	867.85 a	652.24 b	716.42 c
***Labour costs* (€ ha^{-1})**			
Irrigation programming	157.13	157.13	211.42
Pruning	460.58 a	391.61 b	391.61 b
Phytosanitary treatments	70.83	70.83	70.83
Harvesting	73.59	73.59	73.59
Wood disposal	12.88	12.88	12.88
Ploughing	12.88	12.88	12.88
Total labour	787.88 a	718.91 b	773.19 c
***Machinery costs* (€ ha^{-1})**			
Phytosanitary treatments	305.92	305.92	305.92
Harvesting	76.13	76.13	76.13
Shredding of pruning	326.25	326.25	326.25
Ploughing	59.48	59.48	59.48
Total Machinery	767.78	767.78	767.78
***Other costs* (€ ha^{-1})**			
Insurance and tax	100.00	100.00	100.00
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PB (years)	9.00	a	14.50	b	10.00	ab	7.00	a	9.00	b	8.00	ab

FI: fully irrigated treatment; 45RDI$_{CC}$; RDI treatment scheduled with the crop coefficient approach; 45RDI$_{TP}$: RDI treatment scheduled with leaf turgor pressure (TP).

Mean values followed by different letters within the same row and CAP payment option indicate significant differences at 95% confidence level following Tukey test.

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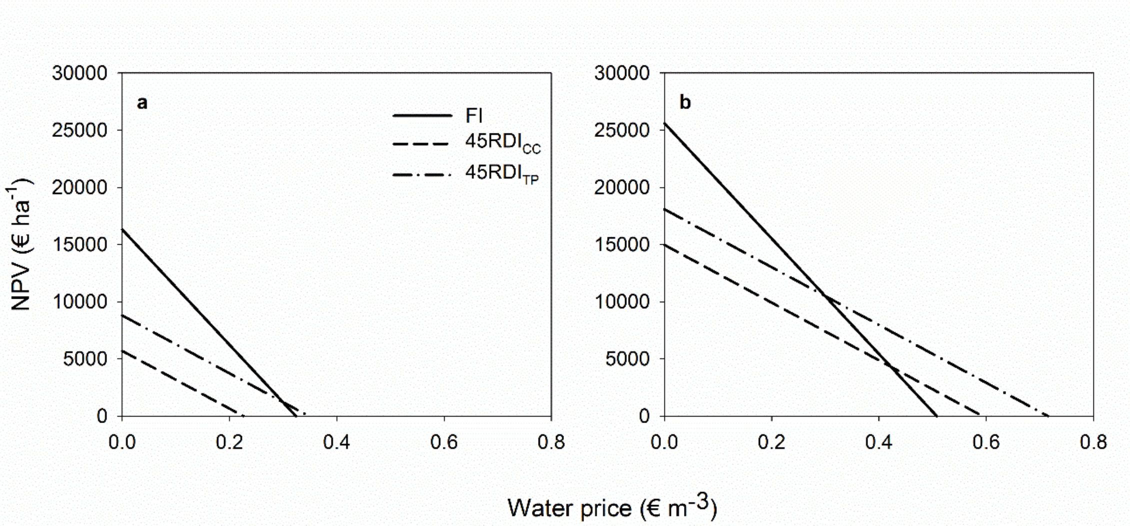

Figure 1. Sensitivity analysis, for the considered irrigation strategies, of Net Present Value (NPV) to irrigation water price, excluding (a) and including (b) Common Agricultural Policy payment (€$_{2007}$). FI: fully irrigated treatment scheduled from the crop coefficient approach, in which the trees received 100% of the crop water needs; 45RDI$_{CC}$ and 45RDI$_{TP}$ were regulated deficit irrigation (RDI) treatments in which the trees received 45% of the crop water needs, but the first was scheduled with the crop coefficient approach and the second from leaf turgor pressure related measurements.

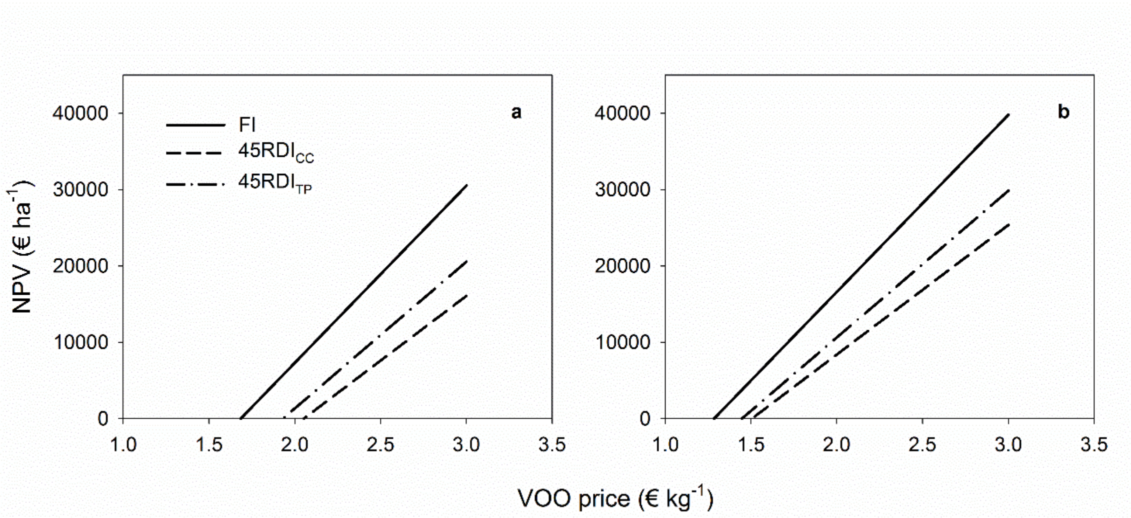

Figure 2. Sensitivity analysis of Net Present Value (NPV) of irrigation strategies to Virgin Olive Oil price excluding (a) and including (b) Common Agricultural Policy payment (€$_{2007}$). See Fig. 1 for details on the irrigation treatments.

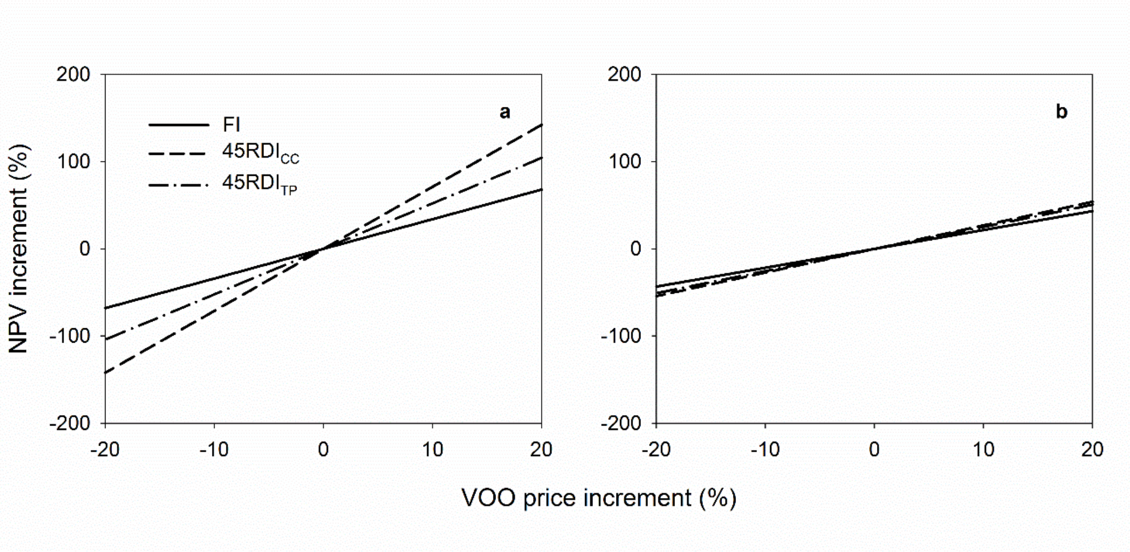

Figure 3. Net Present Value *(*NPV*)* percent variation as a consequence of the Virgin Olive Oil price percent variation in the three irrigation strategies assessed including (b) and excluding (a) Common Agricultural Policy payment. See Fig. 1 for details on the irrigation treatments.