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Real-time irrigation: Cost-effectiveness and benefits for water use and productivity of strawberries

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ABSTRACT

Although California is experiencing permanent water deficits compensated by irrigation, the state accounts for more than 90% of total strawberry production in the United States. There is a critical need to optimize yield and crop water productivity (CWP), as influenced by irrigation management. Although studies have reported that irrigation management based on soil matric potential (ψ) has the potential to increase yield and CWP compared to conventional practices, the cost of this technology may be a limiting factor for some growers. In this study, we assessed the cost-effectiveness of wireless tensiometer technology (WTT) for field-grown strawberries in California in comparison with the conventional irrigation management. As a second step, we evaluated the cost-effectiveness of deficit irrigation. Using data from eight sites, we calculated multiple linear regressions (MLR) to describe the relationship between: (1) fresh market yield and average soil matric potential reached before irrigation initiation (ψ_{irr}) and (2) water use and ψ_{irr}. Based on MLR results, we evaluated the technical performance of each irrigation management method and conducted an economic analysis. Our results showed that adopting a precise irrigation scheduling tool such as WTT is cost-effective and leads to water savings relative to conventional irrigation. Our results also revealed that any water savings associated with a deficit irrigation strategy are costly for strawberry growers.

1. Introduction

With more than 1.3 million metric tonnes of strawberries (*Fragaria x ananassa* Duch.) produced each year, the United States is the world's second largest supplier for both fresh and frozen markets (FAOSTAT, 2016). Remarkably, California leads all states in strawberry production, accounting for more than 90% of U.S. production (U.S. Department of Agriculture, 2013). Because of sustained and severe drought conditions, the major strawberry growing regions of California experienced substantial water supply problems between 2011–16 (USDA, 2016). The state relies heavily on irrigation, with much of the surface irrigation water supplied by state and federal water projects (USDA, 2016). In

drought years, however, many farmers compensate for reduced surface water delivery by increasing water withdrawals from groundwater wells (USDA, 2016). In addition, certain areas of coastal California do not have access to the delivered irrigation water and therefore rely solely on well water. The western United States is currently facing a number of difficulties, including long-term aquifer depletion, potential land subsidence, and salt water intrusion and nitrate contamination in local aquifers (California Departement of Water Resources, 2014; Fulcher et al., 2016; Gallardo et al., 1996; Gray et al., 2015; Scanlon et al., 2012). This situation can be particularly critical when aquifers are non-renewable sources of freshwater with naturally low recharge rates, which is found in many areas (USDA, 2016). Consequently, there

is a critical need to increase crop water productivity to ensure rational freshwater use in areas of intensive agricultural activity (Lea-Cox et al., 2013).

Strawberry plants are sensitive to water stress (Hanson, 1931) due to their shallow root system (Manitoba Minister of Agriculture, Food and Rural Development, 2015). When the crop is drip irrigated, adequate irrigation management is required to meet plant water requirements because only limited volumes of soil are wetted (Coelho and Or, 1998). The effectiveness of such irrigation is highly dependent on its scheduling, and it is thus important to determine the best timing and duration of irrigation events to limit over-watering, which often results in wasted water and soluble nutrients and lower crop yields (Saleem et al., 2013; Létourneau et al., 2015). Irrigation management practices have been studied extensively in field-grown strawberries (El-Farhan and Pritts, 1997). The methods most commonly used in California are based either on crop evapotranspiration (ET) or on soil moisture measurements.

Evapotranspiration estimates the quantity of water used by the crop during a given time period based on weather data and a field estimate of crop coefficients (Kc) (Grattan et al., 1998). Several studies have reported that ET-based irrigation has the potential to optimize water applications in strawberries (Cahn et al., 2016; Hanson and Bendixen, 2004; Yuan et al., 2004). Despite being an inexpensive decision-making tool (costs are negligible as many websites offer free access to potential evapotranspiration calculations and tabulated crop coefficient values; Allen et al., 1998; California Irrigation Management Information System, 2017), this approach estimates water usage indirectly and therefore is not as accurate as direct-measurement methods (Lea-Cox, 2012). To compensate for crop evapotranspiration losses (Allen et al., 1998), ET estimates past water requirements to predict future water applications, thus eliminating the possibility of managing irrigation in real-time. While common grower practices aim for water applications equivalent to approximately 100% of crop ET, recent studies suggest that improved irrigation scheduling methods, such as irrigation based on soil matric potential (ψ), can generate water savings without compromising strawberry yields or fruit quality, once an optimal irrigation threshold (IT) has been defined (Muñoz-Carpena et al., 2005; Létourneau et al., 2015; Migliaccio et al., 2008; Shae et al., 1999). By optimizing irrigation efficiency, the ψ-based method is likely to enable strawberry farmers to better meet sustainability and economic objectives.

Wireless soil sensor technology combines traditional soil matric potential monitoring with wireless communication, thus allowing real-time data reporting and irrigation management (Chappell et al., 2013; Lea-Cox et al., 2013). In California, it has been shown that yields decreased sharply at soil matric potentials of less than −8 to −12 kPa in sandy loam to clay loam soils, suggesting that ψ-based irrigation may provide optimal yield and CWP at soil matric potentials ranging from −10 to −15 kPa in field-grown strawberries (Létourneau et al., 2015). In similar conditions, Anderson (2015) showed that ψ-based irrigation at an IT of −17 kPa could increase yield and CWP compared to conventional irrigation which was usually drier (ψ$_{irrs}$ of −27, −31 and −42 kPa). These results are consistent with other research studies, where significantly higher strawberry yields were obtained using an IT of −10 kPa compared to ITs ranging from −30 to −70 kPa (Guimerà et al., 1995; Peñuelas et al., 1992; Serrano et al., 1992). Although most growers are receptive to the idea of wireless sensor networks, they have so far been reluctant to adopt WTT because it is more costly – involving an investment in equipment of more than $1500 per hectare – than the conventional irrigation management method (Majsztrik et al., 2013; Lea-Cox, 2012). However, no analysis assessing the cost-effectiveness of this technology has been conducted for strawberry production in North America.

WTT also opens up a range of possibilities for fine-tuned irrigation strategies, such as deficit irrigation (DI), which has been shown to reduce water use and improve CWP in many crops (Geerts and Raes, 2009; Fereres and Soriano, 2007; Zwart and Bastiaanssen, 2004). In strawberries, Létourneau et al. (2015) obtained higher CWP in drier treatments (lower ITs) than in wetter treatments (−26 kPa vs −10 kPa; −15 kPa vs −8 kPa). Likewise, in Finland, in a strawberry crop grown in a sandy soil, Hoppula and Salo (2007) obtained higher CWP with irrigation initiated at −60 kPa instead of −15 kPa. Considering that most Californian strawberry growers must pay for water, it could be beneficial to develop a controlled dry-irrigation management strategy that uses tension sensors to save water.

In this study, we first assessed the cost-effectiveness of ψ-based management using WTT with an optimal IT of −10 kPa in field-grown strawberries in California, in comparison with the conventional irrigation management method. In a second time, we evaluated the cost-effectiveness of deficit irrigation using WTT by simulating a set of reduced-irrigation scenarios.

2. Materials and methods

2.1. Site description and experimental designs

We collected the data analyzed in this study over five growing seasons and on eight experimental sites covering a range of soil properties, cultivation periods, strawberry cultivars and farming practices used in field strawberry production in California, USA (Table 1). We arranged treatments in all sites except site 1 in a randomized complete block design (RCBD) with three to five replicates (Table 1). We divided sites, all located in a typical temperate, Mediterranean climate, into two groups according to their location: northern strawberry growing region (Group N: sites 1–4) and southern strawberry growing region (Group S: sites 5–8). We grew strawberry plants on raised beds covered with a plastic mulch according to standard farming practices (Strand, 2008), with two (Group N) or four (Group S) plant rows per bed. In Group N, day-neutral strawberries (*Fragaria × ananassa* Duch.) were planted by the farm team in November in silty clay and clay loam soils. Trials ran from April to October on sites 1, 3 and 4, and from mid-April to late June on site 2. In Group S, short-day strawberries were planted by the farm team in sandy loam soils in October with fresh market harvest period falling between January/February and May/June, depending on the growing season.

2.2. Irrigation system specifications and ψ$_{irr}$ measurements

At all sites, sprinkler irrigation was used by the farm team up to proper establishment (for 4–6 weeks after planting). Subsequently, we used drip-irrigation until the end of the season. We irrigated growing beds by two (Group N) or three (Group S) drip lines (0.34–0.70 L·h^{-1} per emitter, depending on the site, with 20-cm emitter spacing). We installed field monitoring stations reporting real-time ψ measurements through wireless networks and web servers in all treatments in one or two blocks (Group N) or in one to three blocks (Group S) (Table 1). A TX3 wireless monitoring station (Hortau, Quebec, Qc, Canada) consisted of two model HXM80 tensiometers, buried at two different depths (15 and 30 cm), that measured ψ at 15-min intervals. In ψ-based treatments, the shallow probe, located in the root zone, indicated when a set IT was reached and when irrigation should be initiated. The deep probe, located below the root zone, indicated when to stop irrigation to prevent water percolation and nutrient leaching under the root zone. In conventional treatments, the probe at a 15-cm depth reported the average soil matric potential reached before irrigation and the deep probe monitored the soil water status at a 30-cm depth.

2.3. Irrigation treatments

Irrigation treatments in our study concern post-establishment irrigation. A total of twenty-five ψ-based treatments consisted of different irrigation initiation thresholds ranging from −8 kPa to −35 kPa

Table 1
Site description and irrigation treatments.

Group	Site	Location (lat; long)	Year	Fresh market harvest period	Soil type	Site area (ha)	Bed length/width (m)	Number of beds per plot	Experimental design	Number of harvest plots (sub-plots)	Number of monitoring stations/trt[b]	Harvest frequency (P[c] or T[d])	Treatments (irrigation management)	
													Conventional[e]	ψ-based (VWC[f])
N	1	Watsonville, CA, USA (3688°; -121,81°)	2011	April to October	Silty clay	0.28	55/0.80	14	No treatment replicate	3	1	P	Grower	-10 kPa (0.60) / -20 kPa (0.55)
N	2	Salinas, CA, USA (3669°; -121,65°)	2012	Mid-April to late June	Silty clay loam	0.56	127/0.80	4	RCBD[a] 3 reps	2	1	P	NA	-8 kPa (0.45) / -13 kPa (0.44) / -18 kPa (0.42)
N	3	Watsonville, CA, USA (3689°; -122,67°)	2013	April to October	Clay loam	0.28	32/0.80	2	RCBD 4 reps	1	1	T	Grower	-10 kPa (0.60) / -17 kPa (0.57) / -25 kPa (0.53)
N	4	Watsonville, CA, USA (3689°; -121,67°)	2014	April to October	Clay loam	0.19	34/0.80	1	RCBD 4 reps	2	2	P	50% ETc / 75% ETc / 100% ETc / Grower	-10 kPa (0.60) / -35kPa/ -10kPa (0.50/0.60)
S	5	Oxnard, CA, USA (34.15°; -119.15°)	2012	February to mid-June	Sandy loam	0.70	130/1.22	3	RCBD 3 reps	2	1	T	NA	-8 kPa (0.36) / -11 kPa (0.35) / -13 kPa (0.34)
S	6	Oxnard, CA, USA (3419°; -119,19°)	2013	January to May	Sandy loam	NA	NA	2	RCBD 3 reps	2	1	P	Grower	-13 kPa (0.34) / -13 kPa (0.34) / -18 kPa (0.33)
S	7	Oxnard, CA, USA (3419°; -119,19°)	2014	January to June	Sandy loam	0.55	127/1.22	1	RCBD 5 reps	2	3	P	Grower	-10 kPa (0.35) / -35 kPa (0.30) / -35 kPa/-10 kPa (0.30/0.35) / Variable thresholds
S	8	Oxnard, CA, USA (3419°; -119,19°)	2015	January to June	Sandy loam	0.55	119/1.22	1	RCBD 5 reps	2	3	P	NA	-10 kPa (0.35) / -35 kPa (0.30) / -35 kPa/-10 kPa (0.30/0.35) / Variable thresholds Grower (ψ-based)[g]

[a]RCBD: Randomized Complete Block Design.

[b]Some sites had replicates with one sensor per experimental unit and did therefore have many sensors per treatments. On other sites, where we were imposed limitation of equipment, there was one tensiometer per treatment. In these cases, core samples (site characterization) were taken at the beginning of the experiment to check the uniformity. Also, early measurements were taken with tensiometers at multiple locations to make sure that the site chosen was representative of the variability.

[c]P (partial yield): when harvest by the research team was done less often than that of the grower.

[d]T (total yield): when harvest by the research team was done as often as that of the grower.

[e]Conventional treatments were essentially estimated from weather data without any direct measurement of soil water status, in contrast with ψ-based treatments, and were irrigated at the same frequency (two to three times weekly).

[f]VWC: volumetric water content. This parameter was not measured on sites and was rather estimated from published water desorption curves from the same sites (Anderson, 2015). As the water content-matric potential relationship depends on soil texture, soil stucture and hysterisis phenomena, the site water content value even within a same site is approximate only. Readings with VWC probes also needs local calibration for more accurate estimate. Local calibration of VWC with tensimeter readings is therefore recommended to establish correspondance with the soil water potential values imposed in these experiments.

[g]The grower treatment on site 8 was included in the ψ-based treatments since wireless tensiometer technology was used to manage irrigation.

(Table 1). We manually initiated irrigation events when ψ at the 15-cm depth reached the predetermined IT, and stopped them once ψ at 30-cm depth reached 5 kPa. "−35/−10 kPa" and "Variable" treatments were based on ψ, with variable ITs throughout the season, as thoroughly described by Anderson (2015).

We refer to the eight conventional treatments as treatments that essentially estimated plant water needs from weather data without any direct measurements of soil water status, in contrast with ψ-based management. Irrigation of these treatments was controlled by each site's manager; however, we also equipped them with tensiometers. They included ET-based managements and grower procedures (Table 1). While grower treatments aimed to apply approximately 100% of the historical average water lost through evapotranspiration via two or three weekly irrigation events (Létourneau et al., 2015), ET-based treatments were managed according to estimated crop evapotranspiration (ET$_c$) and aimed to meet 100%, 75% or 50% of crop's water requirements. Crop water requirements in ET treatments were determined using CropManage web application (UC Cooperative Extension, Davis, CA, USA), as fully explained by Anderson (2015). ET treatments reflected the irrigation frequency (two to three times weekly) typically used by strawberry growers in California.

2.4. Crop yield and water use

We harvested strawberries in the harvest plots (sub-plots) weekly, on either a total or partial basis (Table 1). We classified Group N fruits by size and color as berries intended for fresh market (referred to as "fresh market yield" in the present study) or as processing strawberries (for lower quality berries). On Group S sites, the harvesting period consisted of a first stage, when strawberries were intended for fresh market only (first four or five months of the harvesting period), and then a second stage, when berries were intended for processing only (last couple of months). We only used fresh market yields in the present study. We measured the amount of water applied in each treatment weekly during fresh market harvesting period with model 36WMR2T10 water meter (Netafim™, Fresno, CA, USA) on site 4 and with TM Series® Electronic water meters (Great Plains Industries, Wichita, KS, USA) on all other sites.

2.5. Data analysis

We generated all data analyses using SAS software, Version 9.3. (SAS Institute Inc., Cary, NC, USA). We used multiple linear regressions with dummy variables to develop models for predicting fresh market yields and water use (WU) from ψ$_{irr}$. Predictors comprised a continuous variable (ψ$_{irr}$; in kPa) and three categorical variables: (1) the region where the experiment took place (R: northern or southern region), (2) the year of experimentation (Y: from 2011 to 2015) and (3) the irrigation management method used (IM: conventional or ψ-based).

2.5.1. Prediction of fresh market yield from ψ$_{irr}$

We performed the first MLR to predict fresh market yields (FMY) from ψ$_{irr}$, taking into consideration the effect of each experimental site (region and year) on yields. We used data of total fresh market yield associated with the average ψ$_{irr}$ value in each block where we had installed a monitoring station. Given that there were two or more harvest plots (sub-plots) per block in some cases, we tested the position effect of harvest plots on fresh market yield using a Student's *t*-test ($P > 0.05$) and we found it was significant in one case. For that specific site, we selected fresh market yield closest to the monitoring station for further analyses, as yield in the other sub-plots may have experienced a different water regime, given this observed yield gradient. Otherwise, we calculated the average fresh market yield of all harvest plots in a block.

Depending on the site, we harvested either total or partial fresh market yields in sub-plots (Table 1). Where applicable, we extrapolated partial yields to obtain total yields (see Appendix A in Supplementary

materials). We then used extrapolated and measured total fresh market yields for MLR analysis.

2.5.2. Prediction of WU from ψ$_{irr}$ and IM

We used the second MLR analysis to examine the relationship between average ψ$_{irr}$ and total volume of water used per treatment during the fresh market harvesting period. We further associated each WU with the corresponding irrigation practice (conventional or ψ-based).

Given that both regression models involved a high-order interaction effect, we centered the data on their respective reference intercepts (site 8; R$_S$Y$_{2015}$) to facilitate visual detection of a data pattern (Aiken et al., 1991). We further calculated water productivity as the ratio of predicted fruit production to predicted units of water applied, as deduced from the regression models (Fereres and Soriano, 2007; Gendron et al., 2017).

2.6. Frequency distribution of ψ$_{irr}$ under conventional practice

We used data of average ψ$_{irr}$ from eight conventional treatments aimed at applying full crop water requirements (grower and 100% ET$_c$ treatments) to determine the frequency distribution of ψ$_{irr}$ under conventional management. Indeed, average ψ$_{irrs}$ in treatments that were not ψ-based indicated whether conventional management aimed at applying full crop water requirements generally represented a wet or a dry irrigation strategy. We used these observations to define scenarios in the cost-benefit analysis.

2.7. Economic analysis

We performed an economic analysis to determine the cost-effectiveness of (1) WTT using an optimal IT of −10 kPa, and (2) deficit irrigation controlled by WTT.

As a first step, we used cost-benefit analyses to compare additional costs and benefits associated with the adoption of an irrigation management based on ψ, using an IT of −10 kPa, instead of the conventional management. We calculated benefits based on water savings and yield gains, while costs included variable and fixed costs. Depending on the scenario studied, variable costs included costs associated with increased water use and operating costs associated with yield gains. Fixed costs included the investment in WTT, which we calculated on an annual basis using depreciation of the equipment, annual service fees and depreciated initial costs. We estimated investment and initial fees depreciation using the straight-line method (Penson et al., 2002) considering a life span of five years for WTT. Based on production practices commonly used in California at the time of the analysis, we assumed that one monitoring station would be installed for every 4 ha of production surface.

Along with cost-benefit analyses, we calculated the expected value (EV) to estimate the long-run average value of net change in profit. We calculated EV as the sum of net change in profit values associated with each scenario studied, multiplied by the probability of their occurring over the years. We determined the cost-effectiveness of WTT by calculating payback periods, i.e., the number of years required to generate sufficient revenue to reimburse the initial investment (Gaudin et al., 2011; Levallois, 2010), as well as net present values (NPV) (Arnold, 2014). In this last case, given that WTT had an assumed life span of five years, we considered the proposed irrigation practice cost-effective if NPV, calculated as the difference between present value of net cash inflows and total initial investment costs over a period of five years, was positive. We assumed an annual discount rate of 10% (Arnold, 2014), chosen on the high side to provide conservative payback period estimates. Finally, we calculated a break-even point (BEP), defined as the minimum net gain necessary to generate a payback period within the useful life of the equipment. We then conducted sensitivity analyses to assess the impact of both strawberry and water price variations on payback periods.
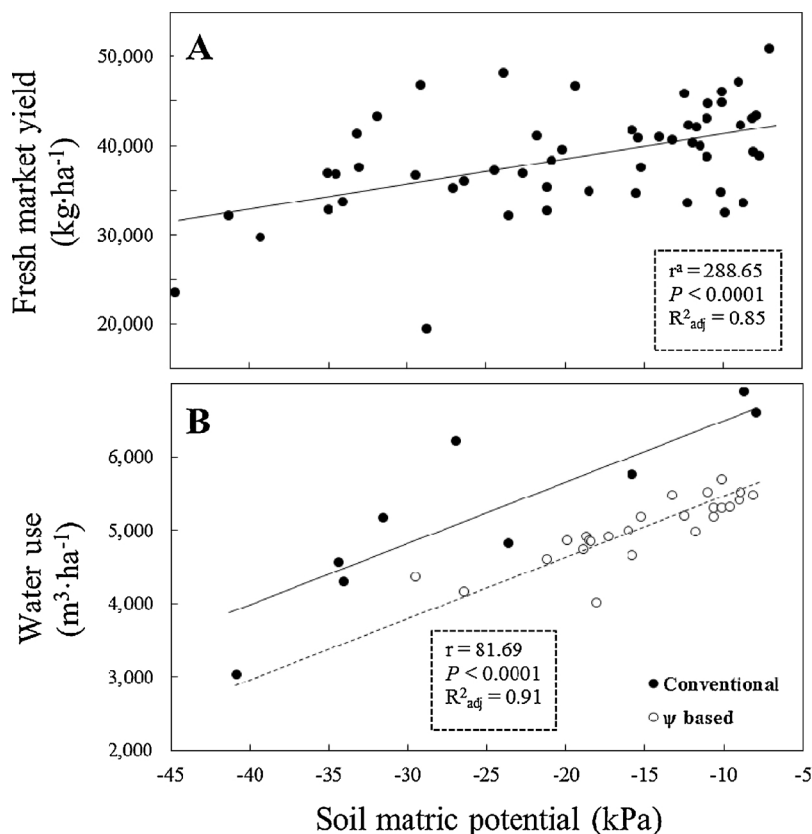
Fig. 1. Centered regression lines describing the relationship between (A) predicted total fresh market yield[b] and average soil matric potential reached before initiating irrigation (ψ_{irr}) and (B) predicted total water use[c] and ψ_{irr}, for each irrigation management method (conventional or ψ-based). Data from eight experimental sites were used to conduct the analyses. In both models, the site effect ($R_j \times Y_i$) was significant. Obtained multiple regression lines of each model were centered on the reference intercept to facilitate visual detection of a data pattern.

[a] "r" is the effect of the predictor variable (ψ_{irr}) on fresh market yield (A) and water use (B). In other words, it corresponds to the slope of the regression lines.

[b,c] 1 kg·ha^{-1} (0.89 lb/acre) and 1 m^3·ha^{-1} (3.28·10^{-4} acre-ft/acre).

As a second step, we conducted cost-benefit analyses to assess the cost-effectiveness of deficit irrigation controlled by WTT. Analyses accounted for variations in yield and water use when DI strategies were adopted instead of the optimal IT of −10 kPa. We conducted sensitivity analyses to assess the impact of water price variations on cost-effectiveness of deficit irrigation.

We conducted cost-benefit analyses on a one-hectare basis, since farm size had a negligible impact on net changes in profit (data not shown). We predicted FMY and WU values from the fitted regression models. We reported input costs and output prices as in Appendix B (in Supplementary materials).

3. Results

3.1. Multiple linear regressions

3.1.1. Prediction of fresh market yield from ψ_{irr}

The multiple linear regression predicting fresh market yield (FMY; in kg·ha^{-1}) based on soil matric potential reached before irrigation initiation showed that both ψ_{irr} and experimental sites (R × Y) were significant predictors of total fresh market yield ($P < 0.0022$ and $P < 0.0001$, respectively). We define the final model (F(7,45) = 45.93, $P < 0.0001$, with an R^2 of 0.877 and $R^2_{adj} = 0.858$) by the following equation:

$$FMY = 44,364 + (25,491 * R_N Y_{2011}) + (-3,177 * R_N Y_{2013})$$
$$+ (34,054 * R_N Y_{2014}) + (3,048 * R_S Y_{2012}) + (-7,523 * R_S Y_{2013})$$
$$+ (18,782 * R_S Y_{2014}) - (289 * \psi_{irr}) \quad (1)$$

where ψ_{irr} is the average soil matric potential (-kPa) reached before irrigation initiation and $R_i Y_j$ corresponds to experimental sites (sites 1–8) and we refer to it as "site effect" in the present paper [R_i being the growing region (N: northern region; S: southern region) and Y_j, the year of experimentation]. We used site 8 ($R_S Y_{2015}$) as the reference site to

perform this analysis for it was the most recent experimental site. This means that the intercept for this site corresponds to the initial intercept of the equation (44,364 kg ha^{-1}).

The results showed that the ψ_{irr} effect on FMY was the same regardless of the experimental site. We thus centered fresh market yield data on the reference fresh market yield intercept to eliminate the site effect (R × Y) and facilitate a visual interpretation of the results obtained. We present the centered regression line in Fig. 1A. For an IT ranging from −44.7 to −7.1 kPa, the results showed that, for all sites, each 1-kPa increase in ψ_{irr} corresponded to a 289 kg·ha^{-1} increase in fresh market yield, confirming that the crop is sensitive to variations in ψ.

We can explain the significant effect of the R × Y interaction on fresh market yield by differences among experimental sites such as: duration of the harvesting periods, strawberry cultivars and climatic conditions, among other factors. Interaction effects for R × ψ_{irr} and Y × ψ_{irr} were non-significant (data not shown).

3.1.2. Prediction of WU from ψ_{irr} and IM

The second multiple linear regression predicting water use (WU; in m^3·ha^{-1}) from on ψ_{irr} revealed that ψ_{irr} ($P < 0.0001$), experimental sites (R × Y: $P < 0.0001$) and irrigation management method ($P < 0.0001$) were significant predictors of total WU. We describe the final model (F(9,24) = 44.13, $P < 0.0001$, $R^2 = 0.943$ and $R^2_{adj} = 0.915$) by the following equation:

$$WU = 2,924 + (866 * R_N Y_{2011}) + (77 * R_N Y_{2012}) + (2,150 * R_N Y_{2013})$$
$$+ (4,166 * R_N Y_{2014}) + (624 * R_S Y_{2012}) + (-503 * R_S Y_{2013})$$
$$+ (1,382 * R_S Y_{2014}) + (1,031 * IM) - (82 * \psi_{irr}) \quad (2)$$

where (1) ψ_{irr} is the average soil matric potential (-kPa) reached before irrigation initiation, (2) IM is the irrigation management method used and is coded as 1 = conventional and 0 = ψ-based management, and (3) $R_i Y_j$ corresponds to experimental sites (sites 1–8) and is thus the
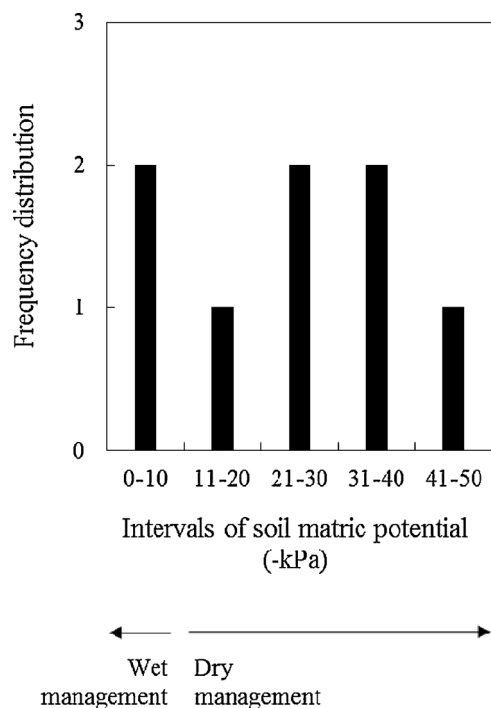
Fig. 2. Frequency distribution of average soil matric potential reached before irrigation (ψ_{irr}) of eight treatments under conventional irrigation management showing to what extent the conventional management is variable. Treatments aimed to apply full crop water requirements and consisted of the grower procedures and of an evapotranspiration (ET) treatment (100% of crop ET).

"site effect" [R_i being the growing region (N: northern region; S: southern region) and Y_j, the year of experimentation]. We again used site 8 ($R_S Y_{2015}$) as the reference site to perform this analysis for it was the most recent experimental site. This means that the intercept for this site corresponds to the initial intercept of the equation (2924).

Since the effect of ψ_{irr} on WU of each IM was the same regardless of the experimental site, we centered the WU data as described above and further increased by 3333 $m^3 \cdot ha^{-1}$ to obtain positive values of WU on the entire range of ψ_{irr}, thus facilitating visual detection of a data pattern. We show the centered regression line in Fig. 1B.

Considering ITs ranging from -40.8 to -7.9 kPa, we found a positive relationship between water use and ψ_{irr}, with a predicted WU increase of 82 $m^3 \cdot ha^{-1}$ per kPa. Moreover, irrigation management method had a significant effect on the amount of water applied. Indeed, the conventional management used constantly more water (1031 $m^3 \cdot ha^{-1}$) than ψ-based method (Fig. 1B). Hence, the results indicate that we can expect an increase in CWP with the use of ψ-based irrigation management with WTT instead of conventional management (see Appendix C in Supplementary materials).

We can explain significant differences in WU between experimental sites by inter-site variations such as: duration of the harvesting periods, climatic conditions, strawberry cultivars, soil types, among others. Interaction effect for $Y \times \psi_{irr}$, $R \times \psi_{irr}$, $R \times IM$ and $Y \times IM$ were not significant (data not shown).

3.2. Frequency distribution and studied scenarios

We presented the variability of conventional irrigation aimed at applying full crop water requirements (Fig. 2). Six of eight conventional treatments represented relatively dry managements while the other two corresponded to relatively wet irrigation managements.

Based on these observations, we defined five conventional scenarios (C1–C5) for the economic analysis (Fig. 3A). Each scenario took into account an average ψ_{irr} that could be observed under conventional irrigation management. Scenarios C1–C5 corresponded to the variations in water use, fresh market yield and water productivity associated with the adoption of ψ-based management with an optimal IT of -10 kPa (new practice) instead of the conventional management (baseline practice). We also reported the BEP scenario, with a baseline practice triggering irrigation at about -11.2 kPa.

We reported three deficit irrigation scenarios (D1–D3) in Fig. 3B. These scenarios represent the variations in predicted water use and fresh market yield associated with the adoption of a deficit irrigation strategy controlled by WTT (new practice) instead of the optimal irrigation management based on ψ with an IT of -10 kPa (baseline practice).

In scenarios C1 and C2, the new practice decreased water use compared to the baseline practice. In scenarios C3–C5, however, it increased water use compared to the baseline practice which represented a dry irrigation management. In all scenarios except C1, the new practice resulted in a higher total yield relative to the baseline practice.

For a same ψ_{irr} (scenario C1), the use of WTT relative to the conventional management increased CWP by 33%. The use of WTT also increased CWP in scenarios C2 and C3, but decreased in scenarios C4 and C5. We can explain the latter results by the fact that dry managements, such as those of the baseline practice in scenarios C4 and C5, are associated with more efficient water use than wet managements such as that of the new practice (Fereres and Soriano, 2007; Geerts and Raes, 2009; Hoppula and Salo, 2007; Serrano et al., 1992; Zwart and Bastiaanssen, 2004).

In all cases, deficit irrigation generated both water savings and yield losses relative to the optimal ψ-based management at -10 kPa. Nonetheless, deficit irrigation improved predicted CWP by 12%–85% compared to the baseline practice, consistent with previous findings (Fereres and Soriano, 2007; Geerts and Raes, 2009; Gendron et al., 2017; Hoppula and Salo, 2007; Serrano et al., 1992; Zwart and Bastiaanssen, 2004).

3.3. Economic analysis

3.3.1. Cost-effectiveness of WTT

We conducted cost-benefit analyses to measure the additional costs and benefits associated with the adoption of WTT with an optimal IT of -10 kPa in comparison with the conventional management (Table 2). Under wet management for both conventional and ψ-based irrigation (scenario C1), we observed a net loss of $356/ha when WTT was adopted. In contrast, when compared with relatively dry conventional managements (scenarios C2-C5), the adoption of WTT with irrigation triggering at -10 kPa led to net gains ranging from $1179 to $8876/ha. Except for C1, the payback periods of all scenarios were under one year (0.9 to 0.1 year). Considering the variability of the conventional irrigation management method (Fig. 2), the expected long-run average net change in profit of adopting WTT in place of a conventional management is a net gain of $4,068/ha (Table 2). This average net gain corresponds to a payback period of 0.3 years and to a net present value of $15,114/ha.

In California, strawberry prices for the 2004–2014 period ranged between $0.72 and $1.17/lb ($1.60 to $2.59/kg), a variation that reaches more than 60% (see Appendix B in Supplementary materials). Therefore, we also evaluated the influence of different strawberry prices on payback periods (Table 3). Overall, excluding scenario C1, we obtained payback periods ranging from 1 month to 2.6 years. For scenario C2, payback periods decreased from 2.6 years to 7 months as fruit prices rose from $1.54 to $2.65 kg^{-1}. We observed the same trend in the other scenarios studied (C3–C5). At the break-even point (BEP), an annual yield gain of 350 $kg \cdot ha^{-1}$ was enough, at an average yearly fruit price of $2.20/kg, to generate a payback period equal to the useful life of the equipment (5 years). Given that the annual strawberry price has been above $1.54/kg since 2007 (see Appendix B in Supplementary materials), payback periods of less than or equal to 1.6 years are
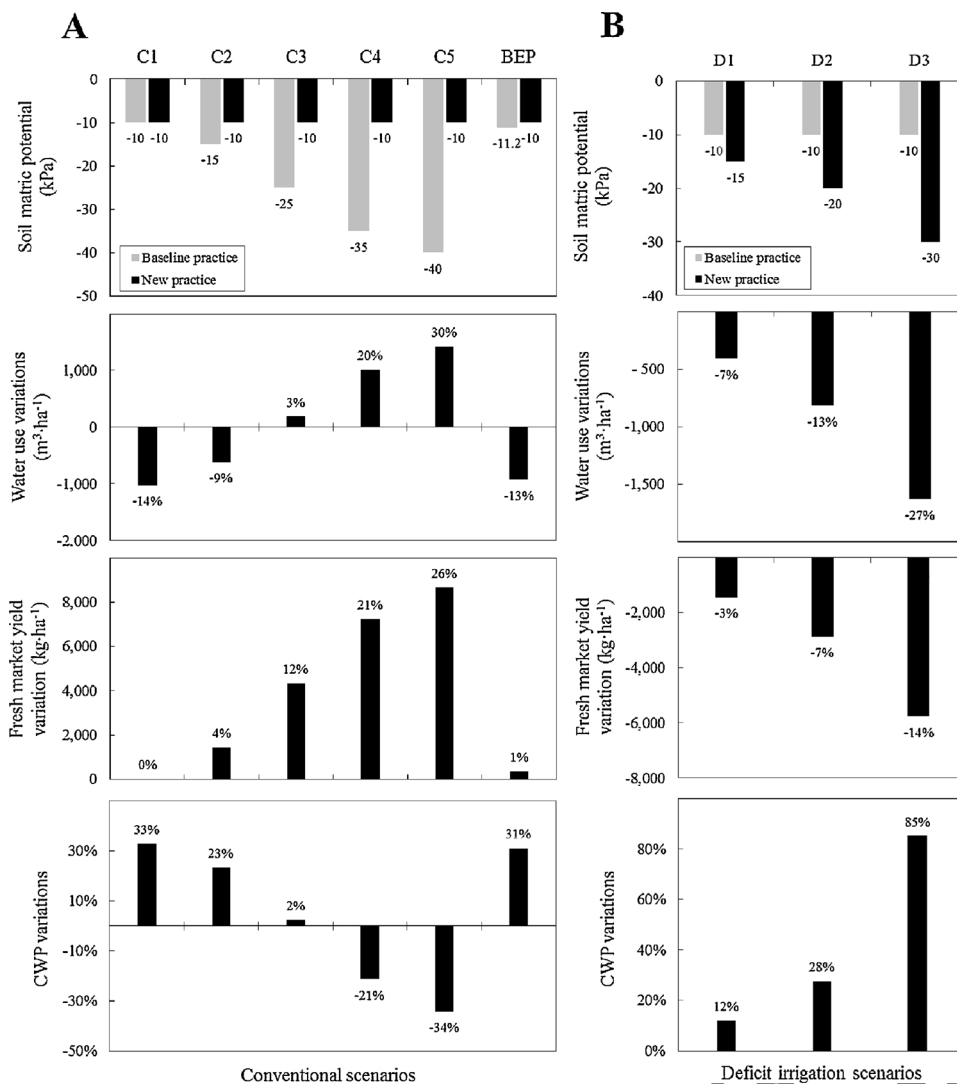
Fig. 3. Scenarios representing the variations in fresh market yield[a], water use[b] and water productivity[c] associated with the adoption of (A) wireless tensiometer technology with an optimal irrigation threshold of -10 kPa instead of the conventional practice (scenarios C1-C5[d]) and (B) deficit irrigation controlled with wireless tensiometer technology instead of the optimal tension-based management at -10 kPa (scenarios D1-D3[e]). The BEP scenario (A) represents the break-even point[f].

[a,b,c] 1 $m^3 \cdot ha^{-1}$ = $3.28 \cdot 10^{-4}$ acre-ft/acre; 1 $kg \cdot ha^{-1}$ = 0.89 lb/acre; $kg_{fruit} \cdot m_{water}^{-3}$ = 2719 lb/acre-ft.

[d] C1: baseline practice = conventional irrigation with an average soil matric potential reached before irrigation (ψ_{irr}) of -10 kPa; new practice = soil matric potential (ψ)-based irrigation with an irrigation threshold (IT) of -10 kPa.

C2: baseline practice = conventional irrigation (ψ_{irr} of -15 kPa); new practice = ψ-based irrigation (IT of -10 kPa).

C3: baseline practice = conventional irrigation (ψ_{irr} of -25 kPa); new practice = ψ-based irrigation (IT of -10 kPa).

C4: baseline practice = conventional irrigation (ψ_{irr} of -35 kPa); new practice = ψ-based irrigation (IT of -10 kPa).

C5: baseline practice = conventional irrigation (ψ_{irr} of -40 kPa); new practice = ψ-based irrigation (IT of -10 kPa).

[e] D1: baseline practice = ψ-based irrigation (IT of -10 kPa); new practice = ψ-based irrigation (IT of -15 kPa).

D2: baseline practice = ψ-based irrigation (IT of -10 kPa); new practice = ψ-based irrigation (IT of -20 kPa).

D3: baseline practice = ψ-based irrigation (IT of -10 kPa); new practice = ψ-based irrigation (IT of -30 kPa).

[f] BEP is the point where adopting wireless tensiometer technology with an irrigation threshold (IT) of -10 kPa becomes interesting at a water price of \$150/acre-ft, due to yield gains and water savings compared to conventional irrigation.

attainable for most growers.

We did another sensitivity analysis to measure the impact of different water prices on payback periods of WTT used with an IT of -10 kPa relative to the conventional management (Table 4). Indeed, water prices for the 2016–2017 period in California varied from \$150 to \$5,000/acre-ft (\$0.12 to \$4.05/m^3) (see Appendix B in Supplementary materials). In the case of a wet conventional management (scenario C1), a water price of \$575/acre-ft (\$0.47/m^3) was necessary to obtain a net gain with the adoption of WTT. The net gain was obtained through water savings alone; no yield gain was obtained with WTT relative to the conventional management in scenario C1, since the conventional management was triggering irrigations at around -10 kPa without using any soil matric potential sensors. The payback period of WTT in this last case was 4.9 years. At a water price of \$150/acre-ft (\$0.12/m^3), increases in fruit yield from 1440 to 8660 $kg \cdot ha^{-1}$ (scenarios C2-C5) under ψ-based management compared to conventional irrigation led to short payback periods (less than one year) for all water prices despite increased WU in some scenarios (Fig. 3A). Notably, increased WU had little effect on payback periods.

3.3.2. Cost-effectiveness of deficit irrigation

We presented net changes in profit associated with deficit irrigation in Table 5. Cost-benefit and sensitivity analyses revealed that deficit irrigation was not always cost-effective compared to the baseline practice. Despite predicted water savings of 7% compared to wet management (scenario D1), we recorded net losses of \$1537 to \$92/ha at water prices ranging from \$150 to \$4500/acre-ft (\$0.12 to \$3.65/m^3). This result is attributable to predicted yield losses of 3% (1440 $kg \cdot ha^{-1}$). We revealed similar trends in the other deficit irrigation scenarios, with greater yield losses (-7% and -14%). However, we obtained net gains in all deficit irrigation scenarios when the price of water reached \$5000/acre-ft (\$4.05/m^3).

4. Discussion

4.1. Optimal irrigation management for field-grown strawberries

Our results indicated that an irrigation management based on ψ was highly cost-effective for strawberry growers when compared with the conventional irrigation management. Given that conventional irrigation is highly variable, representing either dry or wet managements, better control of crop yield and water use is obtained with ψ-based irrigation. Indeed, the first multiple linear regression (MLR) analysis showed that the highest fresh strawberry yields were obtained with an IT of about -10 kPa, consistent with previous work (Guimerà et al., 1995; Hoppula and Salo, 2007; Létourneau et al., 2015; Peñuelas et al., 1992). It also established that consistent yield losses are to be expected with the adoption of dry irrigation managements compared to optimal

Table 2

Cost-benefit analysis associated with the adoption of wireless tensiometer technology with an optimal irrigation threshold of −10 kPa instead of the conventional practice in California (USA). Five scenarios (C1–C5) are analysed. Net change in revenue (dollars per hectare[a]), payback periods (years) and net present value (dollars per hectare) are presented. Prices are expressed in US dollars.

Scenarios[b] Probability of each scenario's occurring	C1 1/4	C2 1/8	C3 1/4	C4 1/4	C5 1/8	Expected Value
Additional benefits						
Yield gain[c]	–	3,168	9,526	15,884	19,052	
Water savings[d]	124	74	–	–	–	
Total additional benefits ($/ha)	124	3,242	9,526	15,884	19,052	9,170
Additional costs						
Variable costs						
Increased water use	–	–	23	121	170	
Operating costs	–	1,584	4,763	7,942	9,526	
Fixed costs (WTT)[e]						
Technology depreciation	245	245	245	245	245	
Interest[f]	–	–	–	–	–	
Annual service fees	225	225	225	225	225	
Depreciation of initial fees	10	10	10	10	10	
Total additional costs ($/ha)	480	2,064	5,265	8,543	10,176	5,102
Net change in profit ($/ha)	−356	1,179	4,261	7,341	8,876	4,068
Payback period (years)	NPB[g]	0.9	0.3	0.2	0.1	0.3
Net present value ($/ha)	−1,658	4,161	15,843	27,521	33,339	15,114

[a] $1.00/ha = $0.40/acre.

[b] C1: baseline practice = conventional irrigation with an average soil matric potential reached before irrigation (ψ_{irr}) of −10 kPa; new practice = soil matric potential (ψ)-based irrigation with an irrigation threshold (IT) of −10 kPa. C2: baseline practice = conventional irrigation (ψ_{irr} of −15 kPa); new practice = ψ-based irrigation (IT of −10 kPa). C3: baseline practice = conventional irrigation (ψ_{irr} of −25 kPa); new practice = ψ-based irrigation (IT of −10 kPa). C4: baseline practice = conventional irrigation (ψ_{irr} of −35 kPa); new practice = ψ-based irrigation (IT of −10 kPa). C5: baseline practice = conventional irrigation (ψ_{irr} of −40 kPa); new practice = ψ-based irrigation (IT of −10 kPa).

[c,d] Fresh market yield and water use are predicted from the regression lines (Fig. 1A and B).

[e] We assumed that one monitoring station would be installed for every 4 ha (10 acres) of production surface. See Appendix B (in Supplementary materials) for more details.

[f] The technology is offered at 0% interest. See Appendix B (in Supplementary materials) for more details.

[g] NPB: No payback on investment.

management with an IT of −10 kPa. Interestingly, the analysis showed that site-specific characteristics, such as region, climatic conditions, soil types, and strawberry cultivars, among others, did influence the total amount of fresh fruits harvested at each site, but did not change the response of yield to the ψ_{irr}. We can thus conclude that optimal irrigation is attained with an IT of −10 kPa in open-field strawberry production in California.

In addition, the results of the second multiple linear regression indicated that conventional irrigation constantly used more water than ψ-based irrigation to obtain a similar yield, regardless of the experimental site. Ψ-based irrigation management thus appears to allow for more efficient water use than the conventional management in open-field strawberry production in California.

Table 3

Impact of different strawberry prices in California (USA) on payback periods of an investment in the wireless tensiometer technology (WTT) for irrigation management based on soil matric potential (ψ) with an optimal threshold (IT) of −10 kPa instead of the conventional management. Prices are expressed in US dollars.

Conventional scenarios[a]	Payback periods (years)					
	Annual fresh market strawberry prices ($/kg)[b]					
	1.54	1.76	1.98	2.20	2.43	2.65
C1	NPB[c]	NPB	NPB	NPB	NPB	NPB
C2	2.6	1.6	1.1	0.9	0.7	0.6
C3	0.8	0.5	0.4	0.3	0.2	0.2
C4	0.4	0.3	0.2	0.2	0.1	0.1
C5	0.4	0.2	0.2	0.1	0.1	0.1
BEP[d]	NPB	NPB	NPB	4.7	3.6	2.9

[a] C1: baseline practice = conventional irrigation with an average soil matric potential reached before irrigation (ψ_{irr}) of −10 kPa; new practice = soil matric potential (ψ)-based irrigation with an irrigation threshold (IT) of −10 kPa. C2: baseline practice = conventional irrigation (ψ_{irr} of −15 kPa); new practice = ψ-based irrigation (IT of −10 kPa). C3: baseline practice = conventional irrigation (ψ_{irr} of −25 kPa); new practice = ψ-based irrigation (IT of −10 kPa). C4: baseline practice = conventional irrigation (ψ_{irr} of −35 kPa); new practice = ψ-based irrigation (IT of −10 kPa). C5: baseline practice = conventional irrigation (ψ_{irr} of −40 kPa); new practice = ψ-based irrigation (IT of −10 kPa).

[b] 1.00 $/kg = 0.45 $/lb.

[c] NPB: No payback on investment.

[d] BEP is the point where adopting wireless tensiometer technology with an IT of −10 kPa becomes interesting at a water price of $150/acre-ft, due to yield gains and water savings compared to conventional irrigation.

4.2. Adopting WTT: economic considerations

Our cost-benefit analyses showed that the cost-effectiveness of WTT was highly dependent on yield. We calculated a payback period within the useful life of the equipment for a yield increase of only 350 kg·ha^{-1} with WTT. Likewise, given that the equipment is expected to last for 5 years, we obtained short payback periods (under one year) for the investment in WTT with high predicted yield gains (4330–8660 kg·ha^{-1}) relative to conventional irrigation, even though these yield gains were associated with increased water use. This suggests that the current cost of water is low since it has little influence on payback periods. Similarly, payback periods were relatively short (1.6–2.6 years) even at very low strawberry prices, between $1.54 and $1.76/kg, suggesting that the cost-effectiveness of the technology is not likely to be affected by strawberry price variations.

In the case where the use of WTT instead of conventional irrigation generated only water savings, the current water price, ranging from $150 to $350/acre-ft ($0.12 to $0.28/m^3) depending on the growing region, was too low to generate a net gain for the grower. Indeed, a minimum water price of $575/acre-ft[1] ($0.47/m^3) would be required to ensure the cost-effectiveness of WTT on the sole basis of water savings. This suggests that current water prices are not high enough to support an investment in water-saving technologies, such as WTT.

However, regardless of water price, farmers can make better management decisions with water allocations that they receive from California groundwater pumping agencies (imposed during drought), while improved in-field monitoring would allow compliance with regional regulations on water use and discharge.

4.3. Deficit irrigation: unfortunately for the environment, an unprofitable strategy so far

Our cost-benefit analyses for deficit irrigation showed that money

Table 4

Impact of different water prices in California (USA) on payback periods of an investment in the wireless tensiometer technology (WTT) for irrigation management based on soil matric potential (ψ) with an optimal threshold (IT) of −10 kPa instead of the conventional management. Prices are expressed in US dollars.

Conventional scenarios[a]	Payback periods (years)					
	Water prices ($/m³)[b]					
	0.12	0.28	0.41	0.47	0.81	4.05
C1	NPB[c]	NPB	NPB	4.9	2.1	0.3
C2	0.9	0.8	0.8	0.8	0.7	0.3
C3	0.3	0.3	0.3	0.3	0.3	0.3
C4	0.2	0.2	0.2	0.2	0.2	0.4
C5	0.1	0.1	0.1	0.1	0.2	0.4
BEP[d]	4.7	2.5	2.0	1.9	1.3	0.3

[a] C1: baseline practice = conventional irrigation with an average soil matric potential reached before irrigation (ψ_{irr}) of −10 kPa; new practice = soil matric potential (ψ)-based irrigation with an irrigation threshold (IT) of −10 kPa. C2: baseline practice = conventional irrigation (ψ_{irr} of −15 kPa); new practice = ψ-based irrigation (IT of −10 kPa). C3: baseline practice = conventional irrigation (ψ_{irr} of −25 kPa); new practice = ψ-based irrigation (IT of −10 kPa). C4: baseline practice = conventional irrigation (ψ_{irr} of −35 kPa); new practice = ψ-based irrigation (IT of −10 kPa). C5: baseline practice = conventional irrigation (ψ_{irr} of −40 kPa); new practice = ψ-based irrigation (IT of −10 kPa).

[b] $1.00/m^3$ = $1233.48/acre-ft.

[c] NPB: No payback on investment.

[d] BEP is the point where adopting wireless tensiometer technology with an irrigation threshold of −10 kPa becomes interesting at a water price of $150/acre-ft, due to yield gains and water savings compared to conventional irrigation.

Table 5

Impact of different water prices in California (USA) on the cost-effectiveness of deficit irrigation (DI). Net changes in revenue associated with the adoption of DI based of soil matric potential (ψ) instead of ψ-based management with an optimal irrigation threshold of −10 kPa are presented. Prices are expressed in US dollars. Net losses are indicated in brackets.

Deficit irrigation scenarios[b]	Net changes in revenue ($/ha)[a]					
	Water prices ($/m³)[c]					
	0.12	0.28	0.41	0.81	3.65	4.05
D1	(1537)	(1471)	(1421)	(1255)	(92)	75
D2	(3086)	(2953)	(2853)	(2521)	(194)	138
D3	(6162)	(5898)	(5700)	(5039)	(414)	247

[a] $1.00/ha = $0.40/acre.

[b] D1: baseline practice = soil matric potential (ψ) based irrigation [irrigation threshold (IT) of −10 kPa]; new practice = ψ-based irrigation (IT of −15 kPa). D2: baseline practice = ψ-based irrigation (IT of −10 kPa); new practice = ψ-based irrigation (IT of −20 kPa). D3: baseline practice = ψ-based irrigation (IT of −10 kPa); new practice = ψ-based irrigation (IT of −30 kPa).

[c] $1.00/m^3$ = $1233.48/acre-ft.

savings associated with reduced water use are minimal relative to the reduction in income associated with the consequent yield losses. Indeed, for all deficit irrigation scenarios, we obtained net losses with all water prices between $150 and $4500/acre-ft ($0.12 and $3.65/m³), while net gains were obtained with a water price as high as $5000/acre-ft[1] ($4.05/m³), which is far above the actual market price and expected prices for desalinated water.

4.4. Further work

Obviously, all costs involved in our study are evolving in time. Therefore, it may be argued that new regulations on water use, price of the commodity, change in labor regulations and evolution of the technology and its performances will impact the results obtained. While this is theoretically true, our study shows a dominant effect of yield increase generating a short payback period for the technology. Given the fact that new version of WTT and new technology may be proposed to growers, further work should be looking at field performance of any new version of WTT on top of its price and the rapidly evolving situation of labor and water issues in California in order to update these conclusions in the near future.

Further research should also be assessing if a larger number of monitoring stations per treatment would be more profitable for strawberry growers due to variability considerations. Indeed, in some sites, the fact that we were imposed limitation of equipment may have caused some variability in the results; however, we think that the large number of experiments used in our study made the risk of bias due to this constraint more limited.

Finally, future studies should be looking at the conclusions on deficit irrigation for June bearing varieties. Indeed, our conclusions apply to day neutral and short-day varieties which crop over a long period of time in California. However, for varieties which crop over a short period of time, such as the June bearers, it would be interesting to test a deficit irrigation strategy to see if it would be more successful outside the fruiting period.

5. Conclusion

Our comparative study shows that ψ-based irrigation management implemented in farm-scale strawberry trials in California is an accurate irrigation management method. In the state's open-field strawberry production, maximum yields are obtained on the wet side of irrigation strategies, i.e. at an irrigation threshold of about −10 kPa. Our study also reveals that ψ-based management substantially improves CWP relative to conventional irrigation management, regardless of the region, the climatic conditions, the strawberry cultivars, etc.

Our cost-benefit analyses confirm that the use of WTT with a defined IT of −10 kPa has the potential to be highly cost-effective for strawberry growers, given the short payback periods (less than one year) obtained with yield gains relative to conventional irrigation ranging from 1440 to 8660 kg·ha⁻¹, although in some cases, these yield gains were associated with increased water use. Nonetheless, a yield gain of 350 kg·ha⁻¹ was enough to generate a payback period equal to the useful life of the equipment. Because the cost of water is presently low, the cost-effectiveness of the investment is, at this time, more contingent on yield gains than water savings.

Finally, our results show that, for the time being, there are no economic benefits associated with increasing water productivity through the use of a deficit irrigation strategy in strawberry production in California, since benefits associated with water savings are negligible compared to consequent yield losses. These findings suggest that, at current water prices, it would be of more benefit to growers to improve CWP by adopting a more accurate irrigation management tool than by adopting a deficit irrigation strategy.

Overall, our results constitute a useful decision-making tool for growers with regard to the adoption of WTT for open-field strawberry production in California.

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Supplementary data.

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