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Matric potential-based irrigation management of field-grown strawberry: Effects on yield and water use efficiency

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ABSTRACT

Effective and adapted criteria for irrigation scheduling are required to improve yield and water use efficiency (WUE) and reduce the environmental impacts associated with water and nutrients losses by runoff and leaching. In this study, field-scale experiments were conducted at four commercial strawberry production sites with contrasting soil and climatic conditions. Within each site, the influence of different soil matric potential-based irrigation thresholds (IT) on yield and WUE was evaluated. Matric potential-based irrigation management was also compared with common irrigation practices used by producers in each site's respective areas. At Site 1 (silty clay loam; humid continental (Dfb) climate), an IT of −15 kPa improved yields by 6.2% without any additional use of water relative to common irrigation practices. At Site 2, with similar soil and climatic conditions, the irrigation treatments did not affect yield and the matric potential-based management decreased WUE relative to common practices. However, the results suggested that maintaining the soil matric potential lower than −9 kPa could induce stressing conditions for the plants. At Site 3 (sandy loam; Mediterranean (Cs) climate), the best yield and WUE were obtained with an IT of −8 kPa and suggested that WUE could be further improved by implementing high-frequency irrigation. At Site 4 (clay loam; Mediterranean (Cs) climate), results suggested that an IT between −10 and −15 kPa could optimize yield and WUE, and matric potential-based irrigation considerably reduced leaching under the root zone relative to common practices. Considering the results from all sites, an IT of −10 kPa appears to be adequate as a starting point for further optimizing irrigation under most field conditions.

1. Introduction

Irrigation management is of primary importance for the profitability and sustainability of field strawberry production because it affects yield, water use efficiency and diffuse pollution of ground and surface water. These issues are of great importance in some areas, such as coastal California, Spain and Australia, where water availability is a growing concern. In recent decades, the increased implementation of more efficient water management practices, mainly subsurface drip irrigation (SDI) and the use of plastic mulch, has greatly improved WUE in commercial strawberry production. However, questions remain regarding irrigation management criteria that could improve WUE and reduce the environmental risks of SDI. Currently, the most common criteria are based on climatic water balance (evapotranspiration), plant physiological properties, soil water status measurements or a combination of these factors.

Many studies have shown that evapotranspiration (ET)-based irrigation management could be efficient for strawberry production (Hanson and Bendixon, 2004; Krüger et al., 1999; Yuan, 2004). However, this method is also criticized for its inability to account for rapid changes in climatic conditions and because it generally does not account for differences in the water requirements of different strawberry cultivars (Giné Bordonaba and Terry, 2010; Klamkowski and Treder, 2008; Krüger et al., 1999). The availability of locally determined crop coefficients that account for the wetting patterns resulting from the combined effects of SDI system configuration and soil type can also be problematic. Additionally, management based only on ET cannot be used to assess whether the applied irrigation water is lost beneath the root zone due to percolation (Simonne et al., 2012).

Numerous studies have proven that physiological measurements on plants could be used to measure water stress and its effect on plant performance. However, plant-based irrigation scheduling is still limited by many theoretical and practical difficulties, most of which are discussed in a comprehensive review by Jones (2004). In strawberry production, leaf temperature measurements with infra-red thermometers were identified as a potential tool

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for irrigation management because they allow for the detection of severe stresses that affect yield and biomass production (Peñuelas et al., 1992). Photosynthesis, stomatal conductance, and leaf water potential measurements have also been successfully used to detect hydric stress and to understand and differentiate stress adaptation mechanisms among strawberry cultivars. Such measurements have shown great potential to be used for breeding drought-resistant cultivars (Blanke and Cooke, 2004; Klamkowski and Treder, 2006, 2008; Savé et al., 1993). Canopy spectral reflectance or transmittance measurements also present potential for irrigation management because they are correlated with strawberry fruit yield. However, a clear interpretation of their effects still requires topography, soil water content and climatic information (Hoppula and Salo, 2007). Despite the relevance of understanding the physiological parameters tackled in the studies cited above, they do not currently allow for the definition of a criterion for irrigation scheduling or for assessing the appropriate volume of water that should be applied (Jones, 2004).

Soil water status measurement methods, whether based on water content or soil matric potential, have been well documented (Topp and Ferré, 2002; Young and Sisson, 2002) and have frequently been used for irrigation scheduling. In this study, soil matric potential (ψ) measurements were favored over soil water content measurements because of their ease of use in various field conditions (no calibration required for soil types or salinity levels). The soil matric potential is also directly related to the soil's hydraulic conductivity, which is linked to the soil's capacity to supply water at the rate required by plants (Rekika et al., 2014). Because potential gradients are the leading force responsible for water movement in soils, ψ measurements can also be used to infer the direction and magnitude of soil water fluxes. This information can be used to prevent leaching under the root zone (Krüger et al., 1999). ψ-based irrigation management has been successfully used to improve the yields of many agricultural crops and to evaluate the impacts of irrigation practices on water and fertilizer leaching (Pelletier et al., 2013; Périard et al., 2012; Shock and Wang, 2011).

Many studies have evaluated the impacts of ψ-based irrigation management on strawberry yield and WUE. However, their results differ with regard to which ψ value should be used as an irrigation threshold (IT). Similarly, little information is generally provided regarding the optimal duration of each irrigation event. From a field experiment in a sandy loam presenting a significant proportion of coarse particles ($\oslash$ > 2 mm), Bergeron (2010) noted an increase in WUE that did not affect yield when the IT was −18 kPa. For strawberry grown in a sandy loam under a high tunnel, greater yields were obtained when an IT of −10 kPa was used than when a drier regime of −70 kPa was used (Guimerà et al., 1995; Peñuelas et al., 1992). Under similar soil and production conditions, significant yield and fruit quality decreases were observed for ITs of −30, −50 and −70 kPa relative to an IT of −10 kPa, and the highest WUE was obtained when using an IT of −50 kPa. In the same study, the yields from all of the treatments were 150–250% greater than the average yields from growers in the area (Serrano et al., 1992). Based on field experiments, a similar trend was observed in sand with an optimal yield at an IT of −15 kPa and a better WUE at −30 kPa (Hoppula and Salo, 2007). In addition, irrigation regimes were shown to affect fruit quality during greenhouse production. Deficit irrigation was shown to increase the sugar/acid ratios, antioxidant capacity and total phenolic contents of strawberries (Giné Bordonaba and Terry, 2010; Terry et al., 2007).

Nonetheless, not all studies support the previously mentioned benefits of ψ-based irrigation management. After conducting field experiments during three production seasons, Krüger et al. (1999) concluded that ET-based management showed a greater potential for improving yield and WUE, mainly due to economical and practical reasons. However, only one ψ-based irrigation treatment was tested, and irrigation scheduling was based on bi-weekly measurements. Problems with regards to probes locations in the field were also reported. In a bell pepper production experiment, it was shown that the soil matric potential presented large spatial and temporal variability and that several tensiometers were necessary for obtaining representative values for a given field. (Hendrickx and Wierenga, 1990; Hendrickx et al., 1994).

Some of the previously mentioned studies were conducted in greenhouses or tunnels and others in fields. Additionally, the tensiometers installation depths, matric potential measurement frequencies and treatment application procedures varied between studies. Considering this, the optimal IT for given soil and climatic conditions is not obvious. The aim of this study is to determine optimal matric potential based IT for field strawberry production with regards to yield and WUE for a variety of soil type and climatic conditions.

2. Material and methods

2.1. Site descriptions

From 2010 to 2013, field-scale strawberry production experiments were conducted at four commercial sites that were chosen to cover a wide range of soil properties and climatic conditions. The site locations, soil types, climatic conditions and cultural practices are provided in Table 1. Generally, the experimental sites can be classified into two main groups. Group A includes Sites 1 and 2, which are located near Quebec City (Qc, Can) in an area with a humid continental (Dfb) climate where the growing season is short and generally rainy. The historical mean water budget (Precipitation – ETc) of the area is positive during the growing season, but the use of polyethylene mulches make supplemental irrigation necessary, especially in July and August. At these sites, irrigation water is provided by private reservoirs that are filled by snowmelt and rainwater. Thus, the irrigation water is free and usually available in sufficient volumes throughout the growing season. The day neutral "Seascape" cultivar was planted in mid-May and harvested from mid-July to early October, with a production peak in September. Group A sites were located near each other and their soils were very similar. However, Site 1 was a former pasture where strawberries were grown for the first time, and Site 2 had been cultivated in rotation with strawberries, sweet potatoes and oats for many years. Thus, the soil from Site 1 was expected to have hydraulic properties and nutrient element contents that were more favorable for plant growth than Site 2.

Group B includes Sites 3 and 4, which are located near Oxnard and Watsonville in the southern and northern parts of California (USA), respectively. Both areas have Mediterranean or dry subtropical (Cs) climates. At Site 3, a commercial short-day cultivar was planted in October and produced from February to June. At Site 4, locally developed commercial day neutral cultivars were planted in November, were slowly established during the winter, and produced berries from April to mid-October. Both of these sites were near the Pacific Ocean and were characterized by foggy mornings and clear afternoons. Furthermore, most of the precipitation in this region occurred between December and mid-March. Consequently, most of the production period was rain free.

2.2. Experimental setup

At each site, a typical management zone (i.e. a zone that was irrigated independently from the rest of the farm) was selected as the experimental area. That zone was divided in 3–7 blocs where two

Table 1
General descriptions of the experimental sites.

Site	Location (lat,long)	Growing season	Reference period	Soil type	Climate	Rainfall[a] (mm)	Cultural Practices	Irrigation system specifications
1	Quebec city, Qc, CAN (46.90°,−70.94°)	May–October 2011	August–October 2011	Silty clay loam	humid continental (Dfb)	280	2 plant rows per bed; 1 drip line per bed	lateral : 1.6 cm lateral depth: 3 cm emitter spacing: 20 cm emitter flow rate: 0.5 ph
2	Quebec city, Qc, CAN (46.92°,−70.96°)	May–October 2011	August–October 2011	Clay loam	humid continental (Dfb)	280	2 plant rows per bed; 1 drip line per bed	lateral : 1.6 cm lateral depth: 3 cm emitter spacing: 20 cm emitter flow rate: 0.5 lph
3	Oxnard, CA, USA (34.15°,−119.15°)	October 2011–June 2012	February–June 2012	Sandy loam	Mediterranean (Cs)	97	4 plant rows per bed; 3 drip lines per bed; sprinklers in early stages	lateral : 1.6 cm lateral depth: 5 cm emitter spacing: 20 cm emitter flow rate: 0.34 lph
4	Watsonville, CA, USA (36.89°,−122.67°)	November 2012–October 2013	April–October 2013	Clay loam	Mediterranean (Cs)	24	2 plant rows per bed; 2 drip lines per bed; sprinklers in early stages	lateral : 1.6 cm lateral depth: soil surface emitter spacing: 20 cm emitter flow rate: 0.5 lph

[a] Data for the reference period only.

Table 2
Plot size, experimental design, yield measurement specificities and applied treatments on the experimental sites.

Site	Total site area (ha)	Bed length/width (m)	Beds per plot	Design	Harvest measurement frequency	Harvest measurement area	Plants per sub-plot	Applied treatments
1	1.4	142/0.9	4	RCBD 6 replicates	Bi-weekly	Total plot area	NA	*IT10*: −10 kPa *IT18*: −18 kPa *Control*: variable IT
2	1.8	160/0.9	4	RCBD 7 replicates	Bi-weekly	Total plot area	NA	*IT10*: −10 kPa *IT18*: −18 kPa *Control*: variable IT
3	0.7	130/1.22	3	RCBD 3 replicates	Weekly	Sub-plots only	24	*IT8*: −8 kPa *IT11*: −11 kPa *IT13*: −13 kPa
4	0.28	32/0.8	2	RCBD 4 replicates	Weekly	Sub-plots only	20	*IT10*: −10 kPa *IT17*: −17 kPa *IT25*: −25 kPa *Control*: variable IT

to three IT treatments based on ψ measurements were assigned in a randomized complete bloc design (Table 2). At Sites 1, 2 and 4, a control treatment consisting of the common irrigation management techniques used by local producers was also included in the experimental setup. In all cases, the supply line(s) for the drip irrigation laterals was(were) modified to allow for the independent management of each treatment. A typical setup from this study is schematically represented in Fig. 1. More site-specific details regarding the experimental setup are provided in Table 2.

2.3. Irrigation system specifications

At all sites, the types of drip laterals used (diameter, emitter spacing, flow rate) and their configurations (nb of laterals per bed, depth of installation) were determined by the producer and were the same as those used on the rest of their farms. Site-specific details are provided in Table 1. For Group A sites, only drip irrigation was used for all growing stages. For Group B sites, overhead sprinkler irrigation was used during plant establishment. During that period, experimental plots were irrigated simultaneously according to the producers' usual practices. Treatment application began after the plant establishment stage, when only SDI was used to provide water.

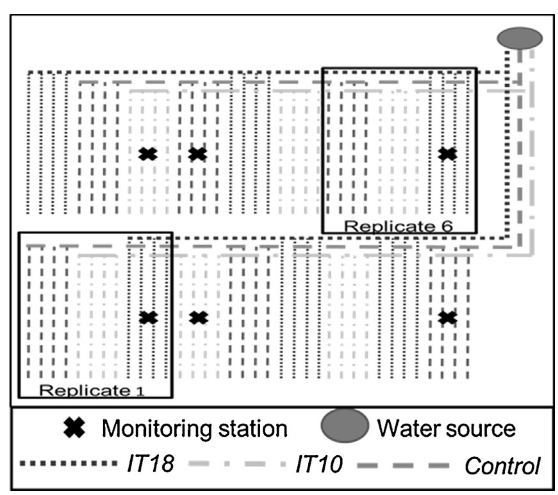

Fig. 1. Typical setup of the drip irrigation system at the experimental sites (Site 1 in this example).Thicker lines represent principal and secondary conduits and thin lines represent drip laterals.

2.4. Soil matric potential measurements

The soil matric potential was measured similarly at all the experimental sites. For all treatments, a ψ monitoring station was installed at mid-length in one (Group B) or two (Group A) replicates. Each monitoring station consisted of two tensiometers buried at two depths. The tensiometers were connected to a wireless transmitter (Hortau, St-Romuald, QC, CAN) to allow for real-time monitoring of ψ. A shallow probe was installed at a depth of 15 cm, where most strawberry roots are found (Bergeron, 2010). Horizontally, this shallow probe was located within a radius of 5–10 cm from a drip emitter. The aim was to place the probe in the active root zone and on the outer edge of the wetted bulb from the emitter. This position was used because it allowed monitoring the effects of root uptake and water application on ψ. A deep probe was installed at a depth of 30 cm, or 3 cm above any impermeable rock layer located at a shallower depth. Rock layers were present at three stations at Site 1 and two stations at Site 2 (out of 6 stations in both cases). Horizontally, the deep probe was located directly under a drip emitter to monitor the matric potential under the root zone (>90% of the roots are usually located within the top 30 cm), which is the area most likely affected by excessive irrigation.

2.5. Spatial variability of the matric potential

At Site 3, two manual reading tensiometers were installed at a depth of 15 cm in all of the experimental plots in early May. Thus, 6 probes were randomly distributed across the experimental area for each treatment. For each treatment, 6 measurement runs were performed from May 15 to June 15 to compare the ψ values obtained from the manual tensiometers with those obtained from the shallow probes of the monitoring stations. For each treatment and measurement run, Student's *t*-test with a 0.05 significance level was performed to test the null hypothesis that the average value from the manual probes did not differ from the value measured at the monitoring station.

2.6. Application of the irrigation treatments

The application of the experimental treatment was the same at all the experimental sites. For the IT treatments, irrigation was simultaneously triggered in all replicates of a treatment when a predetermined IT was reached by the shallow probe(s) from the monitoring station(s) associated with the treatment. When two monitoring stations were associated with a single treatment (Group A sites), irrigation was triggered when the average of the two shallow probes reached the IT. The ITs were chosen as a function of soil type or, in the case of Sites 1 and 2, previous experiments conducted on similar soils (Bergeron, 2010) and are presented in Table 2. The Control treatments consisted of the common irrigation management used by local producers. Irrigation of the *Control* plots was controlled by each site's producer without interference from the experimenters, but *Control* plots were still equipped with monitoring stations. For Group A sites, the common irrigation management method consisted of daily irrigation planning based on basic weather reports and irrigation logs from previous days. For Group B sites, the common practice was to apply approximately 100% of the historical average ETc via two or three weekly irrigation events on predefined days.

2.7. Adjustment of irrigation duration

For the IT treatments, the duration of each irrigation event was initially the same as that used in the *Control* treatments. For the *Control* treatments, the irrigation duration remained constant throughout the growing season. For the IT treatments, the irrigation duration was adjusted as follows. Shortly after planting, while the root uptake in the deeper parts of the bed was null, the ψ value at which the risk of rapid gravitational leaching under the bed was considered minimal was estimated using data from the deep probes of the monitoring stations. A typical example of changes in ψ at a depth of 30 cm following an early season irrigation is presented in Fig. 2. It shows that ψ at a depth of 30 cm sharply increases as the water content approaches saturation within minutes (Group A) or hours (Group B) after an infiltration (in this case irrigation) event. Then, if rapid gravitational leaching occurs, ψ rapidly (within 3 to 4 h) returns to a lower value. Next, a transition period between gravitational and capillary water flows usually occurs. Subsequently, after 16–48 h (depending on the site), water movements or changes in ψ are much slower and mainly result from capillary water redistribution. For the remainder of this study, ψ at the beginning of the capillary redistribution phase (Fig. 2) is referred to as the «bed capacity». This concept is similar to that of field capacity but more adapted to drip-irrigated raised beds, where the wetted bulb has a finite size (similarly to infiltration from an infiltrometer (Reynolds and Elrick, 1990)) and is not necessarily in hydraulic contact with the subsoil and water table. Drip irrigated raised beds generally reach their own equilibrium at ψ values that are much higher than those expected in a standard flat soil (−33 kPa). In this study, it was assumed that the risk of gravitational leaching was minimal at ψ values below the bed capacity. Using a trial and error process that generally required 1–2 weeks depending on the irrigation frequency, the irrigation duration was adjusted so that the bed capacity was not exceeded following irrigation unless leaching was desired to control the salinity in the root zone. Monitoring of the ψ data following irrigation was continued throughout the season, and the irrigation duration was adjusted if necessary. Because the bed capacities observed at all of the sites varied between −2 and −3 kPa, a target post-irrigation value of −3 kPa was used for all of the experimental sites considered in this study.

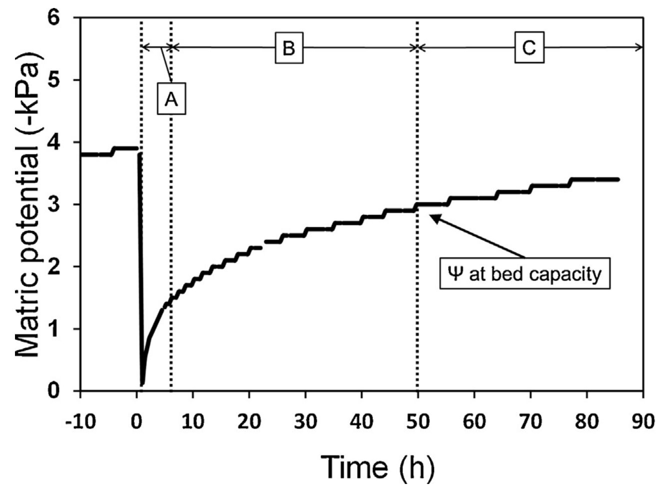

Fig. 2. Example of changes in the matric potential under the root zone (30cm depth) following an irrigation event. Irrigation initiation occurred at $t = 0$ h. A is the gravitational flow period, B is the transient flow period and C is the capillary redistribution period.

2.8. Cultural operations

All other cultural operations (pest, disease and weed management, flower and runner pruning and general maintenance) were executed similarly in all plots by the producers. Fertilizers were applied to the crops through injection into the drip irrigation system. Their type and quantity were controlled by the producer and were identical in all treatments. At Sites 1 and 2, the producer applied fertilizers to all plots simultaneously according to his usual fertilization schedule, regardless of the matric potential measured in the plots. At Sites 3 and 4, the *Control* treatments were fertilized regardless of the matric potential. However, for the IT treatments, fertilizers were only applied when the IT was reached. Thus, the timing of their application sometimes differed from 1 to 5 days among the treatments.

2.9. Reference period for measurements and data analysis

For evident reasons, yield and fruit quality data were available only during the harvest period while water use, soil matric potential and climatic data were available for the entire growing season. In order to compare the influence of the experimental treatments on all variables of interest in this study, site-specific reference periods were established depending on data availability (Table 1). Consequently, all of the results presented in the remainder of this study regarding yield, fruit quality, applied water volumes, irrigation frequency and duration, achieved ITs and average ψ values (Table 3) only consider data obtained during that period. For Group A sites, the reference period was from August 1st to October 1st, 2011. At these sites, the harvest period began on July 10th, but the reference period was shortened because data regarding the applied water volumes were unavailable before August because of a water totalizer malfunction. At Sites 3 and 4, the reference periods were from February 15th, 2012 to June 15th, 2012 and from April 1st, 2013 to October 15th, 2013 respectively.

2.10. Marketable yield, fruit quality and plant growth parameters

At the Group A sites, marketable yields from the total plot area were collected on a bi-weekly basis and four fruit subsamples per plot were used to measure the average fruit size and fruit soluble solid content (Brix index) using a refractometer. At the Group B sites, the same information was gathered from 2 weekly harvested sub-plots per each experimental plot. At the latter sites, 2–5 plants per sub-plot were selected to obtain weekly measurements of crown diameter and canopy coverage area. More information on the configuration of sub-plots is provided in Table 2. The plots at the Group B sites were normally harvested several hours before commercial fruit harvest. On some occasions, coordination problems between the harvest crew and the research team occurred and the fruits were collected without sorting according to the experimental treatments. Hence, the cumulative marketable yield at these sites represented only a fraction of the total yield for the reference period.

2.11. Irrigation parameters

At all sites, a water totalizer was installed on the supply line for the drip laterals associated with each treatment and the applied irrigation water volume was measured weekly during the reference period. WUE was calculated by dividing the marketable yields by the volume of applied water. An irrigation log was used to keep track of the frequency and duration of the irrigation events and the ψ measured at a depth of 15 cm at irrigation initiation was used to calculate the average ITs achieved for the reference period. The reference ET (ET_o) was calculated using climatic data from an on-site or nearby weather station and the FAO modified Pennman–Montheith equation and converted to crop ET (ET_c) by using appropriate crop coefficients according to canopy coverage (Grattan et al., 1998) and/or the number of days after planting (Hanson and Bendixon, 2004).

2.12. Soil physical properties

Conventional loose soil samples and undisturbed core samples were collected at depths of 15 and 30 cm from the growing beds during the first weeks following planting. Conventional samples were used to measure the soil texture using the hydrometer

Table 3
Average thresholds, marketable yield, fruit quality and water use efficiency results from the different experimental sites, where ψ is the soil matric potential and WUE is the water use efficiency.

Site	Intended IT (treatment) (−kPa)	Avg achieved IT (−kPa)	Avg ψ 15 cm (−kPa)	Avg ψ 30 cm (−kPa)	Marketable yield[a] ($kg\,ha^{-1}$)	ETc (mm)	Applied irrig. water (mm)	Nb of irrig	Avg irrig. duration (min)	Irrig. freq (d)	WUE ($kg_{fruit}\,m^{-3}{}_{water}$)	Fruit size (g per fruit)	Sugar content (Brix index) (%)
1	*IT10*	13.3 ± 7.5	7.3	6.4	10687.9 ± 869.6 a	135.2	29	19	41	2.7	36.3	15.8 ± 0.5 a	8.8 ± 0.4 a
	IT18	14.9 ± 4.9	6.1	7.9	10518.3 ± 510.9 a		13	9	44	5.8	84.4	15.3 ± 0.7 a	8.8 ± 0.2 a
	Control	24.7 ± 6.8	10	7.2	**9981.1 ± 1151.6 b**		13	6	60	8.7	79.8	15.3 ± 0.7 a	8.8 ± 0.2 a
2	*IT10*	12.9 ± 8.6	5.0	4.5	12305.9 ± 1623.4 a	135.2	37	20	40	2.9	32.9	14.2 ± 0.8 a	8.2 ± 0.3 a
	IT18	18.0 ± 7.5	6.8	5.0	11492.9 ± 2087.2 a		29	15	42	3.8	41.5	14.4 ± 0.7 a	8.4 ± 0.3 a
	Control	13.5 ± 10.3	6.1	3.3	12127.9 ± 1168.8 a		16	14	60	4.0	69.9	14.4 ± 0.7 a	8.3 ± 0.2 a
3	*IT8*	8.1 ± 2.2	5.5	4.7	**48989.5±5473.4 a**	257	277	60	58	2.2	17.7	30.7 ± 0.3 a	8.1 ± 0.1 a
	IT11	12.5 ± 5.8	7.9	7.5	41898.0 ± 6359.7 b		248	49	76	2.7	16.9	31.1 ± 1.0 a	7.9 ± 0.3 a
	IT13	15.2 ± 8.5	8.1	10	41874.3 ± 4943.6 b		247	42	77	3.2	17.0	30.6 ± 0.6 a	8.2 ± 0.2 a
4	*IT10*	10.1 ± 1.1	7.2	6.6	36352.3 ± 4971.2 a	392	412	88	43	2.2	8.8	20.9 ± 0.8 a	10.3 ± 0.4 a
	IT17	18.5 ± 3.8	10.1	9.8	**29799.3 ± 4791.4 b**		367	71	49	2.8	8.1	21.0 ± 0.6 a	10.2 ± 0.4 a
	IT25	26.4 ± 3.9	14.7	15.4	**30452.9 ± 4909.0 b**		298	52	53	3.8	10.2	20.1 ± 0.8 a	10.4 ± 0.3 a
	Control	7.9 ± 3.1	5.5	3.8	35780.2 ± 5194.8 a		542	62	~75[b]	3.2	6.6	21.2 ± 0.4 a	10.3 ± 0.7 a

Note: The treatments with the same letter do not differ at the 0.05 significance level.
[a] For clarity, the cumulative marketable yield during the reference period for each site is presented here, but the statistical analyses were conducted on individual harvests throughout the season with a repeated measure mixed model. At all Sites, the interaction term between harvest dates and yield was not significant at the 0.05 significance level.
[b] From personal communication with the producer, this is an approximation since the producer did not keep track of irrigation durations in his irrigation log.

method (Gee and Or, 2002a) [Sites 1 and 2] or the laser light scattering method (Gee and Or, 2002b) [Sites 3 and 4]. In addition, the soil electrical conductivity was determined using the 1:1 saturated soil paste extract method (Rhoades, 1982). Core samples were used to measure the saturated hydraulic conductivity (K_{sat}) using the constant head method (Reynolds et al., 2002). Desorption water retention curves were obtained from core samples with suction tables and pressure plate extractors (Dane and Hopmans, 2002a; Romano et al., 2002) for Sites 1 and 2 and with pressure cells (Dane and Hopmans, 2002b) for Sites 3 and 4. The soil bulk density was determined by oven drying and weighing the core samples. For the Group A sites, samples were collected from 27 locations across a regularly spaced grid to assess the spatial variability of the soil properties by using basic (experimental variogram only) geostatistical analysis (Yates and Warrick, 2002). For the Group B, samples were collected at 2–3 locations per plot for a total of 12 and 15 samples at Sites 3 and 4 respectively.

2.13. Soil salinity measurements

At all sites, weekly measurements of the electrical conductivity and pH of the soil solution were performed on samples extracted using suction lysimeters to insure that they did not exceed the recommended values for strawberry production (Barroso and Alvarez, 1997). For the same purpose, soil samples were collected monthly at a depth of 15 cm in all plots to measure the soil electrical conductivity by using the 1:1 saturated paste extraction method (Rhoades, 1982).

2.14. Statistical analysis

To statistically analyze the yield, fruit size and soluble solid content, an analysis of variance test was performed using a linear mixed-effects repeated measures model with the *nlme* package in R (Pinheiro et al., 2013). The main effect contrasts were determined using the *multcomp* package (Hothorn et al., 2008), and a 0.05 significance level was used in all tests. For the Group B sites, the yield data from the first harvest were discarded from the statistical analyses because not all of the plants began producing fruit simultaneously and because early variability results from uncontrollable differences in plant size and vigor that were present at the moment of planting or occurred due to the adequacy of the planting technique (crown depth, root damage).

3. Results and discussion

3.1. Site 1: Soil matric potential

Abundant and frequent precipitations, soil water retention properties and fertigation events conducted by the producer made the achievement of the intended IT difficult at Site 1. Hence, the applied treatments did not result in major differences in the soil matric potential during the reference period (Fig. 3). For *IT10* and *IT18*, the average achieved ITs were −13.3 and −14.9 kPa rather than the intended −10 and −18 kPa, respectively. The average ψ values at both measurement depths were also similar between the IT treatments. *IT10* was in fact maintained in slightly dryer conditions than *IT18* at a 15 cm depth, but it was maintained slightly wetter at a 30 cm depth (Table 3). For the *Control* treatment, the (unintended) achieved IT was −24.7 kPa and the average ψ at a depth of 15 cm was 2.7–3.9 kPa lower than for *IT10* and *IT18*, respectively (Table 3). The failure to obtain the intended IT for *IT10* can be explained by the water retention curve of this soil (Fig. 4). Similarly to coarse sand, the water retention curve presents a sharp decrease in water content in the wet part of the curve (0 to −5 kPa). However, similar to clay, the water content decreases very slowly when

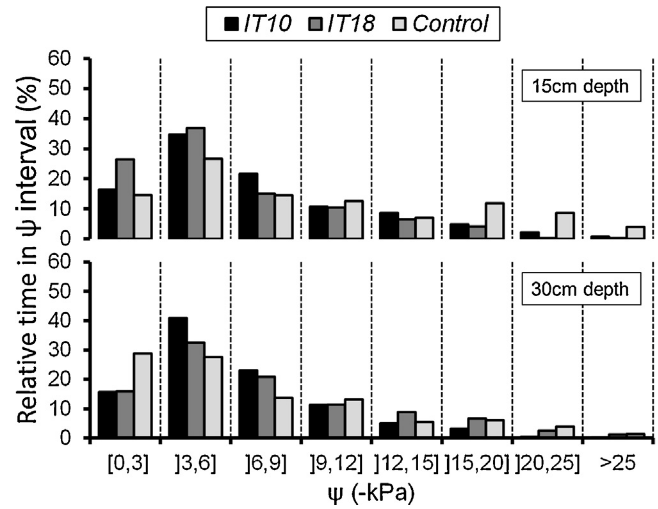

Fig. 3. Relative time spent within the different matric potential ranges during the reference period of the experiment at Site 1.

ψ is less than −6 or −8 kPa. Consequently, ψ in this soil decreases rapidly above values of −6 to −8 kPa. This allows little intervention time for initiating irrigation before the threshold is exceeded. For *IT18*, fertigation events conducted by the grower before the IT was reached explain why the achieved IT was higher than intended.

3.2. Site 1: Yield and fruit quality

Even if not perfectly achieved, the application of the irrigation treatments resulted in a significant increase in the marketable yield of 6.2% for *IT10* and *IT18* relative to *Control* ($p = 0.01354$). However, *IT10* and *IT18* did not significantly differ from one another (Table 3). The statistical analysis also showed that the interaction term between harvest date and yield was not significant ($p = 0.3029$). Hence the yield increase achieved with both IT treatments relative to *Control* remained constant during the reference period. No significant difference in fruit quality or size was observed between any of the treatments (Table 3). Therefore, the yield improvements obtained with the IT treatments were due to differences in the number of fruits produced by the plants.

The results regarding the influence of the treatments on ψ and on yield can be used to estimate the optimal IT range for this Site. Fig. 3 shows differences between *IT10* and *IT18* with regards to the relative time spent with ψ at a 15 cm depth in the [0,−3], and [−6, −9] kPa ranges. It is particularly clear that *IT18* was maintained above

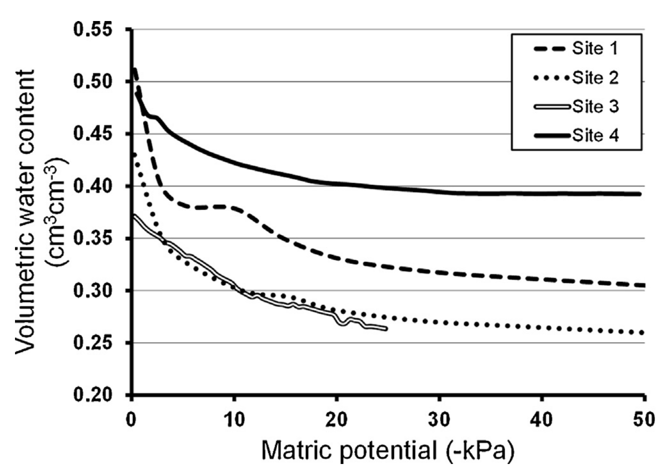

Fig. 4. Average water retention curve from the four experimental sites.

−3 kPa for longer durations than *IT10*. However, the same yields were achieved with both IT treatments. This suggests that maintaining the bed under wet conditions (>−3 kPa) do not improve fruit production. Fig. 3 also shows that ψ in all treatments was between −9 and −15 kPa for similar durations; and that the relative time in the [−15, −20] kPa range was 163% more important for *Control* than for the IT treatments. Hence, the hydric stress that reduced yield for *Control* potentially occurred when ψ was lower than −15 kPa. If only yields were to be considered, −15 kPa would thus be an adequate IT at this site.

3.3. Site 1: Water use efficiency

Regarding water application, the *IT18* and *Control* treatments required similar volumes of water, whereas the *IT10* treatment resulted in a 136% increase in water application relative to the other two treatments (Table 3). The *IT10*, *IT18* and *Control* plots were irrigated 19, 9 and 6 times during the reference period, and the average irrigation durations were 40, 48 and 60 min, respectively. Hence, even when not perfectly achieved, the intended ITs and the irrigation duration adjustment procedure had notable impacts on the applied water volume and on the irrigation frequency and duration. The WUE was better in the *IT18* and *Control* treatments despite significant total yield decrease associated with the latest. By definition, WUE is related to yield and applied water volumes only. In this case, it does not account for any increased application efficiency in *IT18* relative to the *Control*. This increase in efficiency occurred because monitoring the matric potential under the root zone most likely prevented excessive leaching. This is supported by the fact that ψ at a depth of 30 cm was more frequently within the [0, −3] kPa range (above bed capacity) in *Control* than in *IT18* (Fig. 3). This indicates that gravitational leaching was most likely more frequent in *Control* than in *IT18*. *IT18* was only irrigated on 3 more occasions than *Control*, and the same total amount of water was applied in both treatments, which demonstrates the critical issue of irrigation timing. The additional water applied to *IT10* relative to *IT18* did not affect yield but substantially reduced the WUE. Despite being classified as a silty clay loam, the soil from Site 1 had a an important proportion of rock fragments and a low bulk density. In agreement with the previously discussed water retention properties this suggests that macropores represent an important part of this soil's poral network, resulting in a drainage capacity much better than expected for a silty clay loam. In these conditions, it is likely that the excess water did not generate anoxic conditions that could be detrimental to the plants. In summary, the results from this site suggest that an IT of approximately −15 kPa could optimize strawberry yield and WUE (Fig. 5). This result is consistent with the optimal values reported for a sandy soil with a high organic matter content (Hoppula and Salo, 2007) and with the values reported by Bergeron (2010) for a nearby field.

3.4. Site 2: Soil matric potential, yield and fruit quality

At Site 2, the intended and achieved irrigation thresholds agreed well. Nonetheless, the average ψ values at both measurement depths were very similar for all treatments (Table 3), and the differences between the treatments with respect to the relative time spent in different ψ ranges were minimal (Fig. 6). Statistical analysis of the yield data indicated no significant difference between the treatments, but orthogonalcontrasts revealed that the 6.6% yield increased achieved with *IT10* relative to *IT18* was nearly significant ($p = 0.0561$). Fig. 6 shows that *IT10* spent half as much time as *IT18* in the [−9, −12] kPa range. In addition, ψ was maintained lower than −15 kPa over similar durations in both treatments. This result suggests that a yield-affecting hydric stress could occur between −9 and −12 kPa. However, since the yields were not significantly different, additional experiments are needed to confirm this finding. Again, no differences in fruit sugar content or size were observed among any of the treatments (Table 3).

Observations subsequently made on Sites 3 and 4 could explain the absence of significant differences at Site 2. At Sites 3 and 4, it was observed that the yields rapidly decreased when a certain IT was exceeded (Fig. 5). For lower ITs, the effects of a decrease in IT on yield were less evident. It is possible that at Site 2, all treatments exceeded the optimal IT and were within or near the «plateau» part of the yield response curve to IT. This hypothesis is supported by unsaturated hydraulic conductivity measurements made at a nearby site during the following season, which suggested that the water transfer rate in the soil matrix might become limiting between −5 and −8 kPa on days with high evapotranspiration

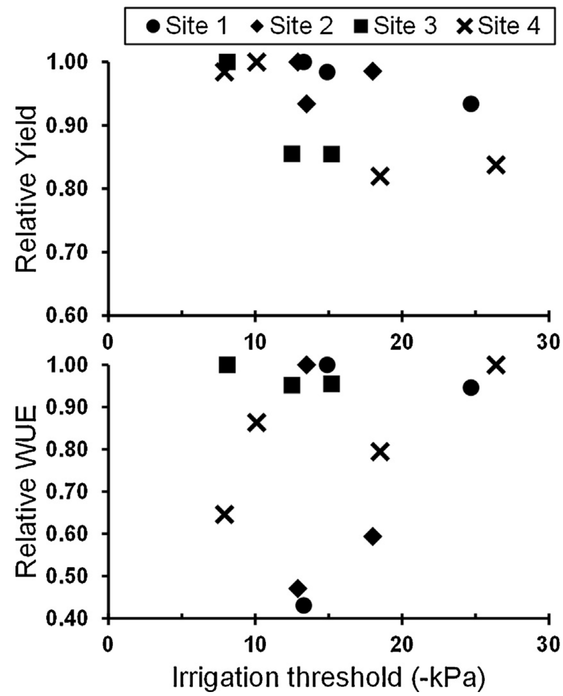

Fig. 5. Effect of the irrigation threshold on the within site relative yield (upper plot) and relative water use efficiency (lower plot) for all experimental sites.

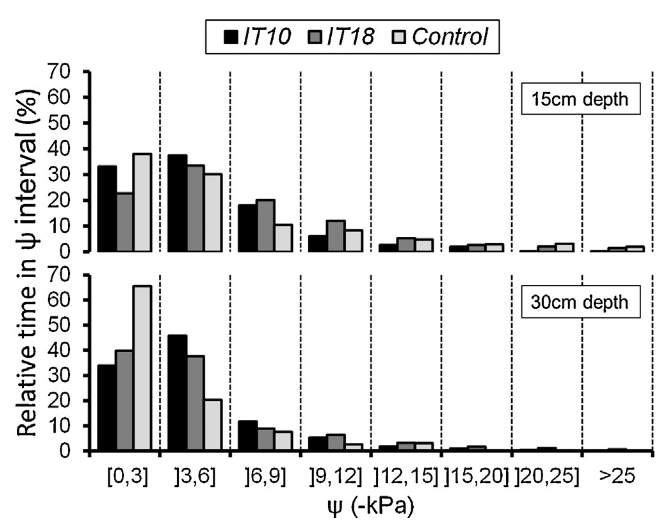

Fig. 6. Relative time spent within different matric potential ranges during the reference period of the experiment at Site 2.

Table 4
Basic physical properties of the soils from the experimental sites, where ρ_{bulk} is the soil bulk density, and K_{sat} is the hydraulic conductivity.

Site		Sand content (%)	Silt content (%)	Clay content (%)	Particle > 2 mm content (%)	Organic matter content (%)	Soil depth (cm)	ρ_{bulk} (g cm^{-3})	K_{sat} 15 cm depth (cm h^{-1})	K_{sat} 30 cm depth (cm h^{-1})
1	Avg	18.1	48.4	33.5	32.8	5.7	20–30	1.04	158.8	67.0
	CV (%)	*41.3*	*12.0*	*15.7*	*37.9*	*16.8*		*9.8*	*69.7*	*114.2*
2	Avg	28.4	44.8	26.8	NA	2.8	30–40	1.23	115.1	55.8
	CV (%)	*23.2*	*9.9*	*12.7*	*NA*	*24.2*		*8.4*	*61.1*	*148.8*
3	Avg	60.0	27.9	12.1	<1	1.2	> 100	1.53	1.3	13.1
	CV (%)	*3.0*	*7.0*	*5.1*	*NA*	*9.6*		*4.0*	*79.7*	*140.9*
4	Avg	37.6	32.5	29.9	<1	2.4	> 100	1.32	44.7	NA
	CV (%)	*7.4*	*4.6*	*6.3*	*NA*	*11.8*		*11.8*	*188.2*	*NA*

demands. However, additional experiments with higher irrigation thresholds are needed to confirm this finding.

3.5. Site 2: Water use efficiency

Relative to *Control*, *IT10* and *IT18* led to increases in applied water volume of 128% and 78% respectively. This greatly reduced their WUE (Table 3). Tensiometer-based irrigation has also been reported to increase the volume of applied water (from 47 to 267%) relative to the climatic water balance management in a similar experiment when using an IT of −20 kPa (Krüger et al., 1999). The *IT10*, *IT18* and *Control* plots were irrigated 20, 15 and 14 times during the reference period, and the average irrigation durations were 40, 42 and 60 min, respectively. The reduction of irrigation durations for both IT treatments relative to *Control* most likely reduced the fraction of the applied water that was leached under the root zone. Three phenomena could explain the poor WUE of tension-based irrigation in this case. First, the water application method was likely inadequate for the soil type. Although the soil at Site 2 was classified as a silty clay loam, it presented saturated hydraulic conductivity values (Table 4) and water retention properties (Fig. 4) that were similar to those of coarse sand. Consequently, the downward movement of water was very fast, with minimal lateral water movement. Thus, most of the applied water was rapidly leached to the soil below the root zone and became unavailable to plants, which would explain the limited effects of irrigation.

Second, it is possible that the abundant precipitation during the reference period, combined with the presence of a water-movement-restricting layer under the monitored depth of 30 cm, allowed the soil to maintain a sufficient water reserve for the plants. During the reference period, the strawberry plants most likely had a root system that reached 30 cm and could benefit from such a reserve. This hypothesis is supported by the observation that the matric potential at a depth of 30 cm was maintained near bed capacity during most of August and September. Because of the plastic mulches over the beds, rainwater does not significantly affect the matric potential at 15 cm and the poor capillary rise capacity of the soil from Site 2 does not favor recharge from the bottom soil layers. It is possible that although sufficient water for root uptake was available at greater depths, the matric potential at 15 cm continued to decrease, which triggered irrigation.

Finally, the short scale spatial variability of soil properties could explain the absence of a yield response to irrigation regimes. Even if the variographic analysis showed no spatial structure at the investigated measurement scale at the site (data not shown), the coefficients of variation of the soil properties (Table 4), especially the sand and organic matter contents, were important. This most likely influenced the response of the matric potential to irrigation and root uptake. For the IT treatments, irrigation was triggered based on the average ψ value obtained from two monitoring stations. However, at the time of irrigation initiation, substantial discrepancies were often observed between ψ measurements from the two stations for both *IT10* (Fig. 7) and *IT18* (not shown). None

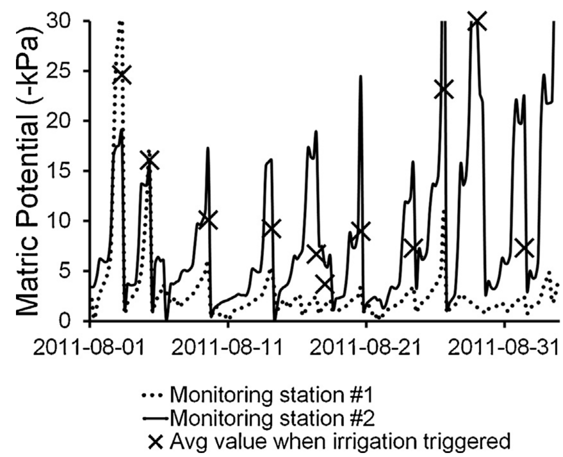

Fig. 7. Example of the differences between the averaged matric potential used to trigger irrigation and the values from the two monitoring stations for IT10 at Site 2 during the month of August.

of the soil properties measured near the monitoring stations justified such a difference in hydraulic behavior. However, it is possible that coarse particles (> 2 mm), such as schist fragments, were located near some of the tensiometers. In such cases, rapid drainage would be favored as the water retention capacity decreased, which would require more frequent irrigation. Variographic analysis of the proportion of coarse particles at a nearby site (Letourneau 2015, unpublished) indicated a significant nugget effect and no spatial structure at any scale. Hence, random effects of coarse particles potentially altered the effects of the applied treatments.

3.6. Site 3: Spatial variability of the matric potential

Table 5 compares the mean ψ values from the manual tensiometers that were spread across the experimental site with the values obtained from the monitoring station. It also presents the results from the Student t-tests that were performed to verify if they were significantly different. Out of 18 data sets, the measurements with both methods were significantly different on only two occasions. In more than 50% of the cases, the differences between the matric potentials were less than 1 kPa. In addition, these comparisons were performed by the end of the season when the effects of variability were likely highest because plant development and root uptake would have been affected by the differences in soil water status for 7 months. At the scale of this experiment (i.e. for an area of 0.25 ha per treatment), tension measurements from a single monitoring station in one replicate were representative of observations in all 3 replicates. In this case, the soil from this site was very uniform, as shown by the low coefficients of variation of most of the soil properties (Table 4). More experiments would be required to determine the number of monitoring stations required for larger plots or for less uniform soils.

Table 5
Results from the Student t-test procedure used to compare the matric potential observations from the monitoring station and the mean value from the manual tensiometers, where ψ is the matric potential at 15 cm.

Measurement run	*IT8*				*IT11*				*IT13*			
	ψ Monitoring station (−kPa)	Avg ψ manual probes (−kPa)	Degrees of freedom	*p* Value of *t*-test	ψ Monitoring station (−kPa)	Avg ψ manual probes (−kPa)	Degrees of freedom	*p* Value of *t*-test	ψ Monitoring station (−kPa)	Avg ψ manual probes (−kPa)	Degrees of freedom	*p* Value of *t*-test
1	5.2	4.3 ± 2.6	5	0.4429	7.8	6.2 ± 0.8	3	**0.0289***	6.6	6.2 ± 4.0	3	0.8453
2	7.6	7.1 ± 1.8	4	0.5921	12.6	9.6 ± 4.5	3	0.2690	9.7	10.7 ± 4.9	3	0.7222
3	5.9	5.4 ± 3.0	5	0.7172	6.9	6.3 ± 1.4	3	0.4632	4.6	7.7 ± 3.5	3	0.1790
4	7.0	2.9 ± 1.3	4	**0.0021***	8.8	6.9 ± 1.3	2	0.1169	7.0	6.4 ± 3.5	4	0.7013
5	4.5	3.6 ± 1.6	5	0.2099	7.9	5.2 ± 2.4	3	0.1041	9.3	11.9 ± 4.5	3	0.3368
6	5.0	4.6 ± 1.0	4	0.3936	5.7	4.0 ± 1.8	4	0.1013	10.7	10.7 ± 7.4	4	0.995

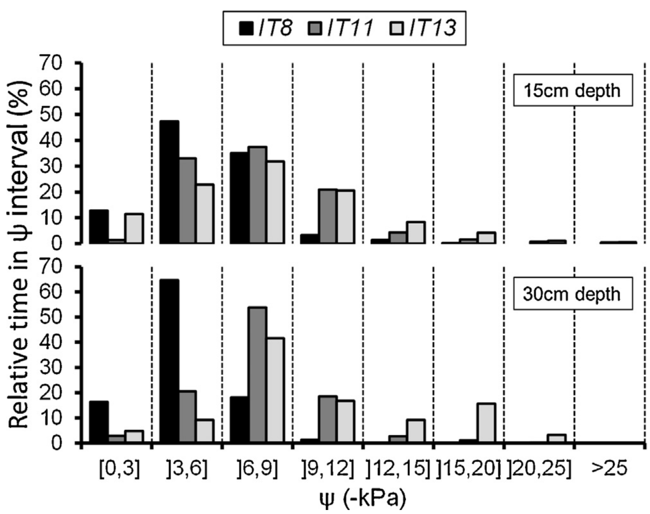

Fig. 8. Relative time spent within different matric potential ranges during the reference period of the experiment at Site 3.

3.7. Site 3: Soil matric potential

Except for the end of the production season, when ETo reached values of up to 6 mmd^{-1} and the ITs were occasionally exceeded for all treatments, the agreement between the intended and achieved ITs was good (Table 3). As shown in Fig. 8, *IT8* was maintained at a ψ above −9 kPa at both measurement depths during 95% of the reference period. Respectively, *IT11* and *IT13* remained above −9 kPa for 72 and 66% of the reference period. Both *IT11* and *IT13* spent equivalent amounts of time between −9 and −12 kPa at both depths. As shown by the average ψ values at both depths (Table 3) and in Fig. 8, the most noticeable difference between *IT11* and *IT13* was that the latter was maintained in drier conditions at a depth of 30 cm. A greater difference in IT between *IT11* and *IT13* would likely be required to induce notable differences regarding the amount of time spent in different ψ ranges. Overall, it was not very practical to achieve a separation of only 2 kPa without using an automated irrigation system.

3.8. Site 3: Yield and fruit quality

With respect to the marketable yield, orthogonal contrasts indicated that *IT*8 resulted in a significant ($p = 0.0434$) 17% marketable yield increase relative to *IT*11 and *IT*13 (Table 3). This difference in yield roughly corresponded to the amount of time spent within the [−9, −12] kPa range at both depths for *IT11* and *IT13* (19%), which suggested that irreversible yield-affecting stress principally occurs within this range. No differences between the treatments regarding the fruit sugar content and size were observed. Thus, yield differences were attributable to a difference in the fruit number. As for Site 1, the interaction term between harvest date and yield was not significant ($p = 0.6473$). Hence the difference in yield between *IT8* and the other treatments remained constant during the reference period. These results are consistent with previous studies. Optimal yield was obtained with an IT of −10 kPa for production under high-tunnel in a similar soil (Guimerà et al., 1995). Regular EC measurements from soil saturated paste extracts and suction lysimeter samples showed that soil salinity remained at similar levels for all treatments and did not reach values that could have affected plant growth. For all treatments, SAR was less than 2.0, which is much lower than the critical value (6.0) for berry production. This result differed according to the position within the growing bed, which was expected in a drip irrigation context (Hanson and Bendixon, 2004) but not between treatments. Knowing that the same fertilization method was applied to all treatments and that the salinity most likely did not affect the yields, we can confidently assert that the yield differences between the treatments mostly resulted from water availability.

3.9. Site 3: Water use efficiency

The application of water to *IT*11 and *IT*13 agreed well with the calculated ETc for the reference period (257 mm), while *IT*8 required the application of 7.4% more water than ETc (Table 3). The WUE of *IT8* was better than the WUEs in the other treatments because the yield increase was greater. Regarding the irrigation frequency and duration, irrigation was required on average every 2.2, 2.7 and 3.2 days for durations of 58, 76 and 77 min for *IT*8, *IT*11 and *IT*13, respectively. Such a difference in yield with an irrigation frequency difference of less than one day shows that daily measurements are not sufficient for optimizing strawberry irrigation management, regardless of the criterion used (climatic-, soil- or plant-based measurements). This finding is consistent with reports from Jones (2004) that real-time or hourly measurements are required for optimal irrigation scheduling. Fig. 8 shows that *IT8* was maintained between 0 and −3 kPa at a depth of 30 cm for 16% of the reference period, which is 4 times more than *IT11* and IT13. In this case, more leaching likely occurred under the root zone. This finding suggests that the method used to adjust the duration of irrigation events could require some adjustments for soils with such low hydraulic conductivities (Table 4). This soil's poor water transfer capacity mainly occurred because 80% of its sand particles were smaller than 0.25 mm (classified as fine to very fine sand), which increased the proportion of flow restricting micropores. Due to slow water infiltration, it is difficult to adjust irrigation durations to obtain target matric potentials at both measurement depths simultaneously. In Summary, the experiment at Site 4 showed that triggering irrigation at −8 kPa provided optimal yields and WUE. They also suggest that high-frequency and short-duration irrigation

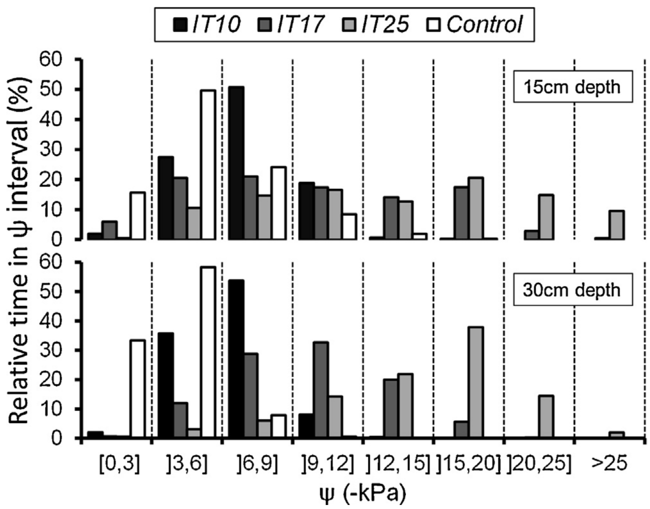

Fig. 9. Relative time spent within different matric potential ranges during the reference period of the experiment at Site 4.

could minimize leaching under the root zone in these conditions, thus further improve WUE.

3.10. Site 4: Special considerations

Except for the K_{sat} measurements in which variability is frequently elevated because of sampling and measurement errors (Reynolds et al., 2002), the soil properties from Site 4 had low variation coefficients. Thus, the soil was considered as uniform. Because the experimental area was nearly 3 times smaller than that at Site 4, it was assumed that measurements from a single monitoring station per treatment would represent the ψ values across the entire area.

Similar to many other fields in the area, the experimental site was affected by cyclamen mites that affected the general plant vigor by feeding on the plant material and altered flower pollination and reduced the fruit size. One replicate of the *IT17* treatment was particularly affected and removed from the statistical analysis. However, all of the other experimental plots were equally affected. On average, approximatively 10,000 kg/ha of berries were misshaped or smaller than industry standards and classified as unmarketable, with no significant differences between the treatments. In addition, canopy coverage was reduced relatively to normal values in the area, which reduced the ETc. No significant difference in canopy coverage was observed between any of the treatments. When calculated with Kc values derived from canopy coverage as described by Grattan et al. (1998), the ETc value for the reference period was 392 mm. However, when calculated using historical monthly adjusted Kc values, the ETc value was 467 mm.

3.11. Site 4: Soil matric potential, yield and fruit quality

At Site 4, the achieved and intended thresholds were in good agreement; and average ψ values at both depths confirmed that IT treatment application was successful (Table 3). This was facilitated by the low rainfall (24 mm) and regular evapotranspirative demand during the reference period. As intended, decreasing the IT from −10 to −25 kPa resulted in notable differences in the time spent within the different ψ ranges (Fig. 9). Managed by the producer without a pre-determined IT, the *Control* treatment was maintained under the wettest conditions. Consequently, orthogonal contrasts showed that *IT10* and *Control* led to a significant ($p = 0.0111$) 19.7% yield increase relative to *IT17* and *IT25* (Table 3). No significant differences were observed regarding fruit sugar content and size. Again, the interaction term between harvest date and yield was not significant ($p = 0.7180$). The effects of treatments on yield (Table 3) combined with their impacts on the soil water status (Fig. 9) can be used to deduce the optimal ψ range for fruit production. First, under wet conditions, large differences between *IT10* and *Control* regarding the amount of time spent in the [0,−3], [−3,−6] and [−6,−9] kPa ranges did not affect yield. The yields in *Control* were not increased relative to that of *IT10* by spending a greater proportion of the reference period at a ψ above −6 kPa. Second, ψ at a depth of 30 cm in *Control* was maintained above the bed capacity (−3 kPa) for as much as 33% of the reference period, which implies that an important fraction of the applied water was leached under the root zone. This excessive water application did not have any adverse effects on fruit production and is consistent with physiologically oriented observations indicating that strawberry plants can maintain their photosynthetic activity while flooded by partially closing their stomata (Blanke and Cooke, 2004). Third, all IT treatments spent similar amounts of time within the [−9,−12] kPa range without any negative effects on yield for *IT10*. Finally, considering both measurement depths, the relative time below −15 kPa was nearly 4 times greater in *IT25* than in *IT17* without any effect on yield. Together, these observations suggest that [−6,−12] kPa is the optimal range in this soil for strawberry yields, and that most of the yield-affecting stress occurs in the range of [−12,−15] kPa. In this case, the time spent in the [−15, −25] kPa range did not affect the yield. However, more experiments would be required to determine if drier conditions would induce a gradual or stepwise yield decrease.

3.12. Site 4: Water use efficiency

With regard to water use, *IT10*, *IT17*, *IT25* and *Control* plots were irrigated 88, 71, 52 and 62 times during the reference period, and the average irrigation durations were 43, 49, 53 and approximatively 75 min, respectively (Table 3). The applied irrigation water depths were 105, 94 and 76% of ETc for *IT10*, *IT17* and *IT25*, respectively. For *Control*, 138% of ETc was applied; however, irrigation was used in the control to compensate for the historic ETc, which, was expected to be higher, as discussed above (Table 3). In fact, by applying 532 mm of irrigation water during the reference period, the grower applied 116% of the expected value (467 mm) based on historic monthly means. Considering the water application efficiency and possible salt leaching needs, this amount of water would most likely have been appropriate for the same reference period during an average growing season (i.e. for healthy strawberry plants). However, in this case, the additional water applied to *Control* resulted in a decreased WUE relative to *IT10*. The WUE decreased from *IT10* to *IT17*, mainly because of a yield reduction, and increased between *IT17* and *IT25* mainly due to a reduction in the amount of water applied. Even in a water scarcity situation, it is not likely that growers would sacrifice yield to improve WUE, which was the case for *IT25*. From a practical perspective, it would be interesting to conduct further experiments to identify a point between *IT10* and *IT17* that would allow for a compromise between yield and WUE.

These results show the adaptability of ψ-based irrigation management. Without any special considerations during treatment application, the water applied to *IT10* and *IT17* was very similar to the calculated ETc (Table 3). By contrast, adjusting the amount of water applied to *Control* in order to compensate the actual water requirement of insect affected plants (which was not an objective in this study), would have required monthly or bi-monthly canopy coverage measurements. These measurements are common for research purposes but are rarely performed in a production context. In this experiment, the ETc was lower than anticipated due to mites. However, these observations suggest that matric potential-based irrigation could automatically (i.e. without any additional measurements) account for most uncontrolled (pest, disease, weather) or planned (varieties, plant density) factors that could affect plants because it is directly related to root uptake. In addition, on a volumetric basic, the water applied to *IT10* and *IT17* was very similar to the ETc estimations but resulted in major differences in yield. Again, this stresses the importance of irrigation timing. In this case, proper timing allowed *IT10* to remain above the presumed critical ψ value of −12 kPa, leading to better yield relative to IT17. In summary, ETc calculations have been shown here and in many other experiments to serve as a very interesting tool for determining the amounts of water required by plants. However, to optimize irrigation management, ETc should be used in combination with another criterion available over a short time interval. At this site, real-time monitoring of the matric potential was shown to be an efficient criterion.

4. Conclusion

Experiments conducted at the Group A sites indicated that matric potential-based irrigation management could positively affect the marketable yield and WUE, even for short production periods with abundant precipitation (Fig. 5). These experiments also allowed to identify potential limitations of that type of management. These limitations were (1) the difficulty of achieving intended thresholds in production conditions, (2) the effect of the unstructured spatial variability of soil properties and (3) management difficulties associated with inadequate wetting patterns from the SDI irrigation system. Additional experiments designed to understand and differentiate the effects of these limitations would be required to optimize matric potential-based management under these conditions. The results from Sites 1 and 2 may be useful for improving irrigation management practices on farms located in the same areas as the experimental sites. Unfortunately, because of the specific properties (schist fragments) of the soils at these sites, it is not appropriate to use information regarding the yield responses to IT that were obtained from these experiments to infer optimal thresholds for soils with similar textures because conventional textural classification only includes particles smaller than 2 mm. Knowledge of more complex properties, such as water retention and hydraulic conductivity, or conducting similar experiments on more typical soils from different soil types would be required to apply these results to other sites.

At the Group B sites, which have uniform soils and nearly no precipitation, the effects of IT management on yield and WUE were much more pronounced (Fig. 5). Initiating irrigation at a proper matric potential allowed to improve the yield and WUE, respectively, by as much as 20 and 33% relative to conventional irrigation practices in this area. In general, the yields from the Group B sites were not negatively affected by high matric potentials (wet conditions), for which aeration could be limiting. However, the yield decreased sharply for matric potentials of less than −8 to −12 kPa, depending on the site. In dryer conditions, the yield response to IT appeared to reach a plateau for IT values between −12 and −25 kPa depending on the site. This suggests that the soil matric potential range for which a compromise between optimal yield and WUE is possible would be between −10 and −15 kPa, depending on the site. At Site 4, leaching under the root zone was also considerably reduced relatively to conventional practices by monitoring the matric potential at a depth of 30 cm following irrigation. Of course, additional experiments could result in further optimization of irrigation practices at all of these sites. It would be interesting to verify if high-frequency and short-duration irrigations could reduce leaching while maintaining high level yields. The soil from Site 3 is a typical fine textured sandy loam, and the soil from Site 4 is a typical smectitic clay loam. Both soils are well represented in their respective areas. Thus, the results could be used as a guideline to improve irrigation practices in similar soils. The results from sites with contrasting properties, varieties and cultural practices were similar under temperate (Group A) and warm (Group B) climatic conditions. It is thus likely that an IT of −10 kPa would provide good results in most type of soils and under most climatic conditions. It would at least represent a good starting point for further optimization of irrigation management of field grown strawberries.

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