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Original article – Thematic Issue

Limited irrigation of field-grown strawberry (*Fragaria* × *ananassa* cv. 'Elsanta') in a temperate climate: Effects on yield and quality

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Summary

Irrigation is essential in the production of field-grown 'Elsanta' strawberry, even in the Belgian temperate climate. Current irrigation guidelines in Mediterranean and arid environments for strawberry recommend a soil water potential (Ψ_{soil}) close to -10 kPa. The hypothesis of the current experiment is that in a temperate climate strawberries can be grown at a dryer Ψ_{soil} while maintaining maximal marketable yield but improving fruit quality. An irrigation experiment was set up where 'Elsanta' strawberry yield and quality was monitored in three experiments with varying locations, years and growing conditions. Irrigation regimes were set up using a soil water balance model, granular matrix (Watermark) Ψ_{soil} sensors and Ψ_{plant} observations. Data of the three experimental trials were pooled in a linear mixed-effects model. The limited irrigation regime did not lead to a significant decline in evapotranspiration nor to a decrease in marketable yield. However a dryer irrigation scheme led to an increased sugar content in the fruits, but also picking date had an important influence. Fruit firmness was not affected by the irrigation regime nor by the picking date.

Keywords
aroma analysis, granular matrix sensor, plant water potential, soil water balance, sugar/acid ratio, sweetness index

Significance of this study

What is already known on this subject?

- Experiments in greenhouses and in the open fields have indicated that water stress may influence fruit sugar content positively.

What are the new findings?

- Irrigation experiments in strawberry fields in a temperate climate show that irrigation can be scheduled to a lower Ψ_{soil} compared to more evaporative demand climates.

What is the expected impact on horticulture?

- Growers can increase sugar content in strawberry providing the irrigation is carefully scheduled with aid of soil sensors and a soil water balance.

Introduction

In Belgium up to 1,900 ha of strawberries are grown yearly. 'Elsanta', a June bearing variety, is the most popular variety in Belgium. The strawberries can be planted before winter and remain on the field during winter and produce flowers and strawberries in spring, in the months of May and July. Alternatively, the small plants can be stored in the fridge during winter and planted out in the open field at the beginning of spring to produce strawberries. Strawberries that are grown in the open field are, despite the temperate climate, nearly always irrigated in Belgium. In Europe 25% of all produced strawberries originate from countries with temperate climate (FAO, 2023). There is no information about the share of open field production in Europe, but in Belgium half of the total strawberry production is grown in greenhouses and the other half is grown in the open fields, however partially grown under plastic tunnels.

A soil water potential (Ψ_{soil}) of -10 kPa was reported to be the optimal irrigation threshold for strawberry in California under high evaporative demand conditions (Gendron et al., 2018). In Gendron et al. (2018) focus was set on total marketable yield disregarding strawberry quality parameters like firmness and sugar concentration. This aligns with previous findings of Serrano et al. (1992) in Spain, also in high evaporative demand conditions. Marcellini et al. (2022) concluded that -30 kPa is an optimal irrigation threshold for three different strawberry varieties in central Italy. In this study a dryer Ψ_{soil} led to an increased concentration of total soluble solids and an increased titratable acidity in two of the three tested varieties.

Irrigation guidelines expressed in Ψ_{soil} depend on the local evaporative conditions (Doorenbos and Kassam, 1986). For strawberry specific irrigation guidelines for temperate evaporative demand conditions are scarce. Létourneau et al. (2015) show a yield decline of 5% at a Ψ_{soil} -25 kPa in a temperate climate, in Quebec Canada, while yield decreased more than 15% at a Ψ_{soil} -25 kPa in warmer and dryer locations in California. Hoppula and Salo (2007) described how in Finland in 2002 marketable yield was 15% higher at a Ψ_{soil} of -15 kPa compared to -60 kPa; however, in 2003 yield was 15% higher in the -60 kPa treatment. Furthermore Hoppula and Salo (2007) conclude that irrigation efficiency was best at -60 kPa. At this Ψ_{soil} of -60 kPa fruit firmness was higher and soluble solids content was lower.

Experiments in greenhouses and in the open fields have indicated that water stress may influence fruit sugar content positively (Terry et al., 2007; Giné Bordonaba and Terry, 2010; Weber et al., 2017; Tunc et al., 2019). Sugar content was higher, mainly due to a lower water uptake by strawberries under water stress, explaining a higher sugar content expressed on a fresh weight basis. However Grant et al. (2010) reports mechanisms of osmotic compensation in potted strawberry plants. Acid concentration can increase as well due to the lower water uptake in deficit irrigated plants. Sugar/acid ratio and a sweetness index have been described to confirm consumers preference for 'Elsanta' strawberry (Keutgen and Pawelzik, 2007). Both measures have been reported to be higher after water stress (Giné Bordonaba and Terry, 2010; Weber et al., 2017). In these studies, fruit size was smaller in the deficit irrigated strawberries. For commercial field-grown strawberry production a tradeoff needs to be defined between optimal yield and elevated sugar concentrations. Due to the variation among water stress response between strawberry varieties (Grant et al., 2010; Martínez-Ferri et al., 2016), this trade-off will be variety dependent. Next to sugar and acid concentrations also fruit firmness may be affected by irrigation (Krüger et al., 2002), although the effect is less pronounced and again variety dependent (Weber et al., 2017). Fruit aroma has been recognized as an important driver in food preferences (Spence, 2015), however the relation with irrigation has only barely been discussed. Only Hoberg et al. (2002) showed a relation between irrigation dose and strawberry aroma in addition to the irrigation experiment of Krüger et al. (2002) where strawberries were partly subjected to severe water stress in a non-irrigated treatment. Hoberg et al. (2002) showed a distinction in aroma signature depending on the irrigation regime, however, also picking date seemed to be a determining factor.

Despite the temperate climate open fields grown strawberry in Belgium is irrigated. Soil sensors that measure soil water content (θ_v) or soil water potential (Ψ_{soil}) are the most commonly used practices for irrigation scheduling. To be able to minimize water contamination risks due to inefficient irrigation, the best irrigation technologies for water delivery off and on-farm should be combined with irrigation scheduling programs based on the knowledge of soil characteristics and the water requirements of local crops (Zinkernagel et al., 2020). A soil water balance calculation provides information about the evapotranspiration of the crop, indicates the possible contribution of capillary rise from a shallow ground water table, and reveals possible percolation of water out of the root zone. The soil water balance can also be used to schedule irrigation when it takes the weather forecast into account (Janssens et al., 2011).

Currently, a higher sugar content in strawberry cultivation has only been observed under severe water stress. However the hypothesis of the current experiment is that a lower irrigation regime can improve fruit flavor in field-grown June bearing 'Elsanta' strawberry without severe yield decline due to the temperate climate, providing the irrigation is carefully scheduled with aid of soil sensors and a soil water balance. To test this hypothesis an experiment was set up in three different planting systems on two different locations over two different growing seasons.

Materials and methods

Set up experiment

Irrigation experiments were set up in two locations in Belgium at the Research Center Hoogstraten in Meerle (51.452417°N, 4.797326°E) and at the PCFruit Research Center in Sint-Truiden (50.7734496°N, 4.1586176°E). Both locations are situated in the middle of the main strawberry growing regions in Belgium. Hoogstraten is situated in the north of Belgium where sandy textured Podzols dominate. Sint-Truiden is situated in the central eastern part of Belgium where the main soil type is Luvisol which has a silt texture. The experiments were conducted as a proxy of open fields strawberry cultivation in commercial farms. The experiments started in spring 2015 and ended in summer 2017. Experiments were set up in the open field, only in 2017 a plastic rain shelter was used in Hoogstraten. Since spring of 2016 was very rainy, total rainfall amount was 228 mm, which was 17 mm more than total evapotranspiration for that period, there was no distinction between irrigation treatments. Therefore, the experiments of 2016 are excluded from this manuscript.

Open field grown strawberries are grown on 0.6 m wide raised beds covered with impermeable polythene and wheat straw. Between the beds there is a strip of 0.9 m soil where water can infiltrate. Irrigation was applied by drip irrigation in the middle of the strawberry ridge beneath the plastic foil. Emitter discharge was 5 L m^{-1} in Hoogstraten and 2.6 L m^{-1} in Sint-Truiden. In Hoogstraten, an electric steering unit was used to program the daily irrigation events while in Sint-Truiden the vanes where manually operated. In Sint-Truiden, a flow meter was used to control the applied water volumes. In Hoogstraten, in 2017 the two irrigation treatments where set up in separate plastic tunnels.

Irrigation was scheduled according with aid of a soil water balance to prevent water stress in a full irrigation (FI) treatment. At the same time, a deficit irrigation treatment (DI) was set at approximately 10% of the FI irrigation dose aiming to induce water stress at the strawberries. In the DI treatment irrigation was only initiated in very dry periods to dissolve the mineral fertilizer. In Hoogstraten in 2017, the irrigation rate was set higher in the DI treatment, up to 30% of the FI treatment, since the strawberries did not receive any natural rain under the plastic shelter. In Hoogstraten in 2015, strawberries were irrigated overhead with 73 mm at planting in order to ensure a good plant development immediately after strawberry planting in both FI and DI treatment. In this study, the three experiments are pooled together as a split plot design with four observation plots per irrigation treatment (Figure 1). A plot was 5 m long and one bed wide, containing 30 strawberry plants.

In 2015 in Sint-Truiden strawberry plants were monitored in spring, although the plants were planted in August 2014, in the open fields, before winter. Plants remained on the field during the winter of 2014–2015. In 2015 in Hoogstraten, strawberry plants were stored in the fridge during winter and planted in the open field on 15/04/2015. In 2017 in Hoogstraten strawberry plants were stored in the fridge during winter and planted on 15/03/2017. In Hoogstraten in 2017 plants were grown in the soil under a 2 m high, 3 m wide, and 50 m long plastic tunnel in order to protect the fruits from rain and hail impact and to stimulate fruit ripening. Strawberry production in plastic tunnels is a common practice in Belgium. During dry periods, the plastic tunnel was opened for ventilation.

In Hoogstraten, a ground water table depth was present approximately 1 m below the root zone, which induced capillary rise. In all experiments, strawberries were planted on a ridge of 0.6 m wide covered with plastic foil. Between two neighboring strawberry ridges, there was a distance of 0.9 m.

Soil water balance calculation

A classical soil water balance model as for example BUDGET (Raes, 2002) calculates the root zone depletion for the simulation period (Δt = 1 day) by considering the measured soil water content in the root zone at day i (D_i), the daily rainfall (R), irrigation (I), estimated capillary rise (CR), and the crop evapotranspiration which is calculated by multiplying reference evapotranspiration (ET_o) with the crop coefficient K_c (Allen et al., 1998). Deep percolation (DP) is considered when soil water content exceeds Field Capacity:

$$D_i \text{ [mm]} = D_{i-1} \text{ [mm]} + R \text{ [mm]} + CR \text{ [mm]} - DP \text{ [mm]} + I \text{ [mm]} - K_c\, ET_o \text{ [mm]}$$

The same model has previously been described and used by Janssens et al. (2011), Janssens et al. (2015b) and Remy et al. (2019) for the calculation of soil water dynamics in pear orchards. The soil water balance has the same basic algorithms as BUDGET (Raes, 2002) and is written in an R code. Further specifications and differences with BUDGET (Raes, 2002) are described in the Supplemental Information. For irrigation scheduling the daily ET_o was calculated according to Penman-Monteith (Allen et al., 1998), forecasted based on regional weather forecast of temperature, relative humidity, wind speed and hours of sunshine. The soil water balance model is used by Soil Service of Belgium to schedule irrigation on 100 farms in Belgium on a yearly basis since 2006.

ET_o was calculated based on meteorological observations collected by Royal Meteorological Institute of Belgium (RMI) the at Deurne and at Bierset for Hoogstraten and for Sint-Truiden, respectively. Both meteorological stations are approximately situated at 30 km from the respective experimental sites. Rainfall was collected on site.

In Sint-Truiden, strawberries were planted in August 2014, before winter, but the irrigation experiment only started 01/04/2015. As the strawberry plants where already well developed at that time, the $K_{c\ ini}$ was set to 0.85 equal to $K_{c\ mid}$ and consistent with Doorenbos and Kassam (1986). In Hoogstraten the strawberry plants were stored in fridge during winter and were also well developed when they were planted out in the field in spring 2015. Therefore, the same K_c factor was used. Only in Hoogstraten in 2017 K_c was set lower, at maximum 0.7, to account for the shade through the opaque plastic rain shelter which has been reported to reduce evapotranspiration (Fernández et al., 2010).

The soil water balance calculation was validated using gravimetric soil samples taken in every plot at 0–30 cm but only on a monthly basis so that the soil in the root zone was only minimal disturbed by the sampling. Samples were taken using a 1.6 cm diameter gauge auger. Each sample consisted of a mixture of at least six subsamples taken in the strawberry ridge. Gravimetric water content was measured by drying the samples at 105°C for 24 h. Gravimetric water content was converted to volumetric water content (θ_v) using bulk density. Bulk density was derived from undisturbed soil samples of 100 cm^3, collected in every plot at a depth of 15 cm to determine the soil water retention points on pF 2 (-10 kPa) and pF 2.7 (-50 kPa). Water retention characteristics were acquired using pressure plates in the laboratory according to ISO NBN EN 11274. Coefficient of determination (R^2) between observed and modelled water content was calculated just as the root means squared error (RMSE) and the Nash–Sutcliffe model efficiency coefficient (NSE).

Monitoring of water status

To monitor soil water potential (Ψ_{soil}), two granular matrix (Watermark) sensors (Irrometer Company, Inc., Riverside, U.S.A.) were placed in three plots per treatment at a depth of 15 cm at 15 cm from the center of the bed where the drip line was situated. Sensors were connected to a data logger (Irrometer Company Inc., Riverside, U.S.A.) that recorded Ψ_{soil} every four hours allowing the calculation of the daily average.

Predawn plant water potential (Ψ_{plant}) was measured in every plot just before sunrise. For each measurement, two leaves per plot were selected. These two leaves were detached and put immediately in a pressure chamber to determine Ψ_{plant} (Scholander et al., 1965).

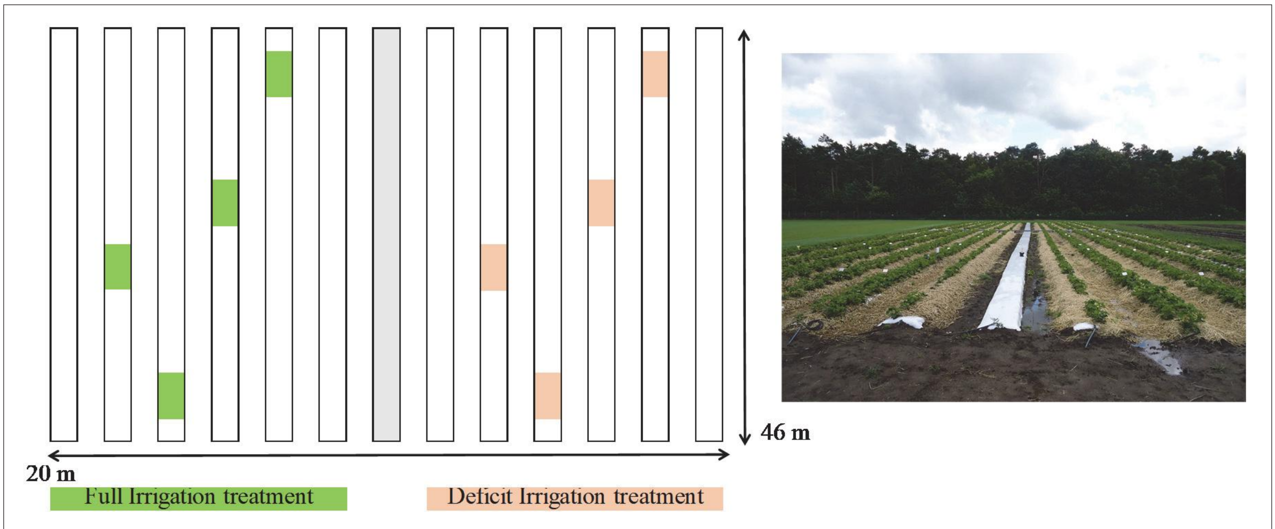

FIGURE 1. Schematic overview and photo of the experiment in Hoogstraten in 2015. Beds with strawberries are indicated with the black line. Plots in FI treatment are indicated in green while plots in the DI treatment are indicated in red.

Strawberry quality

Strawberries were harvested twice a week, collecting all ripe berries per plot. The weight of the 500 g plastic punnets was subtracted to determine the exact fruit weight at each picking date. Since the strawberries were planted at different dates over all the experiments also the fruit samples fruit quality analysis were collected at different moments. In Hoogstraten, in 2015, samples were collected at two different moments in July while at the other two trial fields, Sint-Truiden in 2015 and Hoogstraten in 2017, samples could be collected at three different moments in June.

Fruit firmness was measured with a TA.XT Texture Analyser (Stable Micro Systems, Godalming, U.K.) at 20°C. Tissue from individual strawberries was flash frozen using liquid nitrogen from subsequent sugar and acid analyses. Before analysis tissue samples were thawed on ice, centrifuged at 5,200 rpm at 4°C. From the supernatant 200 µL of juice was transferred to an empty vial and 800 µL of trehalose solution (6.25 g L^{-1}) was added, vortexed and filtered through a 20 µm pore filter. This filtrate was used for the acid analysis. From the filtrate 200 µL was transferred to an empty Eppendorf tube, 200 µL of formic acid solution (0.1% (v/v%)) was added, vortexed, and 50 µL of this mixture was diluted using 950 µL of a dilution solution (75%/20% ACN/H_2O solution). This dilution was used for sugar analysis. Sugar and acid concentration were measured with a HPLC-ELSD (High Performance Liquid Chromatography-Evaporative Light Scattering Detector) as described in detail by Annaratone et al. (2017). All values were expressed in g L^{-1} of strawberry juice. Based on this values sugar/acid ratio and sweetness indicator was calculated according to Keutgen and Pawelzik (2007):

SI =
(1.00 [glucose]) + (2.30 [fructose]) + (1.35 [sucrose])

Table 1. Soil properties of the three experimental fields. For bulk density and water retention characteristics distinction is made between the FI and the DI treatment. For these soil properties standard deviation is indicated alongside the average observation.

Location and year		Sint-Truiden (2015)	Hoogstraten (2015)	Hoogstraten (2017)
Soil type (WRB classification)		Luvisol	Podzol	Podzol
Soil texture (USDA classification)		Silt	Sand	Sand
Carbon content (0–30 cm) (%)		1.7	1.7	2.5
pH-KCl		7.3	5.3	5.5
Bulk density (g cm^{-3})	FI	1.36±0.07	1.38±0.05	1.44±0.07
	DI	1.37±0.05	1.45±0.14	1.42±0.06
Water retention at Ψ_{soil} of -0 kPa (cm^3 cm^{-3})	FI	0.47±0.03	0.46±0.01	0.48±0.02
	DI	0.49±0.02	0.43±0.06	0.49±0.02
Water retention at Ψ_{soil} of -10 kPa (cm^3 cm^{-3})	FI	0.39±0.01	0.30±0.03	0.28±0.03
	DI	0.39±0.02	0.28±0.06	0.29±0.02
Water retention at Ψ_{soil} of -50 kPa (cm^3 cm^{-3})	FI	0.32±0.01	0.21±0.02	0.20±0.02
	DI	0.31±0.03	0.21±0.07	0.20±0.01

Table 2. Input parameters and output summary of the soil water balance calculation in the three experiments in the Full Irrigated (FI) and Deficit Irrigated (DI) treatment.

Trial field	Sint-Truiden (2015)		Hoogstraten (2015)		(Hoogstraten 2017)	
Average estimated depth groundwater (m)	No shallow groundwater		0.93		1.2	
Growing period	01/04–02/07		15/04–14/07		15/03–14/06	
Growing days Kc_{ini}	16		30		30	
Growing days Kc_{dev}	10		30		25	
Growing days Kc_{mid}	70		30		36	
Kc_{ini}	0.85		0.85		0.6	
Kc_{mid}	0.85		0.85		0.7	
Rainfall (mm)	141		110		0 (grown in plastic tunnel)	
ET_o (mm)	279		303		248	
Summary of output soil water balance during complete growing cycle						
Irrigation treatment	FI	DI	FI	DI	FI	DI
Overhead irrigation (at planting)	0	0	73	73	0	0
Drip irrigation (mm)	85	8	37	5	62	21
Capillary rise (mm)	0	0	113	114	77	77
Water losses due to percolation (mm)	10	10	128	129	0	0
ET_c (mm)	262	249	261	259	162	162
ET_a (mm)	249	206	261	252	162	152
ET_a/ET_c	0.95	0.83	1.00	0.97	1.00	0.93

For strawberries picked in Hoogstraten in 2017, fruit aroma was obtained using a Selected Ion Flow Tube Mass Spectrometry (SIFT-MS) (Vendel et al., 2019).

Statistical analysis

It was the objective of this study to reveal effects of reduced irrigation over the three different experiments. However also picking date may have an effect on strawberry quality. A split plot experimental design was used and therefore data from all experiments were pooled in a linear mixed-effects model with irrigation treatment and picking date as fixed effects and trial field as random effect. Significant impact of the variables on the model was tested in an ANOVA analysis. Observations are considered significantly different when $p < 0.05$. Prior to this analysis, it was checked whether the data were normally distributed. Sugar/acid ratio and sweetness index, analyzed over all experiments, are shown in box plots since data were not normally distributed. Statistical data analysis was carried out using R (R Core team, 2019).

Results

Soil water balance calculation

Due to the silt texture the soil in Sint-Truiden retained more water at a Ψ_{soil} of -10 kPa and a Ψ_{soil} of -50 kPa compared to the soil in Hoogstraten (Table 1). Between -10 kPa, which is estimated as field capacity, and -50 kPa, which is the subjected threshold for water stress, 21 mm was readily available in Sint-Truiden while 27 mm was readily available in Hoogstraten. The main difference in soil water status between the two locations is the shallow ground water table in Hoogstraten, which was approximately 0.9 and 1.2 m below the root zone. Capillary rise was estimated to account for 77 to 114 mm during the entire growing cycle. In Sint-

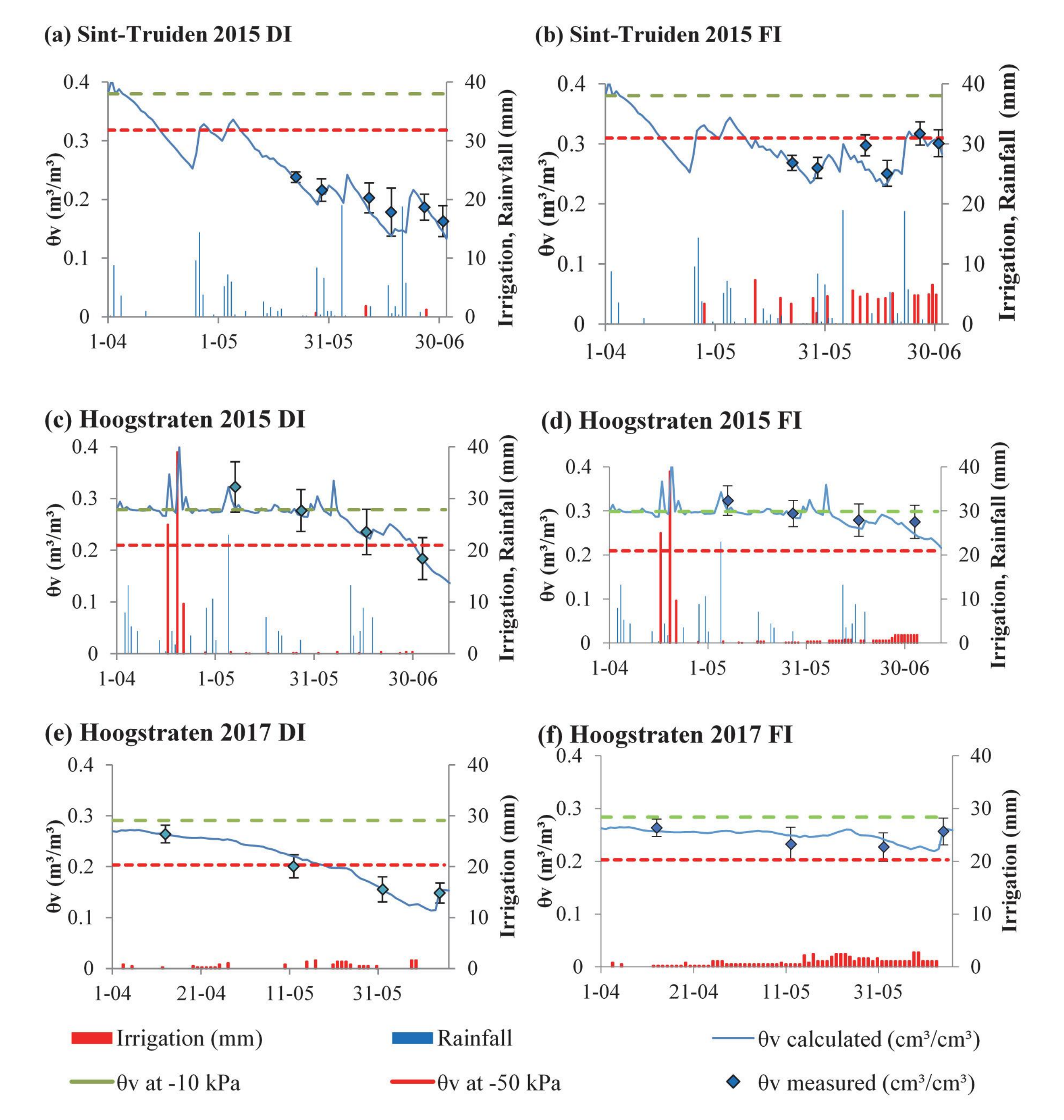

Figure 2. Soil water balance calculated for the three strawberry fields.

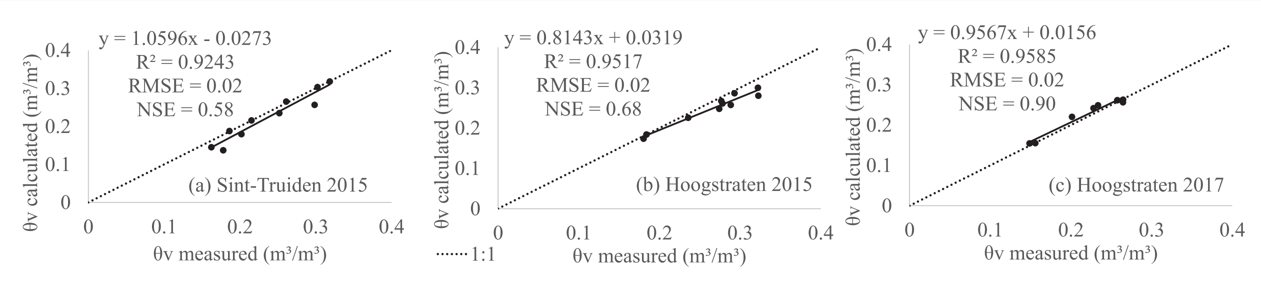

FIGURE 3. Agreement between measured and calculated volumetric soil water content (θv) as indicated by square of correlation (R^2) and slope of the trendline between observed and calculated θv, Root Mean Squared Error (RMSE) and Nash–Sutcliffe model efficiency coefficient (NSE).

Truiden, there was no shallow ground water table, and thus no capillary rise. In all irrigation experiments, percolation of irrigation water out of the root zone was similar between the FI and DI treatment (Table 2). In Hoogstraten, in 2015, 128 mm percolated out of the root zone, which was partly due to the 73 mm overhead irrigation at planting (Figure 2c, d). In the two other irrigation experiments percolation of water out of the root zone was limited.

In 2015, reference evapotranspiration (ET_o) was more than double of rainfall during the experiment. In 2017 in Hoogstraten, there was no rainfall at all due to the plastic rain shelter. Due to this evapotranspiration deficit, it was necessary to irrigate in all FI treatments. Drip irrigation dose was highest in Sint-Truiden in 2015 due to the absence of capillary rise. Despite the high irrigation dose in Sint-Truiden in 2015, θ_v decreased to a Ψ_{soil} of -50 kPa in the FI irrigation treatment (Figure 2b), although there still was clear distinction with the DI treatment (Figure 2a). Calculated actual evapotranspiration (ET_a) was lower in the DI treatment and evapotranspiration deficit ($1-ET_a/ET_c$) was 12% higher compared to the FI treatment in Sint-Truiden (Table 2). In Hoogstraten, the difference in θ_v between FI and DI treatment was lower in both 2015 and 2017 (Figure 2c–f). Due to capillary rise, overhead irrigation immediately after planting in 2015 and the plastic rain shelter in 2017 θ_v remained close to a Ψ_{soil} of -50 kPa even in the DI treatment. Only towards the end of the

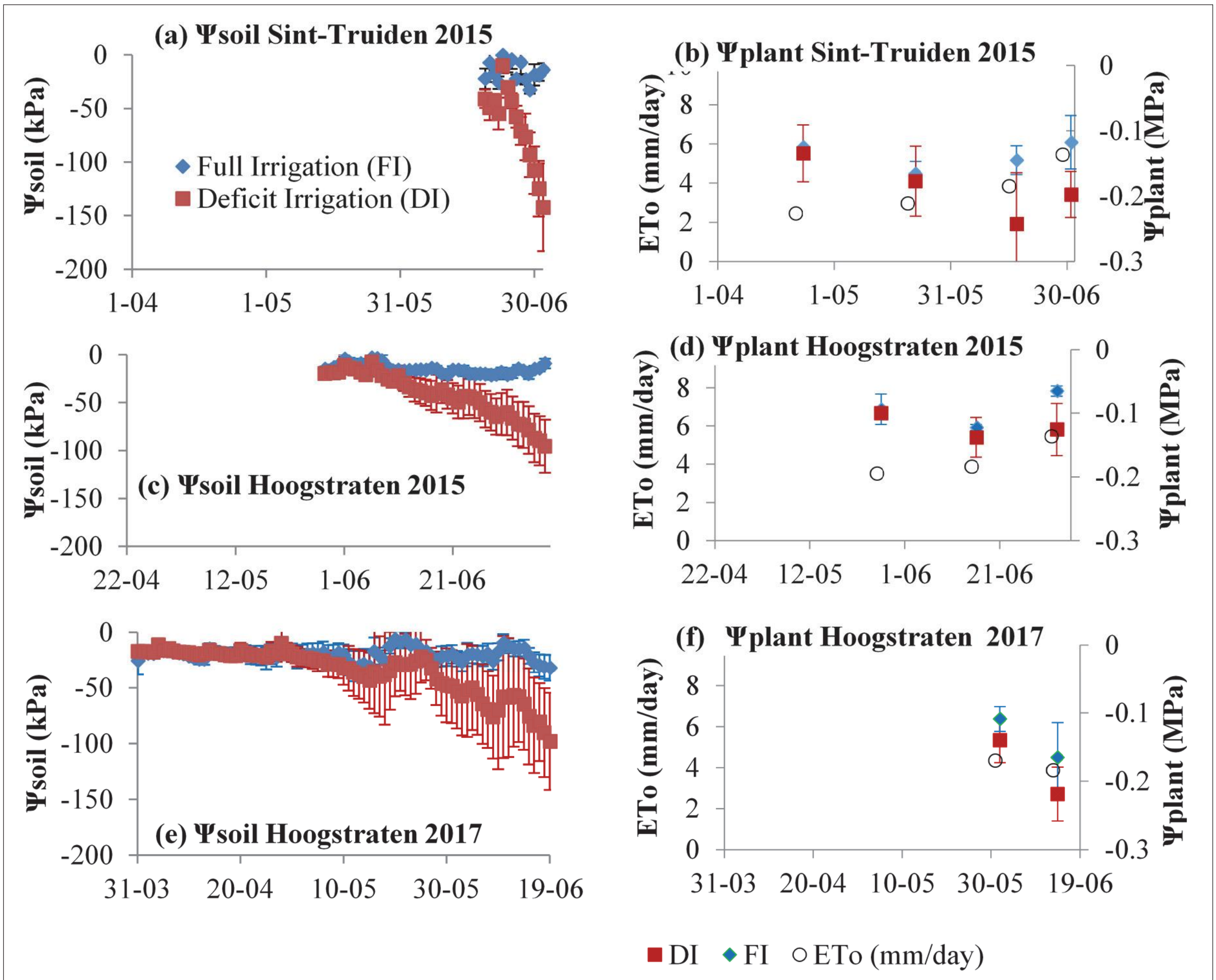

FIGURE 4. Soil water potential (Ψ_{soil}) and predawn plant water potential (Ψ_{plant}) observed in Sint-Truiden in 2015 (a) (b), Hoogstraten in 2015 (c) (d), and Hoogstraten in 2017 (e) (f).

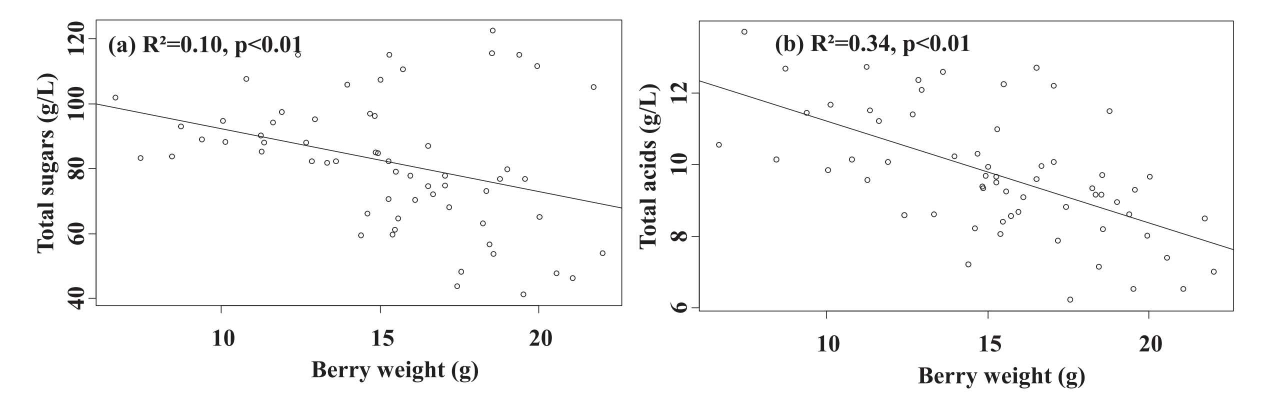

FIGURE 5. Relation between berry weight and amount of sugars (a) and acids (b) calculated over all observations in the three experiments.

growing seasons there was a clear distinction between treatments, which resulted in small differences, lower than 7%, in evapotranspiration deficit between the FI and DI treatment.

Nash–Sutcliffe Model efficiency for the soil water balance calculation was above 0.5 for the three experiments (Figure 3). The RMSE was in all calculations 0.02 $cm^3\ cm^{-3}$. The coefficient of determination (R^2) between observed and calculated θ_v was higher than 0.9, only in Hoogstraten in 2015, the slope of the regression line was slightly lower than the identity line.

Soil and plant water status

In accordance with calculations of the soil water balance, observations of Ψ_{soil} differed at the end of the growing season, during fruit picking (Figure 4a, c, e). In Sint-Truiden the Ψ_{soil} sensors were only available at the very end of the growing season. During this period Ψ_{soil} decreased to -150 kPa in the DI treatment. In the FI treatment Ψ_{soil} maintained close to -50 kPa. In Hoogstraten, in 2015 and in 2017, there was less distinction in Ψ_{soil} between the two irrigation treatments. In the DI treatment Ψ_{soil} decreased to -100 kPa, while it maintained close to -30 kPa in the FI treatment. Observations of Ψ_{plant} confirmed the differences in Ψ_{soil}. Especially during fruit picking the difference between treatments was visible (Figure 4b, d, f). Besides in Hoogstraten in 2017, ET_o was highest at the end of the growing season.

TABLE 3. Marketable strawberry yield (kg m^{-2}) in Deficit Irrigation treatment (DI) and Full Irrigation (FI) treatment in Sint-Truiden in 2015 and in Hoogstraten in 2015 and 2017.

Trial field	FI	DI
Sint-Truiden 2015	4.38±0.45	3.41±0.49
Hoogstraten 2015	1.48±0.43	1.49±0.38
Hoogstraten 2017	2.56±0.09	2.50±0.17
Significance ANOVA analysis linear mixed-effects model		
Irrigation effect	*p* value 0.065	

Strawberry yield and quality

Yield in Sint-Truiden was more than double of the yield in Hoogstraten in 2015 and 2017 (Table 3). The irrigation effect by the linear model had a significance level lower than 0.1 as indicated by the *p*-value. In Sint-Truiden yield was lower in the DI treatment compared to the FI treatment. In Hoogstraten yield was not affected by the irrigation regime. Water use efficiency (WUE), calculated by dividing the yield by the ET_a, was 0.017 kg mm^{-1} in Sint-Truiden in 2015 and was nearly similar in Hoogstraten in 2017. In Hoogstraten in 2015, WUE was only 0.006 kg mm^{-1}.

Berry weight was affected by the irrigation treatment and by the picking date as indicated by the *p*-value that was lower than 0.1. On average berry weight was 8% lower in the DI treatment compared to the FI treatment (Table 4). Berry weight on the first picking date was always highest and decreased towards the last picking date. Irrigation had a significant impact on the sugar content of the strawberries however the influence was less extensive than the effect of picking date as indicated by the *p*-values. The DI irrigation regime caused

TABLE 4. Fruit yield and quality parameters in Sint-Truiden in 2015 and in Hoogstraten in 2015 and 2017.

Trial field	Picking date	Berry weight (g)		Total acids (g L^{-1})		Total sugars (g L^{-1})		Firmness (N)	
Irrigation treatment		FI	DI	FI	DI	FI	DI	FI	DI
Sint-Truiden 2015	12/06	19.7	19.1	6.7	7.8	45.9	52.1	3.5	2.9
	19/06	15.6	16.4	8.1	8.5	63.0	69.1	3.3	3.5
	26/06	15.7	14.9	9.5	9.2	79.2	86.5	3.2	2.8
Hoogstraten 2015	06/07	19.7	15.5	8.8	9.0	113.7	109.4	2.6	2.8
	09/07	12.4	12.7	10.3	10.8	96.9	103.8	3.0	3.0
Hoogstraten 2017	02/06	17.4	18.3	9.4	9.6	69.8	72.5	2.6	2.8
	09/06	17.0	11.3	12.2	12.8	76.3	84.5	3.2	3.4
	14/06	10.6	9.3	11.2	11.1	87.0	96.0	3.0	3.0
Significance ANOVA analysis linear mixed-effects model (*p* value)									
Picking date		0.0937		0.207		<.0001		0.9048	
Irrigation		0.0814		0.0541		0.0061		0.9627	

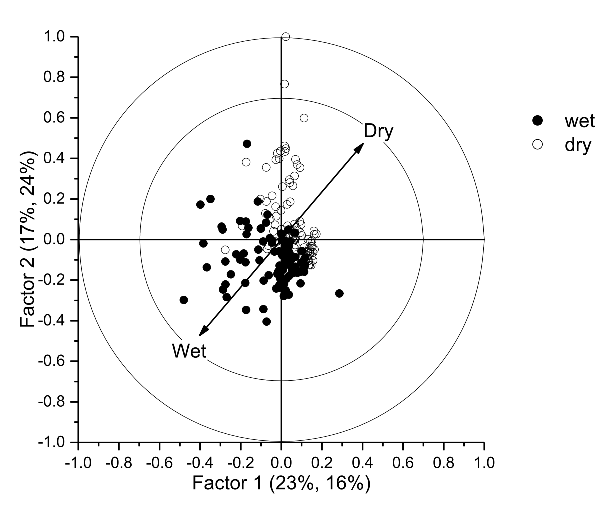

FIGURE 6. The result of the Partial Least Squares Discriminant Analysis (PLS-DA) of the aroma analysis using Selected Ion Flow Tube Mass Spectrometry (SIFT-MS) on strawberries picked in Hoogstraten 2017. Factor 1 covers about 23% of the aroma data describing about 16% of the categorical response, while factor 2 covers about 17% of the aroma data describing about 24% of the categorical response.

an overall significant increase in sugar content of 6%. Berry weight correlated negatively with total sugar concentration in the strawberries (Figure 5a). Correlation between both variables was modest ($R^2 = 0.1$) but significant. Compared to the impact on sugar concentration, the impact of the irrigation regime on the amount of acids was less pronounced with a significance level only lower than 0.1. The concentration of acids was 3% lower in the DI treatment. Just as for sugar concentration there was a significant negative correlation with berry weight (Figure 5b). Irrigation had no impact on fruit firmness. Firmness was highest in Sint-Truiden in 2015 and lowest in Hoogstraten in 2015.

In Hoogstraten, in 2017, the impact of the irrigation regimes is visible in aroma analysis (Figure 6). The PLS-DA describes 89% of the variation using six latent variables, with a root-mean-square-error (RMSE) of 0.17. Sugar/acid ratio and sweetness index were highly dependent of the experimental field (Figure 7). In accordance with total sugar concentration, both parameters were highest in Hoogstraten in 2015, regardless the irrigation regime. On the other hand in Sint-Truiden in 2015 and in Hoogstraten in 2017, the DI treatment resulted in both a higher sweetness index and a higher sugar/acid ratio compared to the DI treatment.

The experiments in Sint-Truiden and Hoogstraten show how a Ψ_{soil} close to -50 kPa has a very small effect on the total evapotranspiration deficit ($1-ET_a/ET_c$). A lower water status resulted in decreased berry weight and increased sugar concentration.

Discussion

The objective of this study was to evaluate whether a lower irrigation regime in a temperate climate can improve fruit quality in field-grown June bearing 'Elsanta' strawberry without inducing yield decline. To schedule irrigation in the study a soil water balance model was used. The quality of the soil water balance calculation was with a maximal RMSE of 0.02 $cm^3\ cm^{-3}$ similar to previous calculations with the HYDRUS model in pear orchards (Janssens et al., 2015a). Calculation with the soil water balance in Hoogstraten show the significance of capillary rise in irrigation management. It explains the higher Ψ_{soil} in the trials fields in Hoogstraten in 2015 and 2017. Shallow ground water tables can contribute significantly to the soil water balance and cannot be disregarded (Kroes et al., 2018). Soil water balance calculations also indicated minimal water losses due to percolation. Only in Hoogstraten in 2015, there was considerable percolation, but this was mainly due to overhead irrigation at the start of strawberry planting.

In Sint-Truiden, in 2015, Ψ_{soil} observations with the granular matrix sensors were only available at the end of the experiment but the difference in water status between the FI and the DI treatment was confirmed. Also in the other two experimental sites, Ψ_{soil} observations differentiated between the two irrigation treatments. In the DI treatments, the variation on the Ψ_{soil} observations with the granular matrix sensors was quite high towards the end of the growing season while variation in observed θ_v remained stable.

Observations of Ψ_{plant} at dawn were consistent with Ψ_{soil} and θ_v. Even in the DI treatment observed Ψ_{plant} was quite high, even higher compared to the water stressed treatments induced by Grant et al. (2010), where water stressed plants were irrigated according to 65% of ET_c. The relative high Ψ_{plant} in the DI irrigated plants is in accordance with the rather low evapotranspiration deficit calculated with the soil water balance as a consequence of the temperate evaporative demand. WUE observed by Grant et al. (2010) was for the variety 'Elsanta' 0.025 kg mm^{-1}, which is only slightly higher than our observations in Sint-Truiden and in Hoogstraten in 2017. Even in the more severe DI treatment Grant et al. (2010) did not report an important increase in WUE.

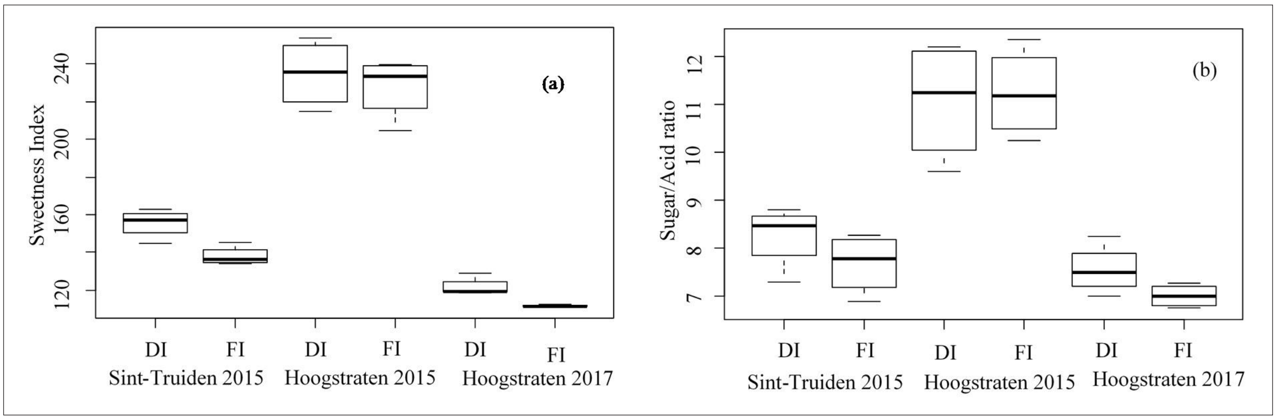

FIGURE 7. Boxplot of average Sweetness Index (a) and average Sugar/Acid ratio (b) in function of the experimental field and the irrigation regime.

There was an important yield decline in Sint-Truiden 2015 in the DI treatment. In this treatment Ψ_{soil} decreased to -100 kPa and evapotranspiration deficit ($1-ET_a/ET_c$) was 17%, while in the FI treatment Ψ_{soil} decreased to -50 kPa and evapotranspiration deficit was only 5%. In Hoogstraten in 2015 and 2017, Ψ_{soil} decreased just below -50 kPa in the DI treatment and remained just above -50 kPa in the FI treatment. Despite this small difference there was no effect on marketable yield. In all treatments evapotranspiration deficit was limited, being maximal 7%. This evapotranspiration deficit is smaller than 30%, which is the irrigation threshold stated by Martínez-Ferri et al. (2016). From the presented results it can be concluded that in a temperate climate the evapotranspiration deficit remains small, with negligible effect on total marketable yield, when a Ψ_{soil} of -50 kPa is used as an irrigation threshold. This threshold is dryer compared to previous studies in more evaporative climates (Gendron et al., 2018; Serrano et al., 1992; Létourneau et al., 2015).

Results suggest that strawberries can be grown in a slightly drier irrigation regime. However, there was a large variation in strawberry yield but also in fruit quality within the three experiments. The yield in Sint-Truiden in 2015 was exceptionally high, approximately double of the yield in Hoogstraten. In Sint-Truiden, in 2015, strawberry plants were planted before winter, in August 2014, and remained on the field during winter. In Hoogstraten plants were stored in the fridge and planted out in the field in early spring. It can be assumed that the plants in Sint-Truiden were stronger at the beginning of the experiment, which resulted in the higher yield. Létourneau et al. (2015) also reported a large variation between experimental sites, with variation between experimental sites also larger than variation between irrigation treatments.

The study confirms previous findings that lower Ψ_{soil} results in higher sugar content. A small difference in evapotranspiration deficit, being maximal 7% in Hoogstraten, had no effect on yield while sugar content increased. In Sint-Truiden a larger evapotranspiration deficit, up to 17%, also led to increased sugar content but was accompanied with yield decline, so irrigation needs to be scheduled carefully. Also sweetness index and sugar acid relation was higher in the DI treatments. However these results need to be treated with caution. Also picking date had an effect on total sugar content in the fruits. The biggest berries where picked first and then berry weight decreased towards the later picking date. A smaller berry weight was correlated with a higher sugar content. Furthermore the amount of sun before fruit picking will have an important impact on photosynthetic rate and sugar accumulation in the fruits. The effect of the water deficit on sugar content was confirmed with the effect on aroma data in Hoogstraten in 2017 similar to Hoberg et al. (2002) and Krüger et al. (2002). The fact that the mild irrigation deficit had a positive influence on fruit aroma offers perspectives to improve the taste experience for consumers (Spence, 2015). In contradiction to other fruit quality parameters, firmness was not affected in this experiment, while Krüger et al. (2002) showed that 'Elsanta' strawberries have a lower fruit firmness at a wetter irrigation regime. Maybe the difference between the irrigation schemes in current experiment where too small to prove an effect over all irrigation experiments on fruit firmness.

Effects of an irrigation deficit on sugar content, previously observed in greenhouses (Terry et al., 2007; Giné Bordonaba and Terry, 2010; Weber et al., 2017) and in the open fields (Tunc et al., 2019) were overall confirmed. Despite the moderate difference in Ψ_{plant} between irrigation treatments, the amount of sugars and acids was higher in the DI treatment. Since the difference in Ψ_{plant} was limited, the difference in berry weight between the irrigation treatments indicates that probably a dilution effect is the reason why sugar and acid concentration was lower in the FI regime. An increase in sugar and acid content was compensated by a decrease in berry weight. It suggests that no extra sugars were pumped in to the plant. Grant et al. (2010) suggested that the variety 'Elsanta' is, due to its high yield potential, more sensitive to water stress, and osmotic adjustment will be less pronounced. For other strawberry varieties, with lower yield potential, results may be different.

Conclusion

Irrigation experiments in strawberry fields in a temperate climate show that irrigation can scheduled be to a lower Ψ_{soil}, up to -50 kPa, compared to more evaporative demand climates. Sugar content was also positively influenced by a lower irrigation regime. It can be concluded that a small evapotranspiration deficit does not lead to yield decline while it has a slightly positive effect on sugar content. However, it must to be noted that also picking date had an important influence on the sugar content of fruits and that there was a large variation between the experimental sites. There was no effect of the treatments on fruit firmness.

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Declarations

The authors declare no conflict of interest.

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Supplemental Information – Figures S1–S3

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