Project title:	Improving the consistency of fruit quality in substrate-grown June-bearer strawberry varieties under precision production systems
Project number:	SF 152
Project leader:	Drs Mark A. Else and Eleftheria Stavridou, East Malling Research
Report:	Annual report, March 2015
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Key staff:	Mike Davies, Clare Hopson, June Taylor, Veronica Martinez, Carlos Angulo
Location of project:	East Malling Research
Industry Representative:	Laurie Adams, Hall Hunter Partnership
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The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

Dr Eleftheria Stavridou

Research Leader

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Signature .... Date ....30/04/2014...

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GROWER SUMMARY

Headline

- Water and fertiliser savings of 34% and 5% were achieved for ’Sonata’ and ’Vibrant’grown under the Irrigation Test Regimes.

Background and expected deliverables

The UK strawberry industry is a vital part of the UK's rural economy and the market continues to grow at a rate of 2.1% by volume and is estimated to sell 106,606 tonnes per annum, worth c. £454 million. The UK portion of the market was worth £218 million in 2013. Irrigation and the addition of fertilisers (fertigation) is essential to produce the high quality berries demanded by retailers and consumers. Modern intensive substrate production systems incur high initial financial investments and require careful management to ensure quality is predictable, consistent and controllable. Nevertheless, the consistency of supply of high quality berries varies between growers and between successive harvests and 32,000 tonnes of fruit picked each year is unmarketable due to small size, skin crazing and unacceptably soft fruit that is predisposed to bruising, rots and diseases. More precise management of water and fertiliser inputs could be expected to reduce fruit waste by at least 30%.

Growers are currently advised to irrigate to achieve 10-25% run-off to prevent the accumulation of damaging ‘salts’ within the substrate. However, AHDB Horticulture-funded research conducted at EMR (SF 107) and on commercial grower sites (SF 136) has shown that run-off can be eliminated without affecting Class I yields and aspects of fruit quality improved. Despite the obvious benefits of our research, concern over perceived problems associated with increased substrate electrical conductivity (E.C.) is limiting growers’ uptake of the new water- and fertiliser-saving techniques developed at EMR. To help growers gain confidence in reducing water and fertiliser inputs, the critical coir E.C. values and the contributory ions that limit fruit size and quality in modern commercial cultivars (cvs) such as ’Sonata’ and ’Vibrant’ need to be determined.

There is an opportunity to improve tolerance to high substrate E.C. by manipulating ammonium-N ($N\text{-}NH_4$) and nitrate-N ($N\text{-}NO_3$) ratios and this approach can also improve fruit number, berry firmness, soluble solids content and shelf-life potential. Manipulating the ratio of $N\text{-}NO_3$ to $N\text{-}NH_4$ would be of particular benefit in cvs such as ’Sonata’ where berries can be soft and vulnerable to bruising. Despite positive reports in the scientific literature, the UK soft fruit industry is wary of using ammonium nitrate as a major source of N. Currently, ammonium nitrate is used to provide N-NH_4 during fruit development, but is usually eliminated two weeks before picking as it can lead to unacceptable softening and subsequent poor shelf-life. Strategic research is needed to test whether altering N nutrition has the potential to improve both tolerance to high concentrations of 'ballast' ions in the substrate (high EC) and yields and quality.

The project aims are:

1. To improve consistency of fruit quality and reduce unmarketable/waste fruit by 30% in 'Sonata' and 'Vibrant'
2. To develop precision fertigation techniques to increase resource use efficiency and environmental performance in substrate soft fruit production

Expected deliverables from this work will include:

- The effects of over-watering and over-feeding on consistency of fruit quality in 'Sonata' and 'Vibrant'
- New grower guidelines for the precision production of substrate-grown 'Sonata' and 'Vibrant'
- Identification of coir E.C. / ion' concentrations that limit fruit size and quality
- To test the potential of manipulating N nutrition to improve tolerance to high coir E.C.

Summary of the project and main conclusions

In this project, irrigation set points for 60-day substrate-grown varieties 'Sonata' and 'Vibrant' that optimise marketable yields, berry quality and resource use efficiency were identified and tested against typical commercial fertigation regimes. 'Sonata' established more slowly than 'Vibrant' and Class I yields were lower than expected, due to a low number of flowers and fruit.

Experimental design

'Sonata' and 'Vibrant' plants were grown in 3 L coir pots in a compartment of the GroDome facility at EMR (Figure 1). Three irrigation regimes were applied:

(i) commercial control treatment (CC) in which run-off of water and fertilisers averaged 20% over the growing season;

(ii) a precision 'closed loop' fertigation (ITR), where run-off was eliminated and coir kept near water holding capacity; and

(iii) a drying down treatment (DD), where coir was allowed to dry to the point that triggered a range of physiological responses.

Figure 1. ‘Sonata’ and “Vibrant” plants were grown in a controlled environment in the GroDome at EMR.

The frequency of irrigation events was determined by measuring coir volumetric moisture content (CVMC) using three SM150 sensors connected to Delta-T GP2 Advanced Dataloggers (Decagon Devices Ltd). Once pre-determined values of CVMC were reached, irrigation was triggered automatically. The duration of irrigation events was adjusted to achieve the desired volume of run-off. Irrigation water was delivered to each pot via a dripper stake connected to a 1.2 L hour^{-1}, non-return, dripper.

In addition, coir VMC, E.C. and temperature were monitored continuously using WET sensors attached to GP2 (Decagon Devices Ltd); ‘spot’ measurements were made using a WET sensor and a hand-held HH2 unit (Delta-T Devices Ltd). Irrigation water inputs and run-off were measured with rain gauges connected to EM50G data loggers with telemetry (Decagon Devices Ltd). Leaf and substrate samples were analysed to determine the effects of the different irrigation treatments on plant nutrition. Routine physiological measurements were carried out on twelve replicate plants per cv. in each experiment. Stomatal conductance, midday stem water potential, rate of photosynthesis, and leaf and fruit growth rate were measured at intervals throughout vegetative and cropping stages in each variety.

Coir Volumetric Moisture Content, EC and nutrient accumulation

In ’Vibrant’, the average CVMC in the CC treatment was maintained between 47 and 55% throughout the experiment, in the ITR treatment between 44 and 47%, while in the DD treatment, irrigation was withheld until the average value fell to 20% (Figure 2). In ’Sonata’, in the CC treatment CVMC was maintained between 52 and 60%, in the ITR treatment between 46 and 54%, while in the DD treatment, irrigation was withheld until the average value fell to 23% (Figure 4).

The coir pore E.C. rose to 2.2 mS cm^{-1} at the end of cropping in both cvs under the DD treatment, but compared to values from the CC and ITR treatments, these differences were not statistically significant.

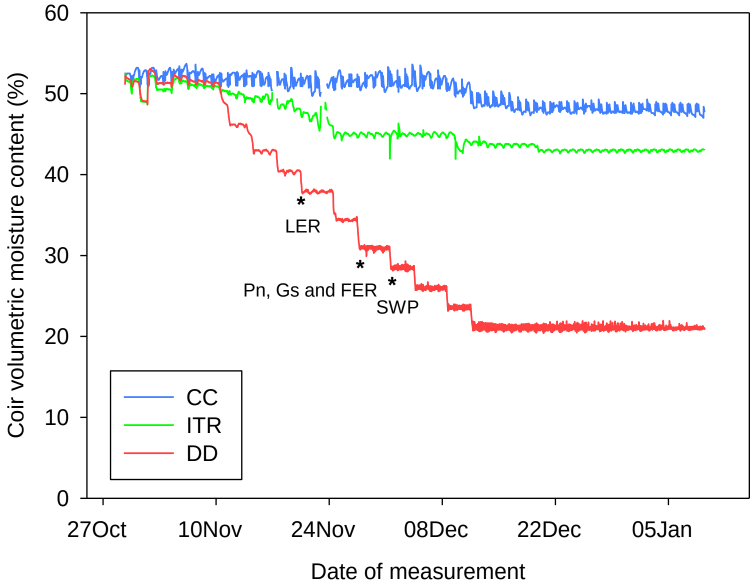

Figure 2. Average coir volumetric moisture contents in the three irrigation regimes of “Vibrant” measured using SM150 moisture probes inserted in the rooting zone

Nutrient analyses of coir and leaf samples collected from each of the three irrigation treatments at the end of cropping indicated that the DD treatment affected nutrient uptake and / or availability. ’Vibrant’ plants under the DD treatment had lower phosphorus, zinc, boron and copper leaf concentrations, but a higher calcium concentration. Coir available phosphorus, ammonia and boron were lower in DD-treated ‘Vibrant’ plants. There were no significant effects of irrigation treatment on leaf and coir nutrient concentrations in ‘Sonata’.

Effect of irrigation regimes on plant physiological response

Midday stem water potential is a sensitive indicator of limited substrate water availability and can be used to detect the very early changes in shoot water balance that occur in response to mild substrate drying. Although such values may be significantly lowered, important agronomic traits such as fruit expansion and the accumulation of precursors for important flavour compounds are often only detected as the stress intensifies. A decrease in midday stem water potential was the first physiological response detected in DD-treated ’Sonata’, statistically significant reductions were triggered at an average CVMC of 38%. In DD-treated ’Vibrant’ plants, statistically significant reductions in stomatal conductance and photosynthetic rate were first triggered at an average CVMC of 30%, while midday stem water potential was lowered at 28%. As expected, no physiological responses were detected in plants grown under the ITR treatment in either cultivar.

Effects of irrigation regimes on fruit marketable yield and quality

Fruit size, fruit number, total and Class I yields (Table) were not affected by the irrigation treatments in either cultivar. Likewise, no statistically significant differences in berry quality attributes including firmness and soluble solids content (SSC [% BRIX]) (Table) were detected. Concentrations of organic acids (citric, malic, oxalic, ascorbic) and sugars (fructose, glucose, sucrose), the sugar:acid ratio and total anti-oxidant capacity were similar in all treatments detected (data not shown).*Water and fertiliser inputs*

Table 1. The effects of the three irrigation regimes on Class I yield and quality.

Irrigation regime	cv. Sonata			cv. Vibrant		
	Class I yield (g plant^{-1})	Average BRIX (°)	Average Firmness (N)	Class I yield (g plant^{-1})	Average BRIX (°)	Average Firmness (N)
CC	112.5a*	7.8a	278.5a	159.4a	7.4a	232.2a
ITR	122.4a	7.3a	292.6a	169.7a	7.1a	233.2a
DD	114.0a	8.1a	291.2a	161.1a	7.8a	256.5a

*means followed by the same letter are not significantly different (p=0.05)

During the cropping period of ‘Sonata’, 11.9, 7.7 and 6.5 L of irrigation water were applied to each plant grown under the CC, ITR and DD treatments, respectively. ’Vibrant’ plants grown under the CC, ITR and DD treatments received a total of 9.0, 8.5 and 5.8 L pot^{-1}, respectively. Therefore, water and fertiliser savings of 36% and 5% were achieved under the ITR treatment, compared to the CC treatment for ’Sonata’ and ’Vibrant’, respectively. For ’Sonata’ the total volume of run-off for the duration of the experiment, excluding flushing events, was 2.4 and 0.5 L per plant for CC and ITR treatments, respectively; while for ’Vibrant’ run-off volumes were 2.3 and 0.2 L, respectively.

Main conclusions from the first year’s work

- The coir volumetric moisture contents that limit important agronomic traits in ‘Sonata’ and ‘Vibrant’ plants were identified.
- This information will be used to inform the irrigation set points to be used in experiments to identify the critical pore E.C values that limit productivity and quality in ‘Sonata’ and ‘Vibrant’.
- Water and fertiliser savings of 34% and 5% were achieved for ‘Sonata’ and ‘Vibrant’ grown under the Irrigation Test Regimes.
- Class I yields and berry quality of ‘Sonata’ and ‘Vibrant’ were not affected by the irrigation treatments.

Financial benefits

The project aims to improve the economic sustainability of substrate strawberry production by improving both water and nutrient use efficiencies and manipulating the form of nitrogen nutrition. Savings associated with a 30-40% reduction in mains water and fertiliser costs are likely to be increasingly significant, provided that yields, quality, and shelf-life are either maintained or improved. Evidence from other on-going projects suggests that avoiding large variations in CVMC through precision irrigation can improve the consistency of fruit quality. Managing the accumulation of ions in the coir and improving plant tolerance to rising pore E.C values will also help to reduce the need for irrigation flushing events, and the subsequent negative impacts on fruit firmness, flavour, and shelf-life potential. A partial cost/benefit analysis will be carried in Year 3 in which the investment and returns associated with deploying the irrigation treatments and manipulating the form of N nutrition will be compared.

Action points for growers

- Monitor run-off at different times throughout the day to establish which irrigation events can be reduced to save water and fertilisers.
- Use substrate moisture and EC probes to help inform irrigation decisions.
- Consider using the coir volumetric moisture content set point developed in the project to optimise water and fertiliser inputs and reduce or eliminate run-off without affecting marketable yields or fruit quality.
- Consider adjusting water and fertiliser inputs to meet the demands of each variety.

SCIENCE SECTION

Introduction

The UK strawberry industry is a vital part of the UK's rural economy and the market continues to grow by 2.1% by volume and is estimated at 106,606 tonnes per annum, worth c. £454 million. The UK portion of the market was worth £218 million in 2013. Irrigation and the addition of fertilisers (fertigation) is essential to produce the high yields and berry quality expected by growers, retailers and consumers. Modern intensive substrate production systems incur high initial financial investments and require careful management to ensure quality is predictable, consistent and controllable. Nevertheless, the consistency of supply of high quality berries does vary between growers and between successive harvests. Some 32,000 tonnes of fruit picked each year is unmarketable due to small size, skin crazing and unacceptably soft fruit that is predisposed to bruising, rots and diseases. More precise management of water and fertiliser inputs could be expected to reduce fruit waste by at least 30%.

Growers are strongly advised to irrigate to achieve 10-25% run-off to prevent the accumulation of damaging cations and anions within the substrate. However, AHDB Horticulture-funded research conducted at EMR (SF 107) and on commercial grower sites (SF 136) has shown that run-off can be eliminated without affecting Class I yields and aspects of fruit quality improved. Despite acknowledging that over-irrigation and high fertiliser inputs can lead to excessive vegetative growth, increased disease susceptibility, lower marketable yields, poor organoleptic quality and a short shelf-life, many growers are reluctant to reduce water (and fertiliser) inputs due to the lack of suitable management tools and crop monitoring systems. To help scale-up the low-input regimes developed by EMR to many hectares of high value commercial substrate strawberry production, innovative technological tools are being developed in two Innovate UK-funded collaborative projects led by BerryGardens Growers Ltd in collaboration with EMR and other industry partners. In the meantime, new scientifically-derived grower guidelines for the precision production of substrate-grown strawberry culivars ‘Sonata’ and ‘Vibrant’ need to be developed.

Despite the obvious benefits of our research, concern over perceived problems associated with increased substrate pore electrical conductivity (EC) is limiting growers’ uptake of the new water- and fertiliser-saving techniques developed at EMR. To help growers gain confidence in reducing water and fertiliser inputs, the critical coir EC values that limit fruit size and quality in modern cultivars such as ‘Sonata’ and ‘Vibrant’ need to be determined. Anecdotal evidence suggests that cv. ‘Vibrant’ is able to tolerate very dry substrates and since the physiological and metabolic adaptations elicited by limited water availability and salinity are similar, cv. 'Vibrant' may also be more tolerant of high substrate EC values. This possibility has yet to be tested.

There is an opportunity to improve tolerance to high substrate EC by manipulating ammonium-N ($N-NH_4$) and nitrate-N ($N-NO_3$) ratios (e.g. Ghanem et al., 2011). This approach can also improve fruit number (Cardenas-Navarro et al., 2006), berry firmness, soluble solids content and shelf-life potential (Tabatabaei et al*.,* 2006, 2008). Manipulating the ratio of $N-NO_3$ to $N-NH_4$ would be of particular benefit in cvs. such as 'Sonata' where berries can be soft and vulnerable to bruising. Despite positive reports in the scientific literature, the UK soft fruit industry is wary of using ammonium nitrate as a major source of N. Currently, ammonium nitrate is used to provide $N-NH_4$ during fruit development, but is usually eliminated two weeks before picking as it can lead to unacceptable softening and subsequent poor shelf-life. Fruit albinism may also be induced with ammonium nitrate if silicon concentrations in irrigation water or substrate are high (Sharma et al., 2006). High ratios of $N-NH_4$ to $N-NO_3$ can limit photosynthesis and fruit quality as well as reducing calcium uptake and the supply of potassium and calcium must be managed carefully to optimise berry flavour and firmness (Ghanem et al., 2011). Strategic research is needed to test whether altering N nutrition in this way has the potential to improve both tolerance to high concentrations of 'ions in the substrate (high E.C.) and yields and quality.

In previous work with cv. 'Elsanta' at EMR (SF 107), changing the percentage of $N-NH_4$ from 10% to either 20% or 30% did not significantly affect plant physiology or fruit quality. In published work, higher ratios of $N-NO_3$ to $N-NH_4$ were needed to elicit physiological responses (*e.g.* 50%:50%, 25%:75%) but during the preparation of the SF 107 proposal, strawberry industry representatives felt that $N-NO_3$ to $N-NH_4$ ratios greater than 70%:30% would limit fruit yields and quality. This was not the case. Work in other cropping systems has shown that a 70%:30% $N-NO_3$:$N-NH_4$ ratio did not affect physiology under normal conditions but improved shoot and root biomass and maintained leaf PSII efficiency under high salinity stress via altered plant hormone signalling (Ghanem et al., 2011). More work is needed to determine the potential of manipulating N nutrition in this way to improve not only aspects of strawberry fruit quality and flavour, but also tolerance to high salinities and the build-up of 'ballast' ions in substrates. The hormonal regulation of tolerance to salinity stress in plants supplied with 70%:30% $N-NO_3$:$N-NH_4$ will be investigated in a separate but allied project. The outputs from SF 152 will also help to address the impact of poor quality irrigation water (high background EC) and increasingly saline irrigation water (due to salt water ingression) on soft fruit production.

More efficient use of inputs including labour, water and fertilisers is vital to the future success of the industry. The Environment Agency (EA) is concerned about the effects of intensive table-top production on groundwater quality in the south east and recently commissioned ADAS to promote ‘best practice’ in a series of grower workshops (which featured EMR’s work in SF 107). Substrate growing is a major capital investment and yet irrigation/fertigation decisions are not often based on scientific evidence. Changes resulting from the Government’s Abstraction Licence Reform programme will begin to be implemented by the EA from October 2015 and drip irrigators must be able to demonstrate an efficient use of irrigation water. The outputs from this project will improve the economic and environmental sustainability of UK soft fruit production by delivering greater water, fertiliser and pesticide use efficiencies, improved plant health, higher marketable yields, better fruit quality and a reduction in waste.

Materials and methods

Plant material

Bare-rooted grade A+ plants of cv. ‘Vibrant’ and grade A plants of cv. ‘Sonata’ were obtained from Hargreaves’ Plants on 13 June 2014 and stored at -2°C until needed. On 17 September 2014, all plants were removed from the cold store and graded to improve size uniformity. Plants were planted in 3 L pots containing Botanicoir^{TM}; there were 60 pots for each cultivar. Plants were placed in the GroDome (a controlled environment facility at EMR) at day/night temperature of 23 ^{o}C/17 ^{o}C with a 12 h photoperiod and 60% relative humidity. Throughout the experiment, all plants received the standard EMR pest and disease spray programme.

Experimental design

Two experiments were conducted simultaneously during 2014, one for each cultivar, to identify the coir volumetric moisture content (CVMC) at which growth and cropping were negatively affected. Sixty experimental plants were included in each experiment and three irrigation treatments were applied:

(i) commercial control regime (CC) in which run-off of water and fertilisers averaged 20% over the growing season;

(ii) precision ‘closed loop’ fertigation (ITR), where run-off was eliminated and coir kept to near holding capacity;

(iii) a drying down treatment (DD), where irrigation was withheld so that the CVMC that triggered a range of physiological responses could be identified.

Both experiments were set up as a complete randomised block design with twelve replicates.

Irrigation application and scheduling

The timing and duration of irrigation events were controlled using a Galcon DC-4S unit (supplied by City Irrigation Ltd, Bromley, UK) connected to manifold housing six DC-4S ¾" valves. Water was sourced from the mains to ensure a reliable supply throughout the experiment. Irrigation water was delivered to each pot via a dripper stake connected to a 1.2 L $hour^{-1}$, non-return, dripper. Dripper outputs were tested prior to the experiment to ensure an accuracy of within 5%.

Coir volumetric moisture content (CVMC), electrical conductivity (EC) and run-off

Coir volumetric moisture content (CVMC) was monitored using Delta-T SM150 probes (Delta-T Devices Ltd). In each treatment, three sensors were connected to a Delta-T GP2 Advanced Datalogger and Controller unit. The average value from the SM150 probes was calculated automatically and if the average CVMC value was equal to or less than the irrigation set point, the solenoid valves were opened. The duration of irrigation at each event was adjusted to deliver the appropriate volume of run-off. These GP2 units were not fitted with telemetry and so values of CVMC were checked daily to provide assurance that the GP2 precision irrigation tool was working reliably and consistently. Twice per week, 'spot' measurements of CVMC and coir pore E.C. in each pot were made with a Delta-T 'WET'

Figure 3. Decagon ECRN-50 rain gauges were used to measure volumes of run-off.

sensor calibrated for coir. Two sets of holes were drilled into the side of the pots, one on the north side and one on the south side. The holes were positioned in the middle of the pot; this allowed for the horizontal insertion of the ‘WET’ sensor and provided a detailed profile of CVMC and pore E.C. throughout the rooting zone. Three plants per treatment were used to measure run-off. These pots were raised by placing them onto an upturned tray; the pots were tilted forward with the aid of wooden batons. The pots were previously placed in saucers which had a hole at the front edge; this hole was positioned directly above a Decagon ECRN-50 rain gauge (Decagon Devices Ltd, USA) which captured and measured the volume of run-off (

Figure 3.3).The loggers were downloaded daily to calculate the %run-off.

Measurement of physiological parameters

Measurements were made in each treatment in each experimental block twice per week. Stomatal conductance of a young, fully expanded leaf from one plant per treatment in each experimental block was measured with a steady-state porometer (Leaf porometer SC-1, Decagon Devices). Midday stem water potential of a young, fully expanded leaf from one plant per treatment in each experimental block was determined using a Skye SKPM 1400 pressure bomb (Skye Instruments Ltd, UK); leaves were covered carefully with aluminium foil for 90 min prior to measurement. Rates of photosynthesis of fully expanded leaves were measured using a portable infra-red gas analyser (LI-6400 XT, LiCor Biosciences).

One fruit and leaf from each plant per treatment was labelled in each experimental block. Fruit expansion rates were estimated by measuring the width of one fruit at two diametrically opposed positions on the fruit shoulder, and the length, using digital callipers. Fruit volume was estimated from these measurements by assuming that the fruit were conical. Measurements were made from fruit set to harvest, and then new fruit were labelled and measured. Leaf extension was determined by measuring the length of the middle trifoliate leaf blade of young expanding leaves twice-weekly until maturity; new expanding leaves were then labelled and measured. In total, leaf extension of two expanding leaves was measured throughout the season.

Fruit yield and quality

Flowers were hand pollinated with a small artist’s brush. Ripe fruit was harvested twice weekly. Fruit was graded, counted, and weighed for Class I, II and waste for each experimental plot.

Berry soluble solids content (SSC or °BRIX) was measured in juice collected by bulking Class I fruit from three experimental blocks using a digital refractometer (Palett 100, Atago

& co. Ltd, Tokyo, Japan). Fruit firmness (maximum load at 8 mm) of a bulk sample of Class I fruit from was determined with a penetrometer (Lloyds LRX TA plus) and with a Firmtech device (UP Umweltanalytische Produkte GMbh). Further samples of Class I fruit were collected from each experimental block from which the calyx was removed, the fruit chopped and sealed into labelled plastic bags and frozen immediately in liquid nitrogen. These fruit were stored at -80 ˚C until required for analysis of berry sugar and organic acid concentrations, and total antioxidant capacity.

Analysis of berry sugar, organic acid concentrations and total antioxidant capacity

Sample preparation

Strawberry samples were removed from -80 °C storage, freeze-dried and then ground to a fine power with a pestle and mortar. Sub-samples of 200 mg were used for sugar, organic acid and total antioxidant capacity analyses.

Sugars

Samples were homogenised in 10 mL of ultra-pure water, shaken for 30 min at 4 ˚C on an orbital shaker, and then centrifuged at 5040 g for 35 min. A 500 µL aliquot of sample was pipetted into a Thomson 0.45 µm PTFE filter vial. Samples of 5 µL were injected into a Waters Alliance 2690 HPLC. Sugars were separated on a Pinnacle II amino column 250 x 4.6 mm, 5 µm internal diameter (Thames Restek UK Ltd) and detected with a Waters 410 differential refractometer (RID). The mobile phase was 80:20 acetonitrile: ultra-pure water with a flow rate of 1.25 mL min^{-1}, column and RID temperature was 40 ˚C. Standards of known amounts of fructose, glucose and sucrose were injected into the high-performance liquid chromatography (HPLC) and Millinium32 software was used to produce linear calibration curves in the range of 5 to 50 µg with an r^2 0.999. These calibration curves were used to determine the concentration of fructose, glucose and sucrose in the samples.

Organic acids

Samples were homogenised in 10 mL of pure water containing 5 mM Tris (2-carboxyethyl) phosphine hydrochloride, shaken for 30 min at 4 °C on an orbital shaker, and then centrifuged at 5040 g for 35 min. A 500 µL aliquot of sample was pipetted into a Thomson 0.45 µm polytetrafluoroethylene (PTFE) filter vial. A five µL injection of sample was made into a Waters Alliance 2690 HPLC. Acids were separated on a Synergi hydro RP C18 250 x 4.6 mm, 5 µm internal diameter column (Phenomenex) and detected with a Waters 996 photodiode array (PDA) detector. Malic and citric acid were detected at 220 nm and ascorbic acid was detected at 243 nm. The mobile phase was 20 mM tri-potassium phosphate pH 2.9 with a flow rate of 1 mL min^{-1} with column temperature at 20 ˚C.

Standards of known amounts of malic, citric and ascorbic were injected into the HPLC. Millinium32 software was used to produce linear calibration curves in the range of 1.5 to 10 µg for malic acid, 2.5 to 20 µg for citric acid and 0.25 to 2 µg for ascorbic acid, each with an r^2 value of 0.999. These calibration curves were used to determine the concentration of malic, ascorbic, and citric in the sample.

Total antioxidant capacity

Samples were homogenised in 12 mL of 80% methanol, shaken for 30 min at 4 °C on an orbital shaker and then centrifuged at 5040 g for 35 min. Total antioxidant capacity was measured using the Trolox Equivalent Antioxidant Capacity (TEAC) method using a UV spectrophotometer (Pharmacia LKB Biochrom Ltd) at 734nm.

Statistical analyses

Statistical analyses were carried out using Genstat 13.1 Edition (VSN International Ltd). To determine whether differences between irrigation treatments were statistically significant, analysis of variance (AVOVA) tests were carried out and least significant difference (LSD) values for $p<0.5$ were calculated.

Results

CVMC and coir pore EC

The Delta-T GP2 Advanced Datalogger and Controller was used to trigger irrigation automatically in each cultivar once the average CVMC from three SM150 moisture probes reached a pre-determined set point in each of the three irrigation treatments. The averaging function of the GP2 ensured that the frequency of irrigation events was adjusted continually during and between days to maintain the CVMC within narrow limits in each of the three irrigation treatments.

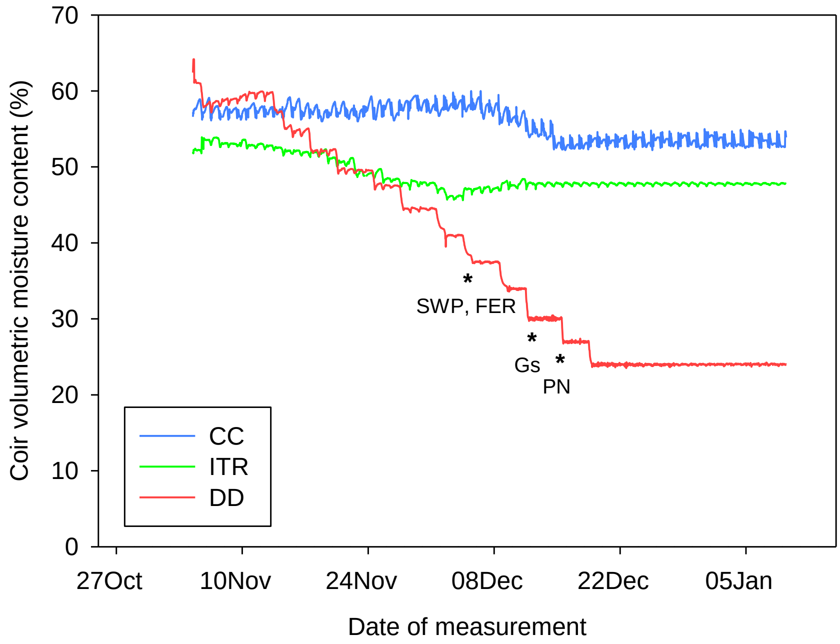

Figure 4. Average coir moisture contents in the three irrigation treatments applied to cv. Sonata measured using SM150 moisture probes inserted in the rooting zone

Throughout experiments, CVMC in the CC treatment was maintained between 47% and 54% for cv. 'Vibrant' (Figure 2) and 52% to 60% for cv. Sonata. In the ITR treatment, CVMC was maintained between 43% and 52% for cv. 'Vibrant' (Figure 2) and 46% to 54% for cv. 'Sonata' (Figure 4).

During the cropping period of cv. 'Sonata', 11.9, 7.7 and 6.5 L of irrigation water was applied to each plant under the CC, ITR and DD treatments, respectively. For the same period cv. 'Vibrant' plants grown under the CC, ITR and DD treatments received a total of 9, 8.5 and 5.8 L pot^{-1}, respectively. Therefore, water and fertiliser savings of 36% and 5% were achieved under the ITR treatment, compared to the CC treatments in cvs. 'Sonata' and 'Vibrant', respectively. For cv. 'Sonata' the total volume of run-of, for the duration of the experiment, excluding flushing events, was 2.4 and 0.5 L per plant for CC and ITR treatments, respectively; while for cv. 'Vibrant' volumes were 2.3 and 0.2 L, respectively.

Twenty-four days after the beginning of the DD treatment, the average CVMC fell to 37% for cv. 'Sonata' and as the DD treatment continued, CVMC gradually fell to 23% at which point each of the measured physiological parameters were significantly affected (Figure 44). Coir volumetric moisture content fell more rapidly in cv. 'Vibrant' than in cv. 'Sonata', probably due to the greater vigour and better establishment of cv. 'Vibrant' plants.

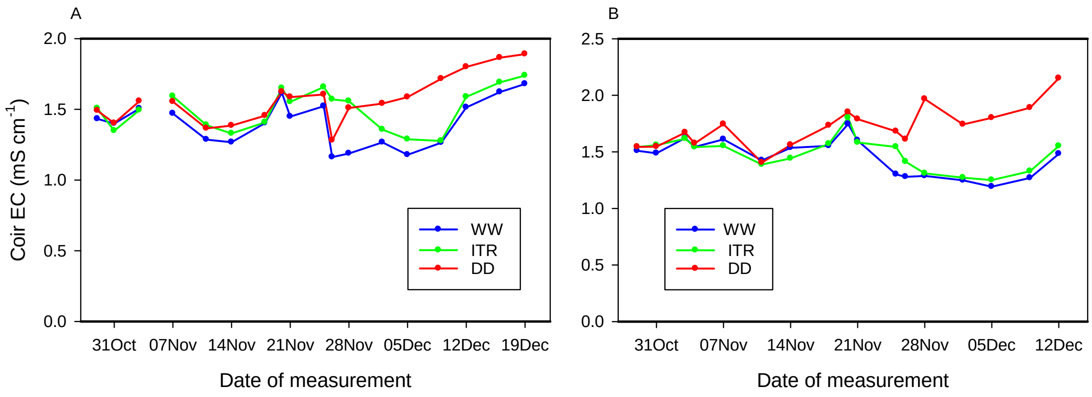

Figure 5. **'**Spot' measurements of coir pore E.C. made throughout the experiment using a WET sensor for cvs. 'Sonata' (A) and 'Vibrant' (B).

Coir pore E.C. values ranged from 1.2 to 2.2 mS cm^{-1} over the course of the experiment (Figure 5). Pore EC values were higher in the DD treatment for both cvs. 'Sonata' and 'Vibrant' towards the end of the growing period; this was a consequence of the reduced run-off in the DD treatments. Coir pore E.C. values were similar in the CC and ITR irrigation treatments over the course of the experiment (Figure 55).

Plant physiological responses to irrigation treatments

Plants respond to limited substrate water availability by adjusting the physiology of the shoots to limit transpirational water loss and since these changes can be measured, the point at which decreasing CVMC begins to affect productivity and fruit quality can be determined. Statistically significant reductions in midday stem water potential (Figure 66E) and the rate of fruit expansion (data not shown) were detected in cv. 'Sonata' under the DD treatment at an average CVMC of 38%. Further drying of the coir triggered the onset of stomatal closure at an average CVMC of 29% (Figure 66C) and a lowered photosynthetic rate (Figure 66A) at 26%. In cv. 'Vibrant', significant reductions in stomatal conductance (Figure 66D) and photosynthetic rate (Figure 66B) were triggered at an average CVMC of 30%, while stem water potential (Figure 66F) was first reduced significantly at 28%. Statistically significant reductions in leaf growth rate ($p<0.5$) was only detected in cv. 'Vibrant' at an average CVMC of 37% (data not shown). Physiological responses to limited coir water availability were not detected in either cultivar under the ITR treatment.

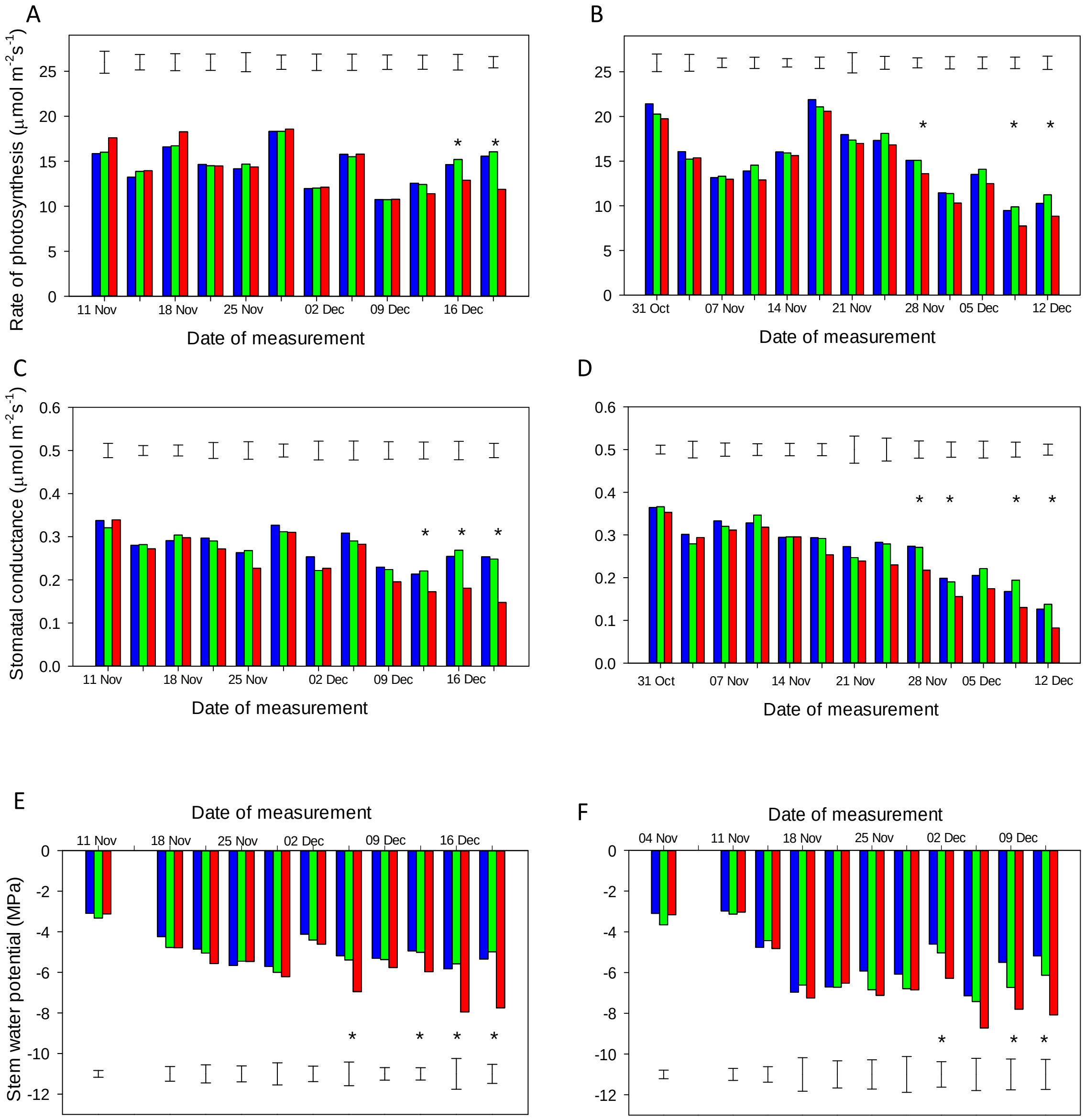

Figure 6. Average photosynthesis, stomata conductance and midday stem water potential of cvs. 'Sonata' (A,C,E) and 'Vibrant' (B,D,F). Asterisks show significant differences between the treatments on the date of the measurement. Vertical bars represent LSD values (p<0.05)

Mineral content of coir and leaf

Nutrient analyses of coir and leaf samples collected from each of the three irrigation treatments at the end of cropping indicated that the DD treatment affected nutrient uptake and / or availability. The cv. 'Vibrant' plants under the DD treatment had lower phosphorus, zinc, boron, and copper leaf concentrations, but a higher calcium concentration. Coir available phosphorus, ammonia and boron were lower in DD-treated cv. 'Vibrant' plants. There were no significant effects of irrigation treatment on leaf and coir nutrient concentrations in cv. 'Sonata'.

Effects of irrigation treatment on fruit yields and quality

Total yields fruit were around 167 g per plant and 217 g per plant for cvs. 'Sonata' and 'Vibrant', respectively (data not shown). The cv. 'Sonata' Class 1 yields were lower than expected, due to fewer fruit rather than an effect on berry fresh weight. This was presumably a consequence of the small crown diameter of the initial plant material (Cocco et al., 2011). Average yields of Class I fruit per plant were unaffected by the irrigation treatments in either cultivar (Table 2).

Table 2. The effects of the three irrigation regimes on Class I yield and quality.

Irrigation regime	cv. 'Sonata'			cv. 'Vibrant'		
	Class I yield (g plant^{-1})	Average BRIX (°)	Average Firmness (N)	Class I yield (g plant^{-1})	Average BRIX (°)	Average Firmness (N)
CC	112.5a*	7.8a	278.5a	159.4a	7.4a	232.2a
ITR	122.4a	7.3a	292.6a	169.7a	7.1a	233.2a
DD	114.0a	8.1a	291.2a	161.1a	7.8a	256.5a

*means followed by the same letter are not significantly different (p=0.05)

There were no significant treatment effects on fruit firmness or soluble solids content (°BRIX) in either cultivar (Table 2). Berry sugar and organic acid concentrations and total antioxidant capacity were also unaffected by the irrigation treatments (data not shown). The berry fresh weight: dry weight ratio was also unaffected by the treatments (data not shown).

Water productivity

Water productivity (WP) values were calculated for CC and ITR treatments in each cultivar (Table 3).The volume of water applied was first recorded from Day 0 (beginning of run-off elimination) and so WP values do not include water that was used to wet-up substrate, water that was applied via overhead irrigation during establishment or the water that was applied during the first four weeks of vegetative growth before the ITR regime was imposed. Consequently, the calculated WP values are artificially low although the low yields of Class I fruit offset this to some extent. Nevertheless, the WP values indicate the potential of using irrigation scheduling to reduce the volume of water used to produce 1 kg of Class I fruit.

Table 3. Volumes of water applied to cv. 'Sonata' and 'Vibrant' plants and Water Productivity values.

Treatment	cv. 'Sonata'		cv. 'Vibrant'	
	Water applied (L)	Water productivity	Water applied (L)	Water productivity
CC	11.9	74.6	9.0	80.0
ITR	7.7	45.4	8.5	69.4

Discussion

Substrate strawberry production is a major capital investment and yet irrigation/fertigation decisions are not often based on scientific evidence. An over-supply of water and fertilisers can limit fruit quality and shelf-life, and these detrimental effects are often accentuated in changeable weather. Producing a consistent supply of high quality, phytonutritious berries with an assured shelf-life is challenging and currently, an estimated 33% of all harvested fruit is wasted each year, due to disorders such as rots, bruising and a poor shelf-life. This project aims to deliver precision irrigation/fertigation management during substrate production of cvs. ‘Sonata’ and ‘Vibrant’.

Despite the fact that statistically significant differences in physiological responses were detected in the DD treatment, there were no significant treatment effects on average fruit yield or quality. As mentioned above, midday stem water potential is very sensitive to limited substrate water availability and can be used to detect the perception of substrate moisture ‘stress’ but information on the relationships between midday stem water potential, photosynthesis, fruit load, fruit expansion rate and CVMC or coir matric potential is needed to identify the point at which declining moisture availability begins to limit fruit size and marketable yields.

The results to date suggest that significant water and fertiliser savings can be achieved in commercial substrate production without affecting berry size, Class I yields or fruit quality if irrigation is scheduled to match demand with supply. Water and fertiliser savings of 5% and 36% have been achieved in our experiments with cvs. ‘Vibrant’ and ‘Sonata’ respectively, without affecting berry quality and yield.

Although, nutrient inputs were significantly reduced during the experiment, particularly for cv. ‘Sonata’, no foliar deficiency symptoms were detected. Moreover, our results suggest that varietal differences exist in nutrient demand and uptake, thus fertiliser formulations will need to be adjusted in some cultivars to account for the reduced input of fertilisers when irrigation is scheduled to match demand with supply.

Substrate pore EC values increased gradually over the experiment in all treatments and especially in the DD treatments, but remained within the perceived optimum range so fruit yields were not affected. The results of the mineral analysis of coir samples will inform the composition of the feed for the EC treatments in 2015 experiments, in order to simulate the build-up of these ions in coir. The time taken for plant and fruit responses to develop under the EC treatments will provide information on both the critical EC values and the duration of exposure needed to reduce fruit yields and quality and will help growers to manage water and fertiliser inputs more effectively.

The range of CVMC contents that should be imposed to achieve effective irrigation scheduling and utilise water and fertilisers efficiently have been identified for both cvs. ‘Sonata’ and ‘Vibrant’. Although the crop load of cv. ‘Sonata’ was low in this experiment, the CVMCs at which physiological response were first triggered are very similar to those identified in another experiment at EMR in 2014 with cv. ‘Sonata’ in which Class 1 yields of over 300 g per plant were achieved. These CVMC values will be used in experiments in 2015 to trigger irrigation automatically using GP2 data loggers and SM150 probes (Delta-T Devices, UK). This approach will also be used to irrigate and determine the critical coir EC values that limit fruit size. This research is needed to test whether the water-saving irrigation strategies can be implemented on grower sites with poor quality irrigation water (high background EC) and to provide fertigation guidelines that improve water and fertiliser use efficiency without reducing marketable yields or quality.

Conclusions

- Irrigation scheduling and deficit irrigation regimes were imposed successfully on 60-day cvs. ‘Sonata’ and ‘Vibrant’ plants.
- In cvs. ‘Sonata’ and ‘Vibrant’, water savings of 36% and 5% were achieved, respectively, without reducing yields of Class I fruit.
- In cvs. ‘Sonata’ and ‘Vibrant’, fertiliser savings of 36% and 5% were achieved, respectively, without reducing yields of Class I fruit. Foliar macro and micro nutrient concentrations were within satisfactory ranges.
- A new irrigation scheduling tool has been developed using irrigation set points based on coir volumetric moisture contents. This approach has the potential to deliver significant water and fertiliser savings in commercial cvs. ‘Sonata’ and ‘Vibrant’ production without reducing marketable yields and quality.
- Substrate EC was increased by 34% under the DD regime by the end of the experiments.
- The coir volumetric moisture contents needed to trigger irrigation automatically to 60-day crops were identified for each treatment and for each cultivar.

Knowledge and Technology Transfer

- The project aims and objectives were presented to the West Sussex Fruit Group, EMR, 29 July 2014
- The project aims and objectives were presented to a Moldovan group of growers, during a visit to EMR, 18 September 2014

- Presentation of the work to Dr John Hammond, University of Reading, 07 October 2015
- The project aims and objectives were presented at the BGG Waitrose Science Day at EMR on 24 October 2014
- The project aims and objectives were presented at the BGG Technical Day at Ashford, 5 November 2014
- The project aims and objectives were included in a presentation 'Improving food chain resilience, quality and security' made to the Agro-Cleantech Cluster, 8 December 2014
- Project aims and objectives were included in a presentation 'Improving resource use efficiency, yields and quality of fresh produce' at the Waitrose Science Day, University of Warwick, 25 February 2015
- Project aims, objectives and results were presented in a article published in the Soft Fruit AHDB Horticulture review magazine, February 2015

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