Project title:	Managing water, nitrogen and calcium inputs to optimise flavour and shelf-life in soil-less strawberry production
Project number:	SF 107
Project leader:	Dr Mark A. Else, East Malling Research
Report:	Annual Report, March 2010
Previous reports:	Not applicable
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Location of project:	East Malling Research, East Malling, Kent
Project co-ordinators:	John Atwood, ADAS
Date project commenced:	1 April 2009
Date completion due:	31 March 2012
Keywords:	Ammonium, calcium, diffuse pollution, 'Elsanta', fertigation, flavour, irrigation scheduling, nitrate, nutrition, shelf-life, 'Sonata', strawberry, substrate culture, water use efficiency

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.

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Contents

GROWER SUMMARY

Headline

Irrigation scheduling and Regulated Deficit Irrigation (RDI) have achieved water and nutrient savings of 45%, reduced leaf canopy and reduced % bruising of Sonata in shelf-life tests, whilst maintaining Class 1 yields.

Background and expected deliverables

The project aims to provide the potential to increase water use efficiency (WUE) and nutrient use efficiency (NUE) in UK substrate-grown strawberry production by 40% thereby saving water, reducing groundwater pollution and improving fruit quality and shelf-life.

Irrigation of substrate-grown strawberries is essential to attain the yields and quality demanded by retailers and consumers. Many growers apply sufficient irrigation to achieve 20% run-off to avoid dry spots within the substrate bags and to reduce the accumulation of salts. However, Defra, the Environment Agency and the soft fruit industry are all becoming increasingly concerned about the future availability of abstracted water for trickle irrigation. Current abstraction rates in the major strawberry-growing regions are unsustainable and growers must now comply with legislation designed to safeguard these resources (The Water Act 2003). Mains water will become progressively more expensive and its use for irrigation of horticultural crops is likely to be restricted in heavily populated areas as pressure on finite supplies intensifies. There is also increasing concern over the contribution of substrate strawberry production to groundwater pollution. Recent research at EMR and elsewhere has provided major opportunities to use water and fertilsers more efficiently while continuing to meet consumer demand for sweet fruit with good flavour and shelf-life.

Irrigation management techniques such as Regulated Deficit irrigation (RDI) offer the potential to deliver large water savings while maintaining or improving crop quality. Deficit irrigation techniques such as RDI replace only a percentage of the water the plant loses *via* transpiration. This saves water and can prevent excessive shoot growth without reducing yields of Class 1 fruit. The smaller, less dense canopy can reduce disease pressure and helps to improve light capture by the plant because there is less self-shading of the leaves. Better light penetration and interception will also help to increase fruit quality including flavour volatile production and bioactive content. The reduction in vegetative growth also provides opportunities to reduce fertiliser inputs without affecting berry flavour. For growers using mains water, there is the potential to reduce annual water costs by up to 40%.

There are two aims to this project:

1. To improve water and nutrient use efficiency in substrate-grown strawberry production.
2. To improve flavour and shelf-life potential by manipulating nitrogen and calcium inputs.

Expected deliverables from this work will include:

- Improved fruit firmness, flavour and shelf-life potential
- Reduced production costs per tonne Class 1 fruit
- Reduced water and fertiliser usage by up to 40%
- Reduced environmental impact
- Improved sustainability

Summary of the project and main conclusions

Critical issues

An increase in the incidence of mildew was noticed in the first week of August 2009, despite routine weekly sprays. The Farm and Glasshouse team were notified and a one-off application of potassium bicarbonate was applied. Unfortunately an error in the written protocol dating from 2006 meant that the spray was applied at 10 times strength. All foliage was scorched and remaining fruit were damaged. Consequently, yields of Class 1 fruit were below those expected. However, sufficient fruit was collected for all chemical and sensory analyses to be completed (see below) before this incident occurred.

Irrigation scheduling and RDI

Sixty-day ‘Elsanta’ and ‘Sonata’ plants were grown in 0.5 m-long substrate bags (80% peat, 20% coir) in a polytunnel at East Malling Research (EMR) (Figure GS 1). Three irrigation treatments were applied:

- Run-off - irrigation was scheduled to achieve between 10 and 20% run-off.
- 100% of daily potential evapotranspiration (ETp) - irrigation was applied to match demand with supply *i.e.* the volume of water

Figure GS 1. The polytunnel experiment at EMR. Photo taken on 14 July 2009 estimated to have been lost in the previous 24 h was replaced.

- RDI 80% - only 80% of the water lost by evapotranspiration each day was supplied.

Irrigation water was supplied to each substrate bag *via* one 4 L h^{-1} pressure compensated emitter fitted with a four-way dripper 'spider' to distribute water evenly throughout the bag (Figure GS 2). For the ETp 100% treatment, potential evapotranspiration was estimated using a Skye Evaposensor and the volume of irrigation water needed to replace that lost by evapotranspiration during the previous 24 h was calculated. Irrigation was pulsed throughout the day to help minimise run-off. In the RDI 80% treatment, plants received only 80% of the daily ETp, again irrigation was pulsed throughout the day.

Changes in volumetric substrate moisture content (VSMC) were logged continuously using Decagon 5TE probes and loggers and Sentek EasyAG probes. Manual measurements of VSMC and substrate EC were made with a Delta-T 'WET' sensor. Measurements made at multiple points within representative bags confirmed that water and nutrients were being distributed evenly in each treatment and for each variety. During the course of the experiment, the VSMC threshold values needed to trigger irrigation automatically to the main season crop in 2010 were identified for each treatment and for each variety.

Figure GS 2. Cropping 'Elsanta' plants under the RDI 80% regime just before the potassium bicarbonate spray. Photo taken on 6 August 2009

Nutrition

The same fertigation regime was applied to all treatments and was formulated after mineral analysis of the irrigation water used for the trial. Hortipray 'Mars', Hortipray calcium nitrate and Hortipray magnesium sulphate were supplied free of charge for the trial by Prayon UK Ltd (Harpenden, Hertfordshire, UK). Nitric acid (60%) was used to reduce the bicarbonate levels in the irrigation water. Different feed formulations were used for the vegetative and fruiting stages and Dosatrons were used to adjust the feed EC levels. EC and pH of the diluted feed solution were measured daily at the drippers, together with the EC of the run-off. All bags were flushed through with a solution of calcium nitrate periodically to prevent the build-up of salts. Since plants were fertigated at every irrigation event, the total amount of fertiliser supplied to the different treatments depended on the duration of each irrigation event which was adjusted to deliver the appropriate volume of water (see below).

Volumetric substrate moisture contents and EC

The average VSMC was maintained between 0.45 and 0.55 m^3 m^{-3} in the run-off treatments in both varieties. Under the ETp 100% regime, the substrate was maintained between 0.2 and 0.3 m^3 m^{-3} during flowering and cropping while VSMC of between 0.1 and 0.2 m^3 m^{-3} were imposed during the RDI 80% regime. Substrate EC rose steadily over the season from 100 to 300 mS m^{-1} but values were similar in the three irrigation regimes for 'Elsanta'. A similar rise in substrate EC occurred in 'Sonata' but by the end of August, substrate EC in the RDI 80% regime was 20% higher than that in the run-off regime. The effects of this accumulation of salts on canopy growth, fruit development and quality could not be assessed fully because at this time, all plants were recovering from the scorching effect of the potassium bicarbonate spray. However, there was no marginal leaf browning which is a common response to high salt concentrations. As expected, substrate EC rose sharply following the spray but all bags were flushed through with calcium nitrate for six days to reduce substrate and run-off EC.

Plant physiological responses

Leaf elongation was slowed in 'Sonata' by the ETp 100% and the RDI 80% regimes compared to the run-off treatment and this resulted in a reduction of total leaf area of 16% and 39%, respectively, by the end of the growing season (Figure GS 3). Leaf elongation rates were also slowed in 'Elsanta' by the ETp 100% and the RDI 80% regimes, but the response was less pronounced and resulted in total leaf area reductions of 14% and 20%, respectively, by the end of the growing season. No treatment effects on stomatal conductance were detected for either

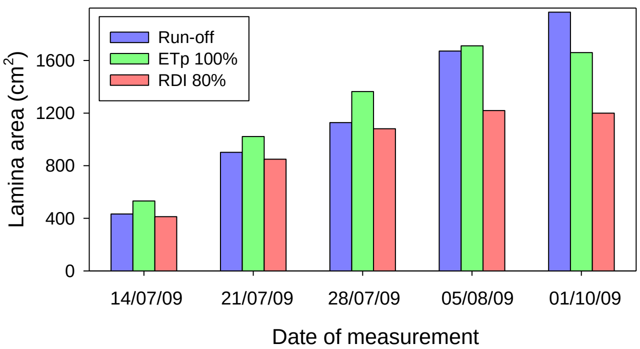

Figure GS 3. Effect of the irrigation regimes on estimated total canopy area of 'Sonata' cultivar and midday leaf water potentials were similar, irrespective of the irrigation regime. These results indicate that excessive vegetative growth was prevented by irrigation scheduling and deficit irrigation without reducing stomatal apertures or shoot water balance. Benefits of a smaller canopy include improved light penetration to developing fruit, a lowered disease pressure, improved resource allocation and improved fruit visibility when picking. Leaf samples were analysed for macro and micro nutrients at the beginning, the middle and the end of cropping. All foliar concentrations were within satisfactory ranges for both varieties under each of the three irrigation regimes with the exception of Ca and Cu which were just below the lower limits.

Fruit yields and quality

Total yields of Class 1 fruit were only around 150 g per plant, rather than the 250-300 g expected, due to the scorching effects of the potassium bicarbonate spray. However, average yields of Class 1 fruit per plant were not reduced by the ETp 100% and RDI 80% regimes in either variety, compared to the run-off controls. Berry firmness was unaffected in either variety by the irrigation regimes and no treatment effect on berry soluble solids content (% BRIX) was detected; values ranged from 8 to 11. Although concentrations of glucose, fructose and sucrose were slightly but significantly reduced in 'Elsanta' by the RDI 80% regime, the sugar to acid ratio was similar in fruit sampled from plants under each of the three irrigation regimes. Furthermore, no significant differences were detected during taste tests by an EMR taste panel. 'Sonata' berry concentrations of ellagic acid, an important bioactive, were increased by the RDI 80% regime and total antioxidant capacity was also raised in these fruit.

Shelf-life potential

Rates of water loss from 'Elsanta' berries held at 5 ºC were greater from fruit that had received the run-off irrigation regime but the rate of development of bruising was delayed in these fruit, compared to that of fruit from the ETp 100% and RDI 80% regimes. However, the percentage of fruit with bruising was similar across all treatments by the end of the 6-day shelf-life test. The rate of water loss from 'Sonata' fruit was slowed in berries previously under the run-off regime. The percentage of 'Sonata' fruit that developed bruising over the 6-day shelf-life test was reduced from 45% in run-off controls to 15% by the RDI 80% regime.

Water and fertiliser use

The volume of irrigation applied to each plant under each of the three irrigation regimes is presented in Table GS 1. Scheduling irrigation to match demand with supply resulted in water savings of 41% and 30% for ‘Elsanta’ and ‘Sonata’ respectively, while the RDI 80% regime delivered even greater water savings.
Since plants were fertigated at each irrigation event, the total amounts of the macro and micro nutrients applied to each bag were reduced in proportion to the irrigation volume. Consequently, fertiliser savings of between 30% and 45% were achieved using the ETp 100% and RDI 80% regimes.

Conclusions

- Irrigation scheduling and deficit irrigation regimes were imposed successfully on 60-day ‘Elsanta’ and ‘Sonata’ plants.
- Yields of Class 1 fruit were reduced in all treatments due to the scorching effect of a 10 times strength potassium bicarbonate spray.
- Water savings of up to 45% were achieved without reducing yields of Class 1 fruit.
- Fertiliser savings of up to 45% were achieved without reducing yields of Class 1 fruit.
- Foliar concentrations of N, P, K, Mg, Mn, Fe. Zn, B and S were within satisfactory ranges in each cultivar under each irrigation regime. Concentrations of Ca and Cu were just below satisfactory values by the end of the cropping season.
- Substrate EC was increased by 20% under the RDI 80% regime by the end of the growing season.

Table GS1. Total volumes of irrigation water applied per plant for each irrigation regime and the percent reduction in water use delivered by the ETp 100% and RDI 80% regimes

Irrigation regime	**Total volume of irrigation water applied (L per plant)**		**Reduction in water use (% of run-off)**	
	‘Elsanta’	**‘Sonata’**	**‘Elsanta’**	**‘Sonata’**
Run-off	9.4	11.1	-	-
ETp 100%	5.5	7.8	41	30
RDI 80%	5.2	6.3	45	43

- Total leaf area reductions of 20% and 39% were achieved for RDI-treated ‘Elsanta’ and ‘Sonata’, respectively.
- The percentage of ‘Sonata’ fruit that developed bruising over the 6-day shelf-life test was reduced from 45% in run-off controls to 15% by RDI.
- The VSMC threshold values needed to trigger irrigation automatically to the main season crop in 2010 were identified for each treatment (run-off, ETp 100% and RDI 80%) and for each variety.

Financial benefits

The project aims to improve the economic sustainability of soil-less strawberry production by improving both water and nutrient use efficiencies and manipulating the form of nitrogen nutrition. Savings associated with a 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. However, achieving these reductions without affecting yields or quality may only be possible by increasing the number of dripper stakes in each substrate bag to ensure that water and nutrients are evenly distributed. A full cost-benefit analysis of implementing the new irrigation and fertigation regimes will be completed in the final year of the project to enable growers to make informed decisions about the best options available to them.

Action points for growers

- Consider using eight dripper stakes per 1-m-long substrate bag to ensure that water and nutrients are distributed evenly throughout the bag.
- Consider reducing the irrigation volume so that run-off is reduced or eliminated.
- Test the potential of RDI by turning off the irrigation for several days to several bags to see how long it takes the plants to show signs of wilting. Correlate this with the evaporative demand over that time and use the result to apply irrigation to a small block of plants one to two days before wilting is predicted to occur. Compare water and nutrient use and yields of Class 1 fruit from this block with the commercial crop.
- It should be noted however that fruit growth will begin to be limited and Class 1 yields reduced if plants begin to wilt.

SCIENCE SECTION

Introduction

All soft fruit produced in England and Wales is reliant on irrigation to ensure that quality at market date matches the specifications demanded by retailers and consumers[1]. Although the majority of production is currently field-grown, the number of growers switching to soil-less production is increasing as they strive to reduce labour costs associated with picking. Current recommendations for substrate growers are to irrigate to achieve a 10-20% run-off[2] or to apply 500-700 ml per plant per day[3]. This approach is used to ensure that the substrate is wetted thoroughly so there are no dry patches within the bag and to reduce the build-up of potentially damaging salts within the substrate bag. However, 84% of all soft fruit grower sites lie within regions where competition for limited water supplies is increasing and 48% are in areas classified by the Environment Agency (EA) as being either 'over abstracted' or 'over licensed' (Figure 1). Abstraction rates in these areas are unsustainable and are predicted to rise by a further 30% by 2050[4]. Legislation designed to safeguard these resources and limit damage to the environment (*e.g.* Water Framework Directive 2000, The Water Act 2003) will place restrictions on future water use and growers will have to demonstrate efficient use of available water before time-limited abstraction licences are renewed. The use of mains water to irrigate soft fruit will become increasingly expensive and environmentally undesirable as water companies strive to maintain supplies.

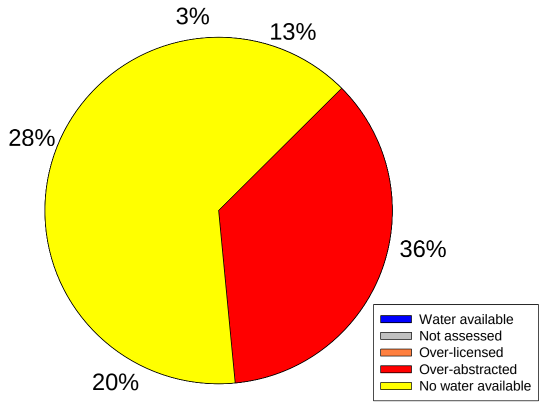

Figure 1. Assessment of water resource availability (for direct abstraction) for the soft fruit sector in 2008 (re-drawn from Knox *et al*., 2009)

Feeding continuously with every irrigation event is also recommended[2] but this approach is also unsustainable. The major strawberry-growing regions are, or will soon be, designated as Nitrate Vulnerable Zones (NVZ's) and although diffuse pollution from strawberry production is perceived as being low[5], the EA are becoming increasingly concerned about the environmental impact of substrate production. In future, growers will have to limit their inputs to comply with legislation (The Nitrates Directive Action

Programme). There is also a financial driver to reduce inputs; fertiliser prices have doubled in recent years and costs of production could be significantly reduced by using fertilisers more efficiently.

In addition to facilitating compliance with legislation, new irrigation guidelines that improve water and nutrient use efficiency could also be expected to improve the consistency of supply of high quality, healthy fruit with good shelf-life and a reduced susceptibility to bruising. One aim of this HDC-funded project is to develop an irrigation scheduling regime that avoids the excessive use of water (and fertiliser) associated with current regimes. We have already shown in pot experiments that if an irrigation scheduling regime is used that matches plant demand with supply, water savings of up to 40% can be achieved compared to current recommendations, without affecting yield or quality of Class 1 fruit[6,7]. However, it will be important to manage the scheduling regime carefully to ensure that the reduced irrigation volume does not lead to a build-up of salts within the substrate bag. Further water savings can be delivered when deficit irrigation is used. Regulated Deficit Irrigation (RDI) involves applying less irrigation water than the plant requires so that some roots are gradually exposed to drying substrate (Figure 2). These roots produce chemical signals that are transported to the shoots where they invoke several physiological responses that limit water loss from the canopy. Canopy areas can be reduced by up to 40% without affecting yields of Class 1 fruit. Fruit quality attributes including soluble solids content (SSC [BRIX]), ascorbic acid (vitamin C) concentration and flavour volatile production can also be improved in deficit-grown plants[6,7]. However, deficit irrigation must be applied carefully

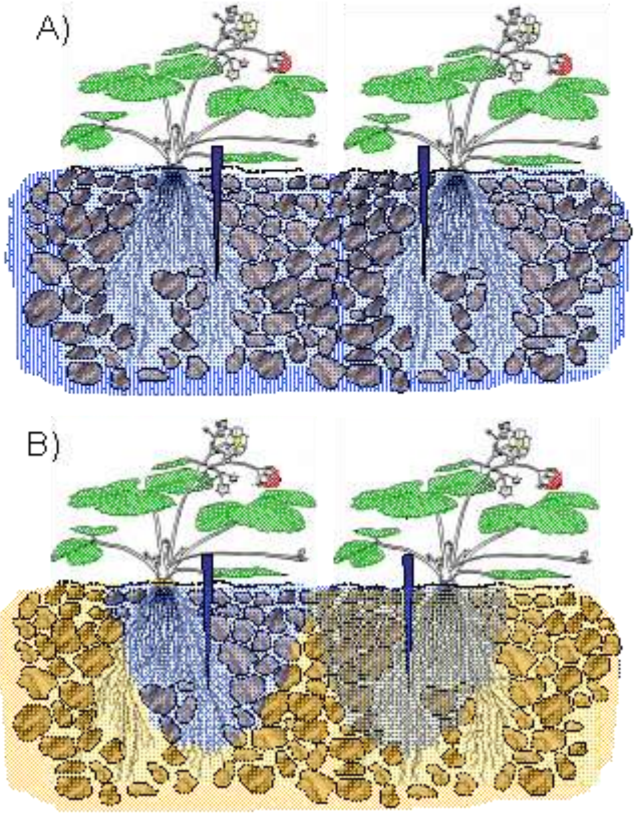

Figure 2. A) When irrigation is scheduled to achieve 'run-off', the substrate is wetted fully and all roots are able to supply water and nutrients to sustain shoot growth and fruit development. B) Under an RDI regime, gradual substrate drying occurs which triggers the production of root-sourced chemical signals that restrict transpirational water loss and limit leaf growth. These root-sourced signals may also impact on fruit quality

as both fruit size and quality can be compromised if the extent of substrate drying is not controlled sufficiently precisely[8]. Again, the effect of the RDI regime on substrate EC and the consequences for plant growth, Class 1 yields and fruit quality needs to be determined.

An irrigation scheduling regime that eliminated run-off and an RDI regime where only 80% of daily ETp was replaced were imposed on 60-day 'Elsanta' and 'Sonata' plants in a polytunnel experiment at EMR in 2009. The effects of these treatments on canopy development, Class 1 yields, fruit flavour components and shelf-life potential were compared with those of an irrigation regime that resulted in between 10 and 20% run-off.

Materials and Methods

Plant material

Bare-rooted grade A+ plants of 'Elsanta' and 'Sonata' were obtained from Hargreaves' Plants on 13 May 2009 and stored at 2°C until needed. Seventy two 0.5 m-long substrate bags containing an 80:20 peat:coir mix with 0.5 kg m^{-3} base fertiliser (NPK 15:10:20) and a wetting agent (Avoncrop Ltd, Somerset, UK) were positioned on table tops in a polytunnel at EMR. All bags were wetted thoroughly prior to planting, irrigation water was delivered to each bag *via* one 4 L h^{-1} pressure compensated emitter fitted with a four-way dripper 'spider' to distribute water evenly throughout the bag. On 22 June 2009, each substrate bag was planted with four of either 'Elsanta' or 'Sonata'; there were 36 bags for each cultivar. Overhead irrigation was applied several times per day to ensure that the crowns were kept moist and that the substrate was thoroughly wetted during establishment. Throughout the experiment all plants received the standard EMR pest and disease spray programme (but see below).

Experimental design

A split plot experimental design was used with cultivar as main plots and irrigation regime as sub-plots (Figure 3). Each table contained three bags of the same cultivar and two tables were combined to form a replicate. A different irrigation treatment was applied to each of the three bags on each table. Three irrigation regimes were imposed: 1) sufficient irrigation to achieve between 10 and 20% run-off (to match current commercial practice); 2) scheduled irrigation where plants received 100% of the daily ETp; 3) RDI where plants received only 80% of the daily ETp.

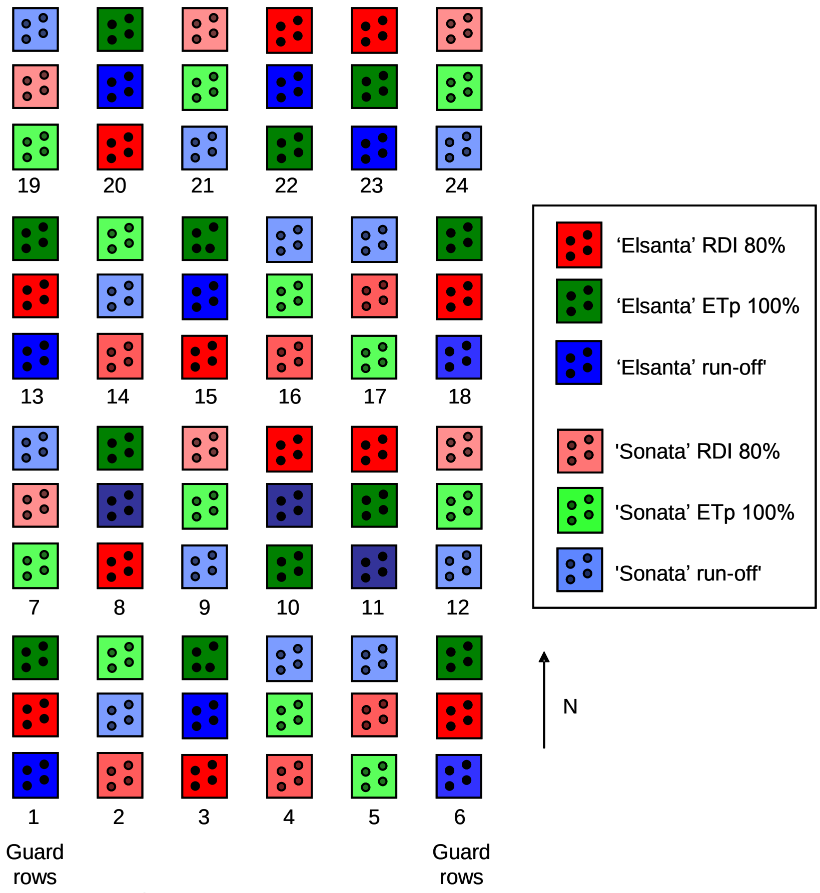

Figure 3. Plot plan showing the experimental design. Rows 1 and 6 were designated as guard rows and all measurements were made on plants in rows 2 to 5. Each substrate bag contained either four 'Elsanta' or four 'Sonata' plants.

Irrigation application and scheduling

The timing and duration of irrigation events was controlled using two Galcon DC-4S units (supplied by City Irrigation Ltd, Bromley, UK) connected to a manifold housing seven DC-4S ¾" valves. Water was sourced from the mains to ensure a reliable supply throughout the experiment. A water meter was connected and measured volumes of water used during different stages of crop development. Dripper outputs were tested prior to the experiment to ensure an accuracy of within 10%. Irrigation was pulsed throughout the day to help minimise run-off in the ETp 100% and RDI 80% treatments.

Figure 4. The Skye Evaposensor and Evapometer used to estimate potential evapotranspiration. Photo taken on 4 August 2009

Irrigation regimes were first applied on 14 July 2009 when the plants were at 50% full bloom. For the run-off treatment, the volume of water leaching from the bags was measured each day and the duration of each irrigation event was adjusted accordingly to ensure run-off of between 10 and 20% of the irrigation volume applied. Potential evapo-transpiration (ETp) values were obtained using an SKTS 500/PRT Evaposensor and SEM 550 Evapometer (Skye Instruments Limited, Llandrindod Wells, Powys, UK). The Evaposensor was positioned amongst the experimental plants and maintained at canopy height (Figure 4).

Leaf areas were estimated weekly to enable the calculation of calibration factors that were used in conjunction with readings from the Evaposensor to calculate the amount of water lost over the previous 24 h. The appropriate volume of water was then applied to ETp 100% and RDI 80% plants during five irrigation events scheduled throughout the day.

Fertigation

The same fertigation regime was applied to all treatments and was formulated by Mr Michael Daly (The Agrology House, Lincs., UK) after mineral analysis of the mains water used for the trial. Hortipray 'Mars', Hortipray calcium nitrate and Hortipray magnesium sulphate were supplied free of charge for the trial by Prayon UK Ltd (Harpenden, Hertfordshire, UK). Nitric acid (60%) was added to each tank in order to reduce the bicarbonate concentration of the water to around 50 mg L^{-1} for buffering purposes. Plants were fertigated from two stock tanks, one containing calcium nitrate (Hortipray, 19% Ca, 14.5% NO_3-N, 1.0% NH_4-N) and a second for the Hortipray 'Mars' (6-11-37, 4 MgO, and trace elements) and magnesium sulphate (Hortipray, 9.6% Mg). Different feed formulations were used for the vegetative and fruiting stages and Dosatrons were used to adjust the feed EC levels. An 'early feed' was applied to the crop for the first three weeks after planting, followed by a fruiting feed when the flowers were setting green fruit. The nutritional composition of the two feeds (including background water and nitric acid) is given in Table 1. EC and pH of the diluted feed solution were measured daily at the drippers, together with the EC of any run-off. All bags were irrigated with a solution of calcium nitrate periodically to prevent the build-up of salts. Since plants were fertigated at every irrigation event, the total amount of fertiliser supplied to the different treatments depended on the duration of each irrigation event which was adjusted to deliver the appropriate volume of water.

Volumetric substrate moisture content and EC

Changes in volumetric substrate moisture content (VSMC) were logged continuously using Decagon 5TE probes and loggers and Sentek EasyAG probes. Substrate EC was also logged continuously using the 5TE probes. Manual measurements of VSMC and substrate EC were made with a Delta-T 'WET' sensor.

Measurement of physiological responses

All routine measurements were carried out on one plant in each of eight replicate bags per treatment in rows two to five (see Figure 3). Tables in rows 1 and 6 were used as guard plants to avoid any edge effects at the sides of the polytunnel. Midday leaf water potential (ψ_L) was measured weekly; for each plant, one young, fully-expanded, trifoliate leaf was excised using a sharp blade and sealed in to a plastic bag containing a sheet of damp tissue paper. Within 30 s of excision, ψ_L was determined with a Skye SKPM 1400 pressure bomb (Skye Instruments Ltd, UK). Stomatal conductance of one young, fully-expanded, leaflet was also measured twice-weekly with a steady-state porometer (EGM-1, PP Systems, UK). Leaf chlorophyll content was measured weekly with a SPAD meter.

Table 1. Nutritional analysis of the early and fruiting feeds diluted 1:100 (including background water and nitric acid).

Nutrient	Concentration in diluted feed (mg L^{-1})	
	Early feed	Fruiting feed
NO_3-N	125	122
NH_4-N	4	3
P	33	40
K	205	251
Ca	151	135
Mg	27	31
B	0.21	0.25
Cu	0.14	0.17
Fe	1.38	1.69
Mn	0.60	0.73
Mo	0.03	0.03
Zn	0.66	0.81
EC (mS cm^{-1})	1.74	1.86

Non-destructive estimates of plant lamina area, leaf number and mean leaf size were made weekly. The areas of three leaflets (small, medium and large, relative to plant size) per plant were measured (LI-3000 portable leaf area meter, LAMBDA Instruments Corporation, USA) and the total number of small, medium and large leaves per plant was counted.

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 five expanding leaves was measured throughout the season.

Fruit harvesting, grading and sampling for quality analyses

Ripe fruit were harvested and recorded from one plant in each of eight bags per treatment in rows two to five (see Figure 3). Ripe fruit were first harvested on 31 July and were collected twice weekly until 1 September 2009. All ripe fruit were harvested and graded into four size categories: 35 mm+, 25-35 mm, 22-25 mm and waste (small, diseased, or mis-shapen fruit). The former two classes constitute commercial Class 1 fruit, with class 2 fruit being 22-25 mm. The fresh weight of fruit in each size class was recorded at each harvest using a portable balance (ScoutPro 4000, Ohaus UK Ltd, UK). Berry firmness of one primary or secondary fruit was measured at two diametrically opposed points using a hand-held penetrometer (HPE II, Bureiss Prüfgerätebau, GmbH) fitted with a 0.5 cm^2 anvil. Each fruit was then cut in half and SSC was measured in one half with a digital refractometer (Palett 100, Atago & Co. Ltd, Tokyo, Japan).

Non-volatile flavour analysis

After measurements of SSC, the calyx and peduncle were removed from the other fruit half; which was then frozen immediately in liquid nitrogen and stored at -80 ^{o}C prior to analysis of non-volatile flavour components. Fruit concentrations of sugars (glucose, fructose, sucrose), organic acids (ascorbic, citric, malic, oxalic) and ellagic acid (a bioactive compound) were determined using HPLC with Refractive Index and Photo-diode Array detection. Total antioxidant activity was also determined for berries harvested from the different irrigation regimes.

Taste tests

Taste tests were carried out at EMR using an experienced taste panel. Berries were harvested on 6 August 2009; fruit were pooled within treatments and cultivar then cut in to four and blended to form a puree. Samples were given in clear plastic cups to six panel members who were asked to place a cross on a 10 cm line with quartiles marked to indicate the level of sweetness of each puree. A palate cleanser of water was used between each puree. The SSC of the purees were also measured.

Shelf-life tests

Shelf-life tests were undertaken for primary fruit harvested on 6 August 2009. For each treatment and for each cultivar, 12 ripe strawberries were harvested and placed in a punnet. All punnets were stored at 5 ºC for seven days. Weight loss from each punnet was measured daily and the number of fruit with visible bruises and rots was recorded on each of the seven days.

Calculation of water productivity

The total volume of water applied during the experiment from 14 July until 1 September 2009 was calculated for each cultivar and for each irrigation regime. The volume of irrigation water (L) used to produce a standard mass of Class 1 fruit (1 kg) was also calculated. This is an estimate of water productivity (WP) and a lower value implies a more productive use of water.

Figure 5. Leaves and fruit damaged by the potassium bicarbonate spray that was applied at 10 times strength. Photo taken on 11 August 2009

Statistical analyses

Statistical analyses were carried out using GenStat 10th Edition (VSN International Ltd.). Analysis of variance tests were carried out and least significant difference (LSD) values for $p<0.05$ were calculated.

Potassium bicarbonate spray

An increase in the incidence of mildew was noticed in the first week of August 2009, despite routine weekly sprays. The Farm and Glasshouse team were notified and a one-off application of potassium bicarbonate was applied. Unfortunately an error in the written protocol dating from 2006 meant that the spray was applied at 10 times strength. All foliage was scorched and remaining fruit were damaged (Figure 5). Consequently, yields of Class 1 fruit were below those expected. However, sufficient fruit was collected for all chemical and sensory analyses to be completed before this incident occurred. Leaf growth and physiology were obviously greatly affected by the spray and although all plants recovered fully, rates of water loss from the scorched canopy were temporarily reduced. Therefore, the estimates of water productivity reported for this experiment will need to be verified in the 2010 cropping season.

Results

Complete data sets for all parameters listed in the Materials and Methods section were collected for both ‘Elsanta’ and ‘Sonata’ under each of the three irrigation regimes. In most cases, there were no statistically significant differences in the measured parameters between the different irrigation regimes for each cultivar. For the sake of brevity, not all results are shown for each cultivar.

Volumetric substrate moisture contents and EC

The average VSMC was maintained between 0.45 and 0.55 m^3 m^{-3} in the run-off treatments in both cultivars; data for 'Sonata' are presented in Figure 6A. Under the ETp 100% regime, the VSMC was maintained between 0.2 and 0.3 m^3 m^{-3} during flowering and cropping while VSMC of between 0.1 and 0.2 m^3 m^{-3} were imposed during the RDI 80% regime (Figure 6A).

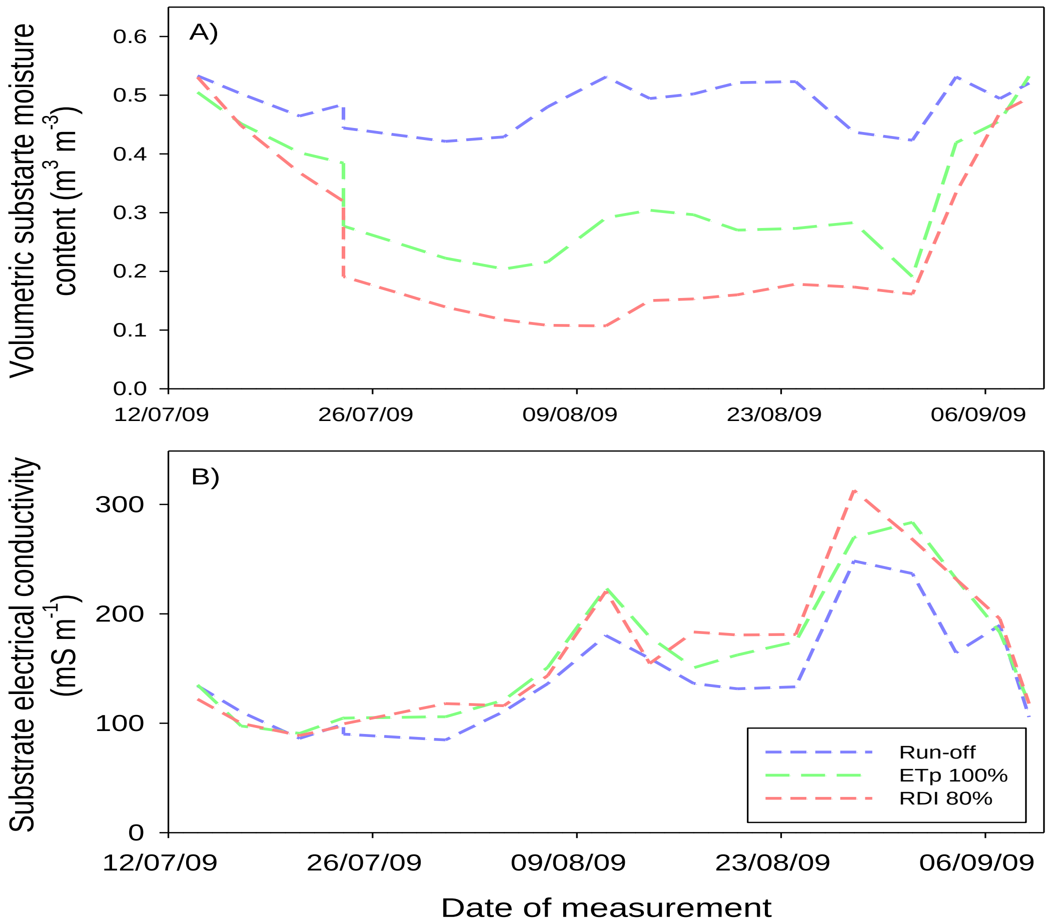

Figure 6. Changes in A) volumetric substrate moisture content and B) substrate EC in bags containing 'Sonata' strawberry plants under the different irrigation treatments. Results are means of measurements taken from eight replicate bags per treatment.

Greater resolution was obtained by continuously logging changes in substrate moisture content using the Sentek EasyAG probes; significant soil moisture deficits developed during the cropping stage and the substrate moisture deficit was maintained around the ‘onset of stress’ threshold (Figure 7). These data confirm that the RDI treatment was being imposed effectively.

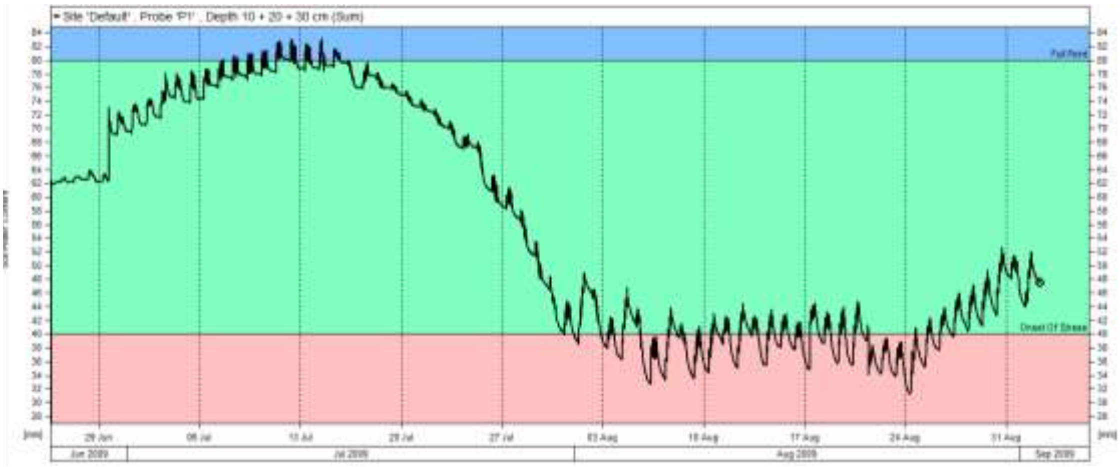

Figure 7. EasyAG probe data collected from a probe in a substrate bag receiving the RDI 80% ETp regime. The ‘onset of stress’ line is an arbitrary value that is 50% of the ‘Full point’ value.

Substrate EC rose steadily over the season from 100 to 300 mS m^{-1} but values were similar in the three irrigation regimes for ‘Elsanta’. A similar rise in substrate EC occurred in ‘Sonata’ but by the end of August, substrate EC in the RDI 80% regime was 20% higher than that in the run-off regime (Figure 6B). The effects of this accumulation of salts on canopy growth, fruit development and quality could not be assessed because at this time, all plants were recovering from the scorching effect of the potassium bicarbonate spray. As expected, substrate EC rose sharply following the potassium bicarbonate spray on 7 August 2009 (Figure 6B) but all bags were flushed through with calcium nitrate for six days to reduce substrate and run-off EC. Manual measurements made with the WET sensor at multiple points within representative bags confirmed that water and nutrients were being distributed evenly in each treatment and for each cultivar (Figures 8 and 9).

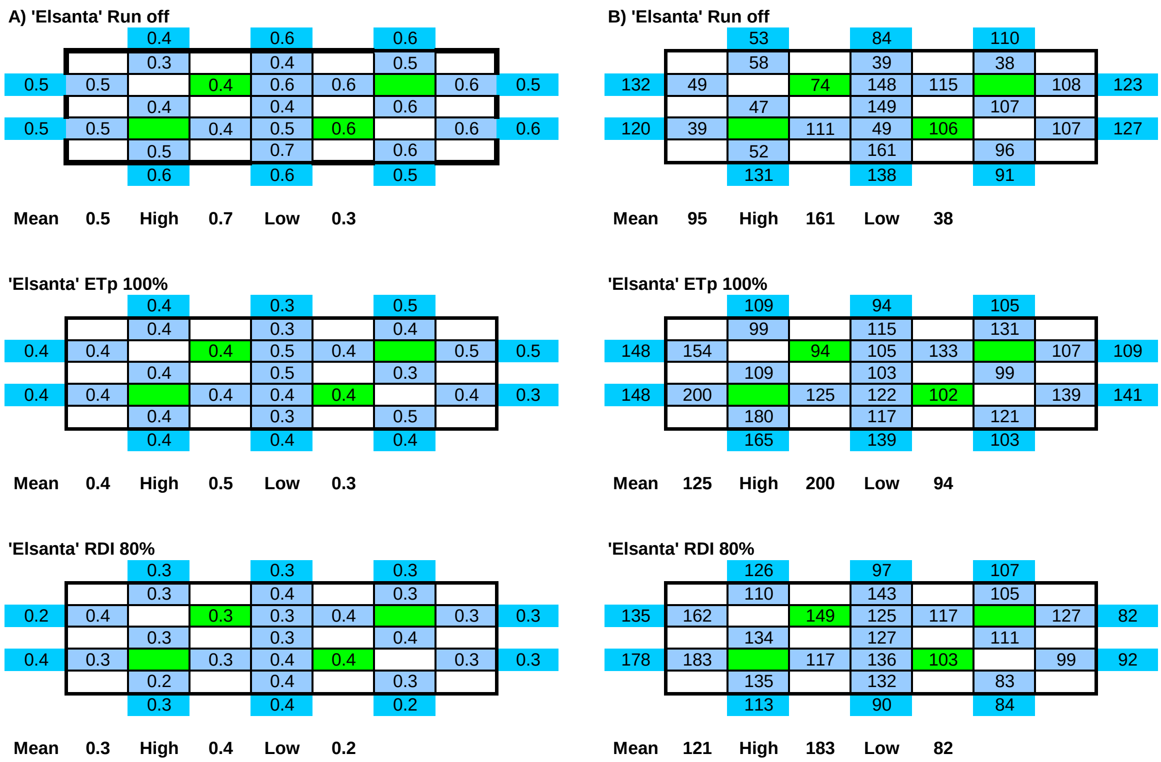

Figure 8. Effects of the three irrigation treatments on A) VSMC (m^3 m^{-3}) and B) substrate EC (mS m^{-1}) at different positions within each peat/coir bag containing four 'Elsanta' plants. SMC and EC were measured with a WET sensor. Green squares represent the approximate position of plants and drippers, the probe was inserted either vertically (light blue squares) or horizontally (turquoise squares).

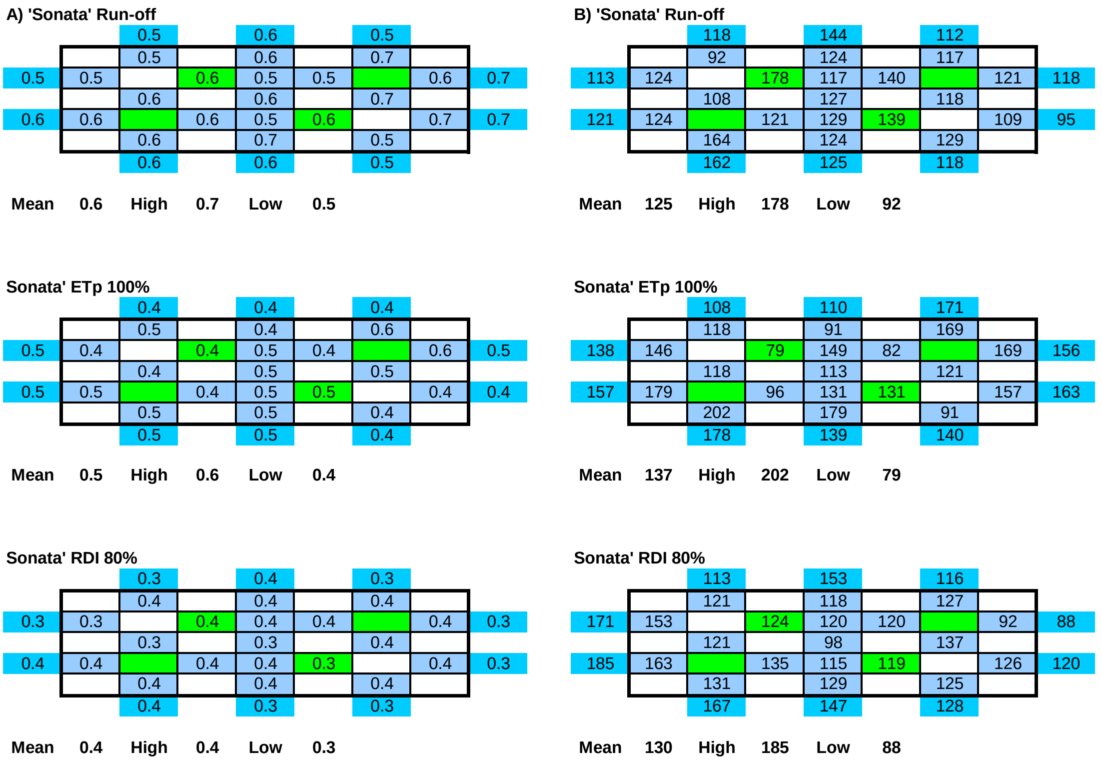

Figure 9. Effects of the three irrigation treatments on A) VSMC (m^3 m^{-3}) and B) substrate EC (m^S m^{-1}) at different positions within each peat/coir bag containing four 'Sonata' plants

Plant physiological responses

Leaf elongation was slowed in 'Sonata' by the ETp 100% and the RDI 80% regimes compared to the run-off treatment (Figure 10).

Leaf number was also reduced in the ETp 100% and RDI 80% treatments (data not shown). Consequently, total leaf area was reduced by 16% and 39%, respectively, at the end of the growing season (Figure 11). Leaf elongation rates and leaf production were also slowed in 'Elsanta' by the ETp 100% and the RDI 80% regimes, but the responses were less pronounced and resulted in total leaf area reductions of 14% and 20%, respectively, by the end of the growing season (data not shown). No treatment effects on stomatal conductance were detected for either cultivar and midday leaf water potentials were similar, irrespective of the irrigation regime (data not shown). These results indicate that excessive vegetative growth was prevented by irrigation scheduling and deficit irrigation without reducing stomatal apertures and shoot water balance.

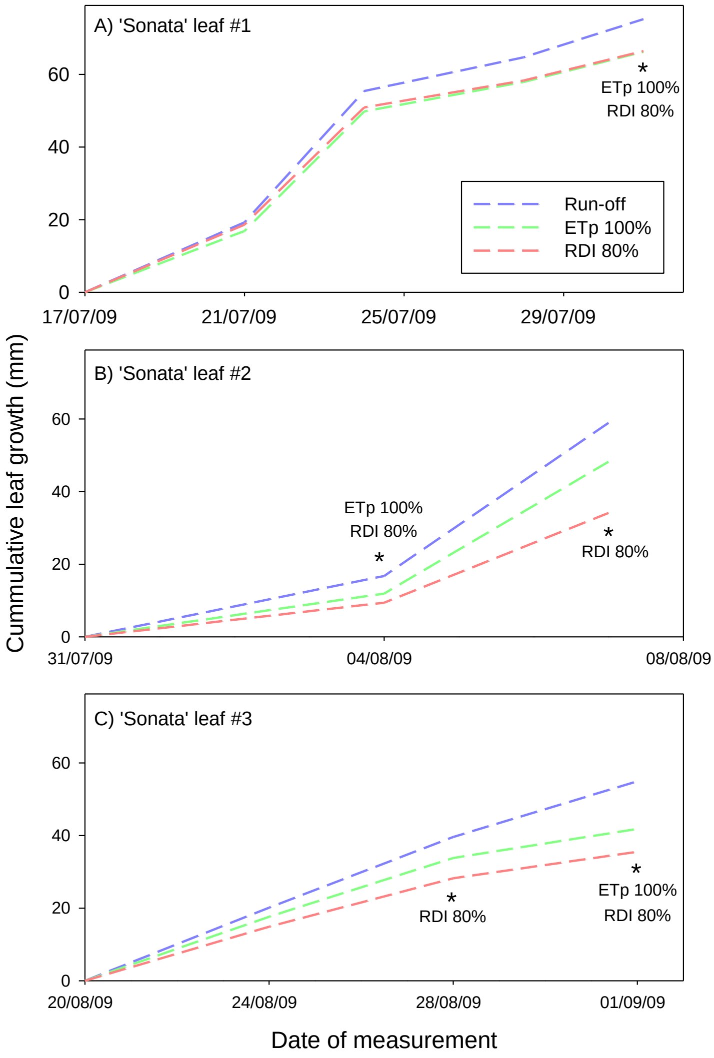

Figure 10. Accumulated leaf growth measured on expanding leaves of 'Sonata' strawberry plants under different irrigation regimes. Results are means of eight replicate plants per treatment; asterisks indicate a statistically significant difference relative to the 'run-off' value with an LSD for p<0.05.

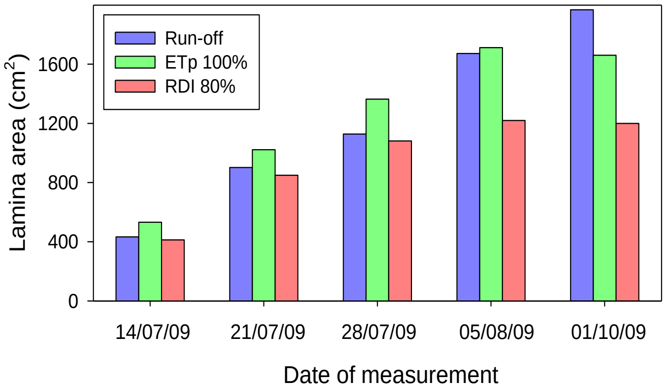

Figure 11. Effect of the irrigation regimes on estimated total canopy area of 'Sonata'.

Foliar mineral analyses

Leaf samples were analysed for macro and micro nutrients at the beginning, the middle and the end of cropping. On 14 July at the start of the irrigation regimes, most macro and micro nutrients were within the normal ranges (see HDC Factsheet 06/07), although N and Mg concentrations were high in both cultivars (Table 2) and Mn was excessively high in 'Elsanta'. At the beginning of cropping, most macro and micro nutrients were within the normal ranges except for Cu which was low in both cultivars under all regimes (Table 3). After cropping, most major and micro nutrients were within the satisfactory ranges (Table 4), although concentrations of N were high in most regimes while Ca and Cu were just below satisfactory values.

Table 2. Foliar mineral analysis for samples collected on 14 July 2009 immediately before the irrigation regimes were imposed. Values in italics or bold are over or under, respectively, satisfactory values given in HDC Factsheet 06/07.

Nutrient	Units	Foliar mineral concentrations		
		Satisfactory	'Elsanta'	'Sonata'
N	(%)	2.0 - 3.5	*3.68*	*3.72*
P	(%)	0.3 - 0.6	0.43	0.46
K	(%)	1.5 - 3.0	2.34	2.24
Mg	(%)	0.3 - 0.6	*0.7*	0.58
Ca	(%)	1.0 - 2.0	1.17	1.04
Mn	(mg kg^{-1})	50 - 250	*312*	108
Cu	(mg kg^{-1})	5 - 20	**4**	**2.7**
Fe	(mg kg^{-1})	50 - 200	69.9	70.1
Zn	(mg kg^{-1})	20 - 65	**16.9**	20.5
B	(mg kg^{-1})	30 - 50	42	41.2
S (%)	(%)	> 0.01	0.21	0.22
N: S ratio	-	-	17.5:1	16.9:1

Table 3. Foliar mineral analysis for samples collected on 31 July 2009 at the beginning of cropping. Values in italics or bold are over or under, respectively, satisfactory values given in HDC Factsheet 06/07.

Nutrient	Units	Foliar mineral concentrations					
		'Elsanta'			'Sonata'		
		Run-off	ETp 100%	RDI 80%	Run-off	ETp 100%	RDI 80%
N	(%)	3.4	3.2	3.2	3.0	3.1	3.1
P	(%)	0.6	0.6	0.5	0.5	0.5	0.5
K	(%)	2.7	2.6	2.4	2.0	2.3	1.9
Mg	(%)	0.5	*0.6*	*0.6*	0.4	0.5	*0.6*
Ca	(%)	1.1	1.3	1.2	**0.9**	1.0	1.3
Mn	(mg kg^{-1})	100.0	129.0	98.0	67.0	57.0	53.0
Cu	(mg kg^{-1})	**3.5**	**2.8**	**2.8**	**3.3**	**2.3**	**1.8**
Fe	(mg kg^{-1})	89.2	132.7	74.8	*227.1*	109.0	75.7
Zn	(mg kg^{-1})	28.3	26.1	20.6	30.3	29.2	21.7
B	(mg kg^{-1})	*52.9*	49.0	*50.8*	39.9	39.2	47.0
S (%)	(%)	0.2	0.2	0.2	0.2	0.2	0.2
N:S ratio	-	17.9:1	17.7:1	17.8:1	15.5:1	14.9:1	16.5:1

Table 4. Foliar mineral analysis for samples collected on 18 September 2009 after cropping was completed. Values in italics or bold are over or under, respectively, satisfactory values given in HDC Factsheet 06/07.

Nutrient	Units	Foliar mineral concentrations					
		'Elsanta'			'Sonata'		
		Run-off	ETp 100%	RDI 80%	Run-off	ETp 100%	RDI 80%
N	(%)	3.5	*3.8*	*3.6*	3.5	*3.6*	*4.1*
P	(%)	0.6	0.6	0.6	0.5	0.5	0.6
K	(%)	*3.1*	*3.1*	*3.1*	2.8	2.8	*3.1*
Mg	(%)	0.4	0.5	0.4	0.4	0.4	0.4
Ca	(%)	**0.9**	1.0	**0.9**	**0.9**	**0.9**	1.1
Mn	(mg kg^{-1})	60.0	65.0	90.0	51.0	67.0	82.0
Cu	(mg kg^{-1})	6.0	5.2	5.0	**4.1**	**4.1**	**4.6**
Fe	(mg kg^{-1})	123.8	117.5	131.8	170.8	135.5	*214.0*
Zn	(mg kg^{-1})	49.6	46.7	48.5	43.7	45.5	49.1
B	(mg kg^{-1})	48.8	*57.5*	*50.8*	37.5	40.8	44.4
S (%)	(%)	0.2	0.2	0.2	0.2	0.2	0.2
N:S ratio	-	17.7:1	18.5:1	17.9:1	15.4:1	17.1:1	18.3:1

Class 1 yields

Total yields of Class 1 fruit were only around 150 g per plant, rather than the 250-300 g expected, due to the scorching effects of the potassium bicarbonate spray. Fifty percent of the total Class 1 yield was picked before the spray; after this fruit development was affected and berry size was greatly reduced. However, average yields of Class 1 fruit per plant were not significantly reduced by the ETp 100% and RDI 80% regimes in either cultivar, compared to the run-off controls (Figure 12).

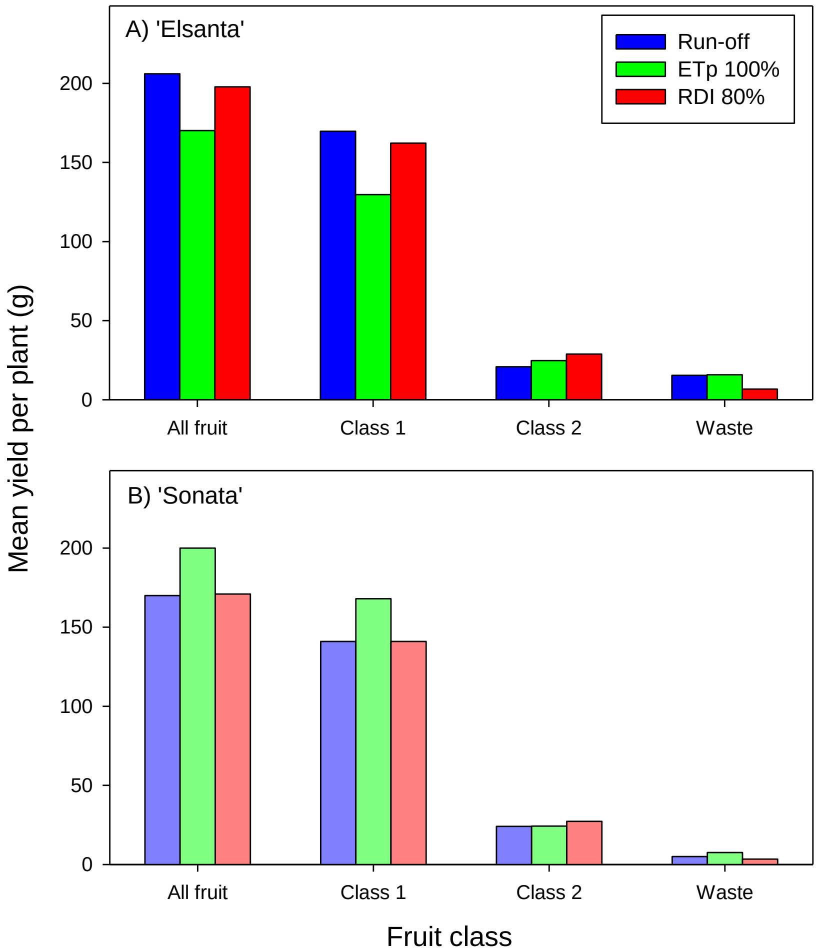

Figure 12. Mean weight of fruit of different size classes from A) 'Elsanta' and B) 'Sonata' strawberry plants under the different irrigation regimes for the 60-day cropping season. Results are means of eight replicate plants per treatment; treatment differences were not statistically significant.

Fruit quality

Berry firmness was unaffected in either cultivar by the irrigation regimes (data not shown) and no treatment effect on berry SSC was detected (Figure 13). Although concentrations of glucose, fructose and sucrose were slightly but significantly reduced in

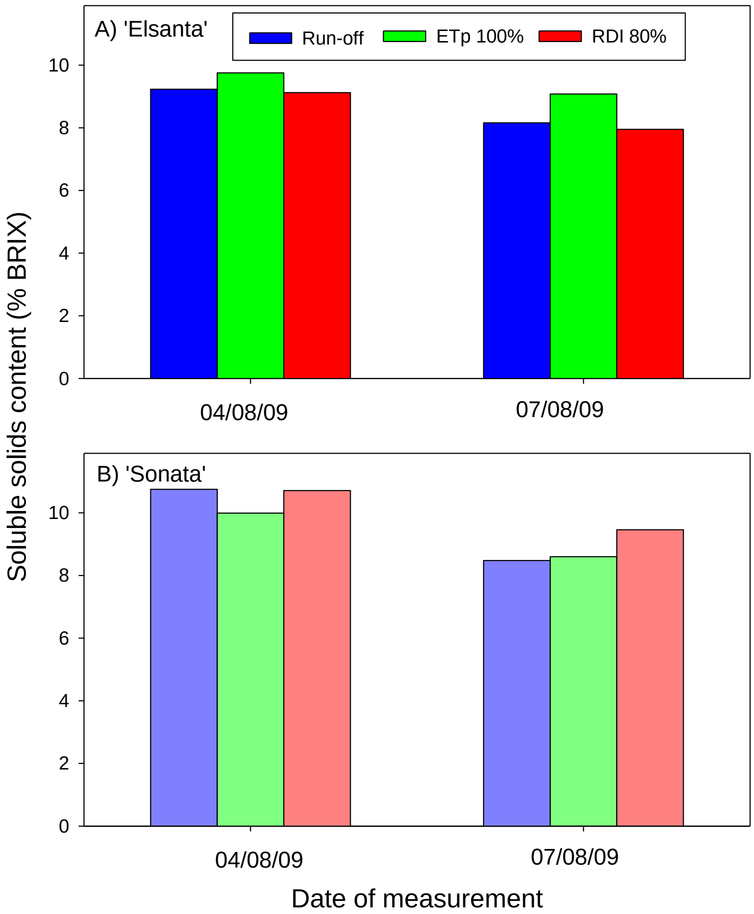

Figure 13. Soluble solid content (SSC) of A) 'Elsanta' and B) 'Sonata' strawberry fruit measured as % BRIX. Results are means of eight replicate berries per treatment; treatment differences were not statistically significant.

'Elsanta' by the RDI 80% regime, the sugar to acid ratio was similar in fruit sampled from plants under each of the three irrigation regimes (Figure 14). The sugar to acid ratio in 'Sonata' fruit was not significantly altered by the irrigation regimes (data not shown). No significant differences between irrigation treatments for either cultivar were detected during taste tests by an EMR taste panel (data not shown). 'Sonata' berry concentration of ellagic acid (a bioactive) were increased by the RDI 80% regime and total antioxidant capacity was also raised in these fruit (Figure 15).

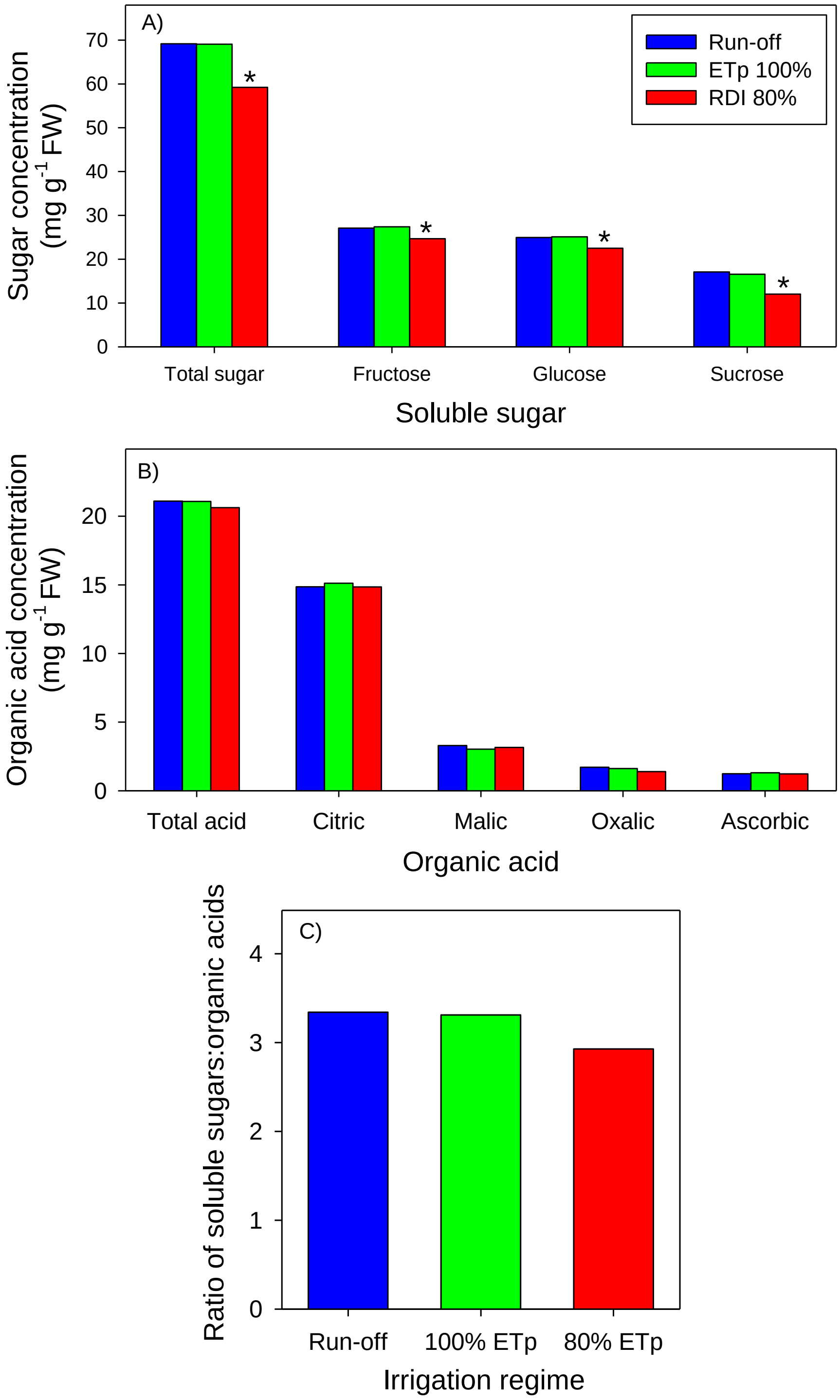

Figure 14. Effect of the different irrigation treatments on A) sugar concentrations, B) organic acid concentrations and C) the sugar to acid ratio of 'Elsanta' berries. Results are means of eight replicate berries per treatment; asterisks indicate a statistically significant difference relative to the 'run-off' value with an LSD for $p<0.05$.

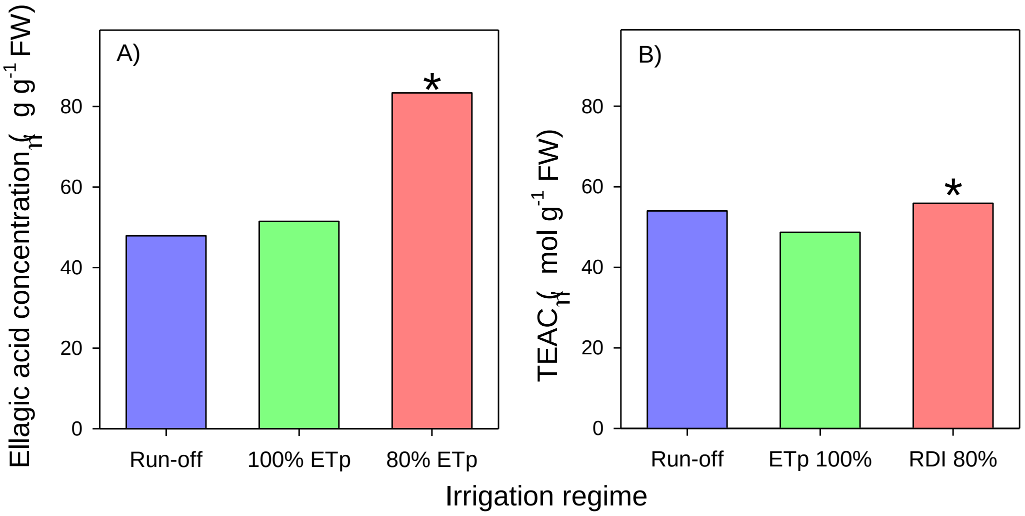

Figure 15. Effect of the different irrigation regimes on A) ellagic acid concentrations and B) total antioxidant activity of 'Sonata' strawberry fruit expressed as Trolox equivalents. Results are means of eight replicate berries per treatment; asterisks indicate a statistically significant difference relative to the 'run-off' value with an LSD for *p*<0.05.

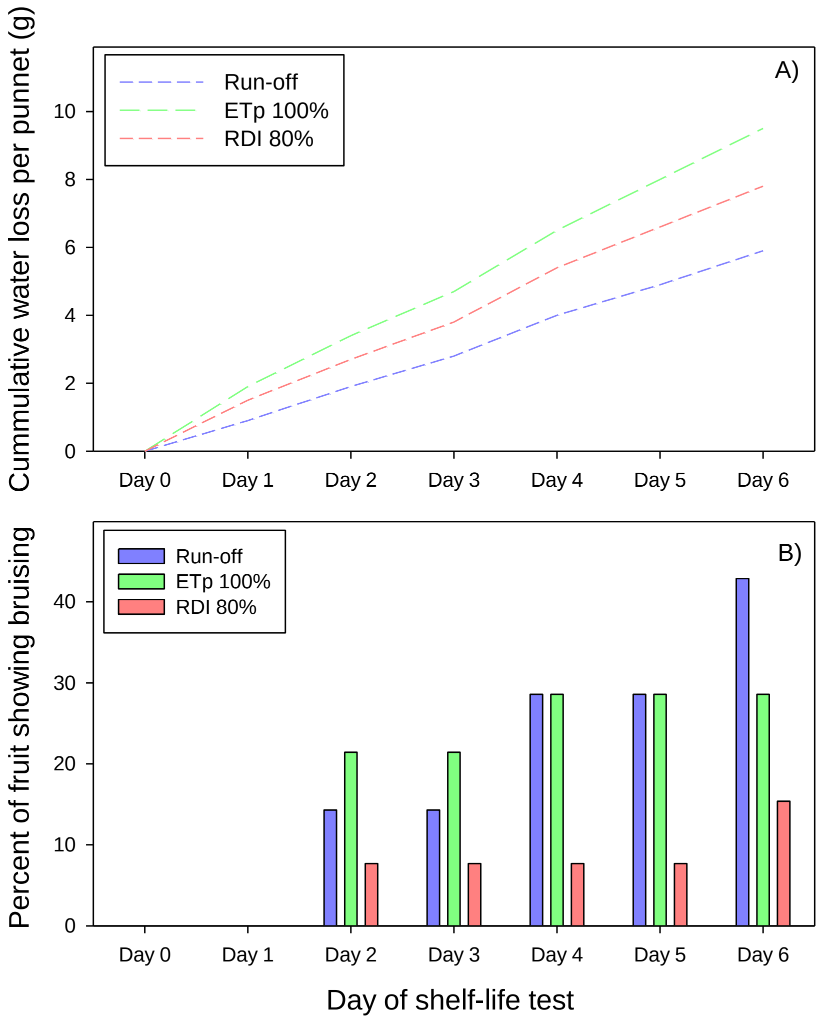

Figure 16. Effect of the different irrigation treatments on A) weight loss per punnet and B) percentage of fruit with bruising visible during a 6-day shelf-life test of 'Sonata' strawberry fruit. Results are means of three replicate punnets per treatment; treatment differences were not statistically significant.

Shelf-life potential

Rates of water loss from 'Elsanta' berries held at 5 ºC were greater from fruit that had received the run-off irrigation regime but the rate of development of bruising was delayed in these fruit, compared to that of fruit from the ETp 100% and RDI 80% regimes (data not shown). However, the percentage of fruit with bruising was similar across all treatments by the end of the 6-day shelf-life test. The rate of water loss from 'Sonata' fruit was slowed in berries previously under the run-off regime. The percentage of 'Sonata' fruit that developed bruising over the 6-day shelf-life test was reduced from 45% in run-off controls to 15% by the RDI 80% regime (Figure 16).

Water and fertiliser use

The volume of irrigation applied to each plant under each of the three irrigation regimes is presented in Table GS 1. Scheduling irrigation to match demand with supply resulted in water savings of 41% and 30% for 'Elsanta' and 'Sonata' respectively, while the RDI 80% regime delivered even greater water savings.

Water productivity values were also calculated for each irrigation regime and for each cultivar (Table 5). The volume of water applied was first recorded from Day 0 (14 July 2009) and so the WP values do not include water that was used to wet up the substrate bags, water that was applied *via* overhead irrigation or the water that was applied during the first three weeks of plant development before the irrigation regimes were imposed. Consequently, the calculated WP values are artificially low although the low yields of Class 1 fruit will have 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 1 fruit. At the moment, typical grower WP are not yet known, but a survey to be carried out by the EMR project team as part of Defra project WU0122 will determine the range of grower WP values for substrate-grown strawberry production.

Table 5. Water productivity values associated with each irrigation regime for 'Elsanta' and 'Sonata'.

Cultivar	Water productivity (L per kg Class 1 fruit)		
	Run-off	ETp 100%	RDI 80%
'Elsanta'	55.6	42.5	31.8
'Sonata'	79.3	46.4	44.8

Since plants were fertigated at each irrigation event, the total amounts of the macro and minor nutrients applied to each bag were reduced in proportion to the irrigation volume. Consequently, fertiliser savings of between 30% and 45% were achieved using the ETp 100% and RDI 80% regimes. The total amounts of N, P, K, Ca and Mg applied during the season to plants under the run-off regime are presented in Table 6.

Table 6. Total mass of macro nutrients applied per plant for 'Elsanta' and 'Sonata' under the three irrigation regimes.

Element	Total mass of nutrient applied per plant (kg)					
	'Elsanta'			'Sonata'		
	Run-off	ETp 100%	RDI 80%	Run-off	ETp 100%	RDI 80%
NO_3 - N	1.15	0.67	0.63	1.36	0.95	0.77
NH_4 - N	0.03	0.02	0.02	0.03	0.02	0.02
P	0.38	0.22	0.21	0.45	0.31	0.25
K	2.37	1.38	1.30	2.80	1.96	1.58
Ca	1.27	0.74	0.70	1.50	1.05	0.85
Mg	0.29	0.17	0.16	0.35	0.24	0.20

Discussion

An irrigation scheduling regime that eliminated run-off and an RDI regime where only 80% of daily ETp was replaced were imposed successfully on 60-day 'Elsanta' and 'Sonata' plants. This was achieved by calculating daily ETp and adjusting irrigation volumes accordingly. This approach could also be used to schedule irrigation in commercial production to achieve the desired percentage daily run-off, thereby removing the need for time-consuming measurements of run-off volumes each day. The potential of this approach will be tested at EMR in a new HDC-funded project[9] on using irrigation scheduling and deficit irrigation regimes to control excessive vigour in raspberry cultivars.

Irrigation water and nutrients was delivered to the substrate around each plant by using four dripper stakes per bag and this ensured an even distribution and prevented dry spots from developing. When the irrigation scheduling and RDI regimes that are being developed in this project are tested in commercial production with 1-m-long bags, it will be probably be necessary to double the number of dripper spikes to eight per bag. The associated extra cost must be set against the water and fertiliser savings and the cost benefit analysis due to be carried out later in the project will help growers to decide whether these techniques are financially viable.

The irrigation scheduling and RDI regimes resulted in substantial water and fertiliser savings compared to the run-off regime where the average daily run-off was maintained between 10 and 20 % of the volume applied. In our experiment, these savings were achieved without reducing yields and quality of Class 1 fruit but the scorching effect of the potassium bicarbonate spray on the numbers and quality of Class 1 berries complicates the interpretation of the results. In the three weeks following the spray, rates of transpirational water loss were slowed and the volumes of water applied were also reduced to maintain VSMC at similar values to those before the spray (see Figure 6). Whether Class 1 yields would have remained unaffected by the ETp 100% and RDI 80% regimes had the correct spray concentration been used is not known. However, our recent and on-going work[6,7] has shown that yields of Class 1 fruit are maintained in substrate-grown strawberry under scheduled or mild deficit irrigation. The experiment will be repeated in 2010 on main season plants to confirm whether the ETp 100% and RDI 80% regimes can maintain Class 1 yields in addition to delivering water and fertiliser savings.

Plants under the ETp 100% and RDI 80% regimes received between 30% and 45% less fertiliser than the run-off controls but most macro and minor nutrients were within satisfactory ranges, except for Ca and Cu which were below the lower thresholds[2]. Presumably, the smaller canopy areas in plants under these regimes meant that nutrient availabilities did not become limiting, despite the lowered inputs. Whether similar reductions in fertiliser inputs can be achieved in the main season crop without affecting Class 1 yields or quality will be determined in 2010.

Substrate EC levels increased gradually over the season in all treatments and increased sharply following the potassium bicarbonate spray. Although substrate EC was subsequently reduced by temporarily switching to a calcium nitrate feed, values were 10% and 20% higher in RDI 80% and ETp 100% regimes, respectively, by the end of cropping. Again, EC was reduced by flushing through with calcium nitrate but any effects of these accumulations of salts on plant growth and fruit development could not be fully assessed because all plants were recovering from the potassium bicarbonate spray at this time. Substrate and run-off EC will be monitored closely in the run-off regimes in 2010 and the effects of the ETp 100% and RDI 80% regimes on substrate EC will be monitored continuously using Decagon 5TE probes.

Despite the degree of substrate drying imposed in the RDI treatment, leaf water status was unchanged and stomatal conductances were not reduced. Leaf extension and leaf production, however, were reduced in both cultivars and this highlights the sensitivity of leaf growth to limitations in available soil moisture. The much reduced canopy area may have limited overall plant photosynthetic capacity and this could have been the cause of the lower total sugar concentrations in berries of 'Elsanta'. Rates of photosynthesis under the different regimes will be determined in 2010. Despite the reduced sugar concentrations, SSC values and the sugar to acid ratio were unchanged in berries from RDI-treated plants and taste tests failed to detect any differences in the perception of sweetness in berries from different regimes. Again, whether berry quality would have remained unaffected by the ETp 100% and RDI 80% regimes had the correct spray concentration been used is not known. However, recent work in our group has shown that berry quality is often improved when mild deficit irrigation regimes are imposed[6,7,10]. Concentrations of ellagic acid, an important bioactive, and total antioxidant capacity were increased in 'Sonata' fruit from the RDI 80% regime. Research at EMR[6,7,10,11] and elsewhere[8] has shown that berry antioxidant content can be increased by deficit irrigation regimes and fruit concentrations of anthocyanins, phenolics and other antioxidants are often improved by increased exposure to daylight[12]. The smaller, less dense canopy of RDI-treated plants may have helped to improve these aspects of fruit quality by improving light penetration. In addition to benefiting consumers, these changes in antioxidant content may help to improve shelf-life potential and it is noteworthy that the development of bruising was also significantly reduced in these fruit. A reduction in susceptibility to bruising would help to reduce waste and reduce production costs.

The water productivity values calculated for the 2009 experiment were influenced both by the lower-than-expected Class 1 yields and the reduced volumes of irrigation water applied in the weeks following the potassium bicarbonate spray. Nevertheless, the calculated WP values suggest that substantial improvements in water use efficiency could be achieved by irrigation scheduling and deficit irrigation. The range of WP values achieved by commercial growers in substrate-grown strawberry production is not yet known but will be established by the EMR project team in a new Defra project[13] in collaboration with Cranfield University.

The ranges of VSMC contents that need to be imposed to achieve effective irrigation scheduling and a mild RDI regime have been identified for both 'Elsanta' and 'Sonata'. These values will be used in the 2010 season to trigger irrigation automatically using GP1 data loggers and SM200 probes (Delta-T Devices, UK). This approach will also be used to irrigate to achieve between 10 and 20 % run-off.

Conclusions

- Irrigation scheduling and deficit irrigation regimes were imposed successfully on 60-day 'Elsanta' and 'Sonata' plants
- Yields of Class 1 fruit were reduced in all treatments due to the scorching effect of a 10 times strength potassium bicarbonate spray
- Water savings of up to 45% were achieved without reducing yields of Class 1 fruit

- Fertiliser savings of up to 45% were achieved without reducing yields of Class 1 fruit. Foliar macro and micro nutrient concentrations were within satisfactory ranges, with the exception of Ca and Cu which were below the lower thresholds
- Substrate EC was increased by 20% under the RDI 80% regime by the end of the growing season
- Total leaf area reductions of 20% and 39% were achieved for RDI-treated 'Elsanta' and 'Sonata', respectively
- The percentage of 'Sonata' fruit that developed bruising over the 6-day shelf-life test was reduced from 45% in run-off controls to 15% by RDI
- The soil moisture content threshold values needed to trigger irrigation automatically to the main season crop in 2010 were identified for each treatment (run-off, ETp 100% and RDI 80%) and for each cultivar

Technology transfer

- Presentation of the work to the HDC Board, 8 June 2009
- The aims and objectives of the work were discussed during the visit of Rt. Hon. Hilary Benn MP, Minister for the Environment & Rural Affairs, 20 July 2009
- An overview of the work was presented during the farm tours at Fruit Focus, 22 July 2009
- Presentation of the work to Sainsbury's food technologists, 16 October 2009
- Presentation of the work to a delegation from ICAR, 4 December 2009
- Presentation of work to West Sussex Fruit Group, 9 December 2009
- Presentation of work to Prof. Ian Crute, AHDB Chief Scientist, 18 December 2009
- Presentation of work at EMRA Pear Day, 25 February 2010
- Regional news broadcasts: BBC South East and Meridian South East
- BBC National News and BBC Breakfast

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Acknowledgements

We are grateful to Mr Michael Daly (The Agrology House) for much helpful advice on fertigation of substrate-grown strawberries and to Prayon UK Ltd for the gift of the fertilisers used in this trial.