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
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DISCLAIMER

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.

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30 May 2012

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GROWER SUMMARY

Headline

In substrate grown strawberries, water savings of between 15% and 45% were delivered using a new irrigation scheduling strategy without reducing Class 1 yields.

Background and expected deliverables

The project aims to provide the potential to increase water use efficiency and nutrient use efficiency in UK substrate-grown strawberry production by 40% thereby saving water, reducing the impact of soft fruit production on groundwater quality and improving fruit quality and shelf-life.

Irrigation of substrate-grown strawberries is essential to ensure the yields and quality demanded by retailers and consumers. Many growers apply sufficient irrigation to achieve 10-20% run-off to avoid dry spots within the substrate bags and to reduce the accumulation of salts. However, Defra, the Environment Agency (EA) and the soft fruit industry are 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).

Figure GS1. Reducing inputs of valuable resources such as water and fertilisers must be achieved without reducing yields and quality of Class 1 fruit

At the time of writing (May 2012), the south east is officially under drought and other major soft fruit growing regions were at high risk of drought in 2012 (Figure GS2) until above-average rainfall in April alleviated the problem in some production areas.

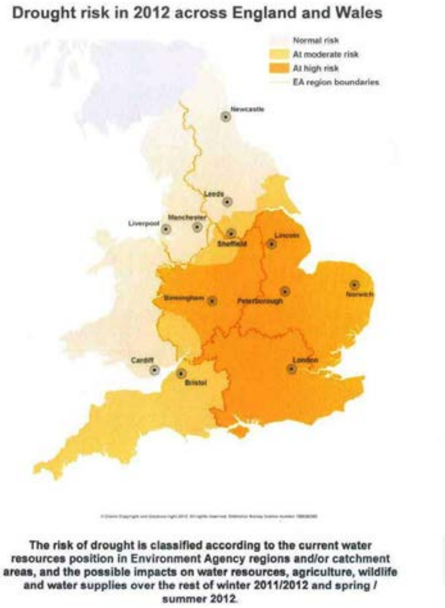

Figure GS2. Assessment of drought risk across England and Wales for 2012. Source: the Environment Agency.

Nevertheless, 'blue water' availability will become increasingly limited, especially in the summer months and mains water will be more expensive; the use of mains water to irrigate 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 soft fruit production to ground water pollution, and the EA recently commissioned ADAS to carry out a study to determine the impact of substrate production on ground water quality in the south east. Clearly, new soft fruit production systems are needed that use resources such as water and fertilsers more efficienctly. Recent research at EMR and elsewhere has provided major opportunities to improve water and nutrient use efficiencies while continuing to deliver high yields of fruit that meet consumer demand for sweet berries with good flavour and shelf-life.

Improved irrigation scheduling techniques and deficit irrigation techniques such as Regulated Deficit Irrigation (RDI) offer the potential to deliver large water savings while maintaining or improving crop quality. The aim of irrigation scheduling is to match demand with supply during changeable weather conditions. 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% and significant reductions in fertiliser inputs are also likely.

There are two aims to this project:

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

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

Developing an irrigation scheduling technique that matches demand with supply

In the first two years of the project, an irrigation scheduling technique that matches demand with supply and so minimises or eliminates run-off was developed using irrigation set points based on volumetric substrate moisture contents (VSMC). The irrigation scheduling regime was imposed on 60-day and mainseason 'Elsanta' and 'Sonata' plants grown in 0.5-m peat bags (Figure GS3). Irrigation was supplied to Commercial Control plants to achieve an average run-off of 20% over the season. In 2009 with 60-day crops, water and fertiliser savings of up to 45% were achieved, compared to the Commercial Control treatment, without reducing yields of Class 1 fruit. Overall, marketable yields were low due to the effect of the x10 strength potassium bicarbonate spray applied in error.

Despite the reduced nutrient input under the irrigation scheduling regime, foliar concentrations of N, P, K, Mg, Mn, Fe, Zn, B and S were within satisfactory ranges in each cultivar under each irrigation regime although concentrations of Ca and Cu were just below satisfactory values by the end of the cropping season.

Figure GS3. The main season ‘Elsanta’ plants used in the 2010 experiments to determine the effects of irrigation scheduling and RDI on water and nutrient use efficiencies and fruit quality. Photo taken on 9 May 2010.

In 2010, although run-off was eliminated and water and fertiliser savings of 50% were achieved using the irrigation scheduling technique, main season ‘Elsanta’ and ‘Sonata’ Class 1 yields were reduced by 27% and by 13%, respectively, compared to the Commercial Control regime. This was due to a reduction in fruit size rather than fruit number and presumably resulted from temporary limitations in substrate water availability under high evaporative demands. Therefore, the lower VSMC irrigation set points were raised for the 2011 irrigation scheduling experiments (see below).

In 2011, *s*cheduling irrigation to match demand with supply so that run-off was minimised or eliminated resulted in water savings of up to 42% and 45% for ‘Elsanta’ and ‘Sonata’, respectively, compared to the Commercial Control treatments where run-off averaged 20% over the season (Table GS1).

Table GS1. Total volumes of irrigation water applied per plant (L) for 60-day ‘Elsanta’ and ‘Sonata’ under the irrigation and NO_3-N:NH_4-N regimes and the associated percent run-off averaged over the season.

Treatment	Volume of water applied (L)		Average run off (%)	
	‘Elsanta’	‘Sonata’	‘Elsanta’	‘Sonata’
CC	31.2	42.7	22.4	19.3
Scheduled	26.5	24.3	4.4	0.0
20% NH_4-N	22.3	33.4	5.6	0.2
30% NH_4-N	18.0	23.6	0.2	4.6

Water productivity (WP) values were also calculated for each irrigation regime and for each cultivar (Table GS2). The volume of water applied was first recorded from Day 0 (27 July 2011) 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 during establishment or the water that was applied during the first three weeks of plant development before the irrigation regimes were imposed. 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. Typical grower WP values are not yet known for substrate-grown strawberries but will be calculated from data gathered at two grower sites during 2012 in SF 136.

Table GS2. Water productivity values associated with irrigation and NO_3-N:NH_4-N regimes for 60-day 'Elsanta' and 'Sonata'.

Cultivar	Water productivity (L per kg class 1 fruit)			
	CC	Scheduled	20% NH_4-N	30% NH_4-N
'Elsanta'	48.6	38.0	42.6	36.3
'Sonata'	78.4	49.4	69.2	51.3

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 15% and 45% were achieved using the irrigation scheduling regimes to reduce or eliminate run-off. Despite these reduced inputs, leaf nutrient concentrations remained within satisfactory ranges in 'Elsanta' throughout cropping. However, Ca concentrations were reduced in leaves of 'Sonata' by the end of cropping although fruit firmness and shelf-life potential was not affected.

The new approach to irrigation scheduling developed in SF 107 has potential to further improve the economic and environmental sustainability of substrate soft fruit production in the UK. Managing the volume of run-off throughout fruit development under changeable evaporative demands in crops of different ages is challenging for commercial growers. Manually collecting and measuring run-off volumes in each block of substrate crop in time to inform irrigation decisions can be time consuming and an automated system that enabled irrigators to react quickly to differing evaporative demands would help to deliver significant water and fertiliser savings. The system developed in this project enables data on water inputs and outputs to be accessed remotely (Figure GS4) so that the percent run-off after each irrigation event can be calculated.

Figure GS4. Rain gauges and data loggers with telemetry are being used to record water input and output volumes in grower trials in SF 136.

This information can then be used to highlight times of the day when run-off is excessive and the duration of these events can then be adjusted to reduce water and fertiliser losses. Continuous monitoring of VSMC also ensures that water availability does not become limiting once run-off has been reduced. The potential build-up of salts can also be monitored using EC probes and managed by flushing through with acidified water or dilute calcium nitrate solutions if needed. During these experiments, equipment from several different manufacturers has been used to develop an automated irrigation system that enables precise control of run-off. For commercial exploitation, these systems need to be integrated into a single controller unit. We are currently identifying the necessary components of this system in Project SF 136.

Testing the potential of RDI regimes to deliver water savings and improved fruit quality

Previous Defra-funded work at EMR had shown that an RDI regime that replaced only 80% of the water lost by evapotranspiration could deliver significant water savings and improved aspects of fruit quality in substrate-grown strawberry. These strategic experiments were carried out on main season crops in 6 L containers and it was important to test the effectiveness of RDI using commercial planting densities where the available substrate volume per plant is considerably less. RDI was imposed on 60-day and main season 'Elsanta' and 'Sonata' plants in 2009 and 2010, respectively, grown in 0.5-m bags of peat. In 2009, an 80% RDI regime reduced total leaf areas by 20% and 39% in 'Elsanta' and 'Sonata', respectively (Figure GS5), and the percentage of 'Sonata' fruit that developed bruising over a 6-day shelf-life test was reduced from 45% in Commercial Controls to 15% by RDI. However, although Class 1 yields were similar to those obtained from Commercial Control plants, substrate EC was increased by 20% under the RDI regime by the end of the growing season.

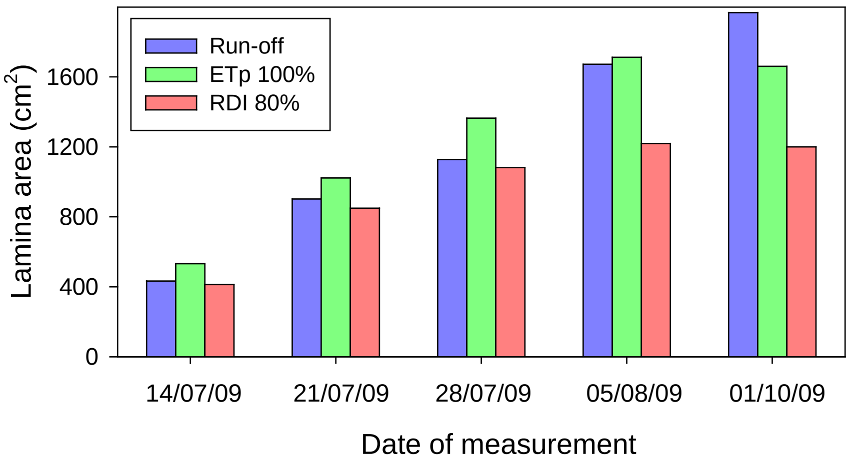

Figure GS5. Effect of the irrigation regimes on estimated total canopy area of 'Sonata'

In 2010, RDI regimes were imposed on mainseason 'Elsanta' and 'Sonata' plants and physiological responses to substrate drying such as lowered stomatal conductances, transpiration rates, leaf growth and photosynthetic rates were detected. Total canopy areas were reduced by up to 58% and 62% in RDI-treated 'Elsanta' and 'Sonata', respectively. However, Class 1 yields were also significantly reduced in RDI-treated plants compared to Commercial Control values (449 g vs 231 g). Although we have shown in strategic experiments that RDI has the potential to deliver significant water and fertiliser savings in substrates, as well as improvements in fruit quality, the technique would be difficult to implement in commercial substrate strawberry production. Maintaining the substrate within the target upper and lower VSMC set points under high evaporative demand would be challenging due to the limited substrate volumes (3-4 L per plant) and growing in coir would further increase the risk of shoot water deficits and associated reductions in Class 1 yields and quality. However, we have shown in SF 83 that RDI can be used very successfully in soil-grown crops to deliver water savings and improved fruit quality.

Manipulating N nutrition

The aim of this work was to test the potential to manipulate ammonium-N (N-NH_4) and nitrate-N (N-NO_3) ratios to try to improve berry firmness and shelf-life potential, particularly in cultivars such as 'Sonata' where berries can be soft and vulnerable to bruising. In our experiment, changing the percentage of ammonium-N from 10% to either 20% or 30% did not significantly affect plant physiology or fruit quality. No consistent effects of altering NO_3-N: NH_4-N ratios on foliar nutrient concentrations were detected and so it was not necessary to increase Ca concentrations in the fertiliser feed mixes. In the 60-day crop in 2011, the different NO_3-N:NH_4-N regimes were applied for only six weeks but during that time, no significant treatment differences were observed. In previous work, higher ratios of NO_3-N:NH_4-N have been needed to elicit physiological responses (*e.g.* 50%:50%, 25%:75%) but during the preparation of the original proposal, industry representatives felt that ratios greater than 70%:30% would limit fruit yields and quality. Work in other cropping systems has shown that a 70%:30% NO_3-N:NH_4-N ratio did not affect physiology under normal conditions but helped to improve tolerance to high salinity stress via altered plant hormone signalling. More work is needed to determine the potential of manipulating N nutrition in this way to improve not only aspects of fruit quality and flavour, but also tolerance to high salinities and the build-up of 'ballast' ions (*e.g.* Na^+, Cl^-) in substrates.

It should be noted that throughout this project, Class 1 yields have been lower than anticipated due to issues associated with powdery mildew. However, the approaches developed in SF 107 have also been trialled in other Defra-funded work at EMR with mainseason substrate-grown 'Elsanta' crops and significant savings in water and fertilisers have been achieved whilst maintaining good commercial yields of high quality fruit.

Main Conclusions

- Irrigation scheduling and deficit irrigation regimes were imposed on 60-day and main season 'Elsanta' and 'Sonata' plants.
- A new irrigation scheduling strategy has been developed for substrate-grown strawberries that reduces or eliminates run-off. In this strategy, irrigation inputs and outputs are monitored continuously using rain gauges and data loggers with telemetry. This information is used to adjust the timing and frequency of irrigation so that run-off is eliminated and demand is matched with supply. VSMC and EC are also measured continuously to ensure that irrigation is scheduled effectively and substrate EC levels are controlled adequately once run-off has been eliminated.
- Water savings of between 15% and 45% were delivered without reducing Class 1 yields using the new irrigation scheduling strategy. Since nutrients were added at each irrigation event, fertiliser savings of up to 45% have also been achieved
- The lower fertiliser inputs under the irrigation scheduling regime resulted in reduced leaf concentrations of Ca in 'Sonata' but fruit quality was not affected.
- An RDI regime was developed that limited excessive canopy growth and improved berry shelf-life potential in 60-day crops. However, Class 1 yields were reduced

by 17% in the mainseason crops, due to temporary losses of shoot turgor at high evaporative demands when substrate water availability was limited.

- RDI would be difficult to implement in some commercial substrate production systems where the accuracy and consistency of water delivery may not be sufficient to maintain VSMCs between upper and lower set points. Under these circumstances, the risk of shoot water deficits and associated reductions in Class 1 yields and quality would be high.
- An automated system has been developed that triggers irrigation automatically once the VSMC has fallen to a pre-determined lower set point. By adjusting the frequency and duration of irrigation events, the volume of run-off can be fine-tuned during different stages of crop development. The system is currently being tested in commercial grower trials in SF 136.
- Altering the contribution of NH_4-N from 10% to either 20% or 30% did not alter plant physiology or aspects of fruit quality in either 'Elsanta' or 'Sonata'. Further strategic work is needed to identify the NO_3-N:NH_4-N ratio that affects plant physiology and fruit quality attributes. The potential of altering N nutrition to improve tolerance to salinity stress in substrate soft fruit production should also be investigated.
- Fertiliser savings of between £448 and £2,025 per ha per annum could be achieved by scheduling irrigation so that run-off was minimised or eliminated.
- New fertigation regimes need to be developed to optimise plant nutrition under water-saving irrigation strategies.

Financial benefits

The project aims to improve the economic sustainability of soil-less strawberry production by improving both water and nutrient use efficiencies. In our experiments, water and nutrients were delivered to the substrate around each plant by using four dripper stakes per 0.5-m bag to ensure an even distribution, to prevent dry spots from developing and minimise the likelihood of run-off. However, in commercial production with 1-m bags, costs associated with doubling the number of dripper spikes to eight per bag may be prohibitive. These extra costs must be set against the water and fertiliser savings (see below) to decide whether this approach would be financially viable. The approach being used in both commercial trials in SF 136 is to use five 1.2 L per hour drippers per 1-m substrate bag. Some growers are beginning to switch to this system instead of using a 6 L per hour dripper with four irrigation spikes per 1-m bag since water would still be supplied to the majority of the substrate should individual drippers become blocked; these could then be readily and inexpensively replaced. Clearly, the economics of this approach are feasible for commercial production systems.

The reduction in fertiliser use of between 15% and 45% could be expected to deliver significant cost savings to growers. The Rural Business Research (RBR) 2008/2009 Farm Business Survey for Horticulture Production in England reported average annual fertiliser costs (across all specialist glass businesses including soft fruit) of £3,250-£4,500/ha. On this basis, a 15% reduction in fertiliser used could, on average, save £488-£675/ha while a 45 % reduction in fertiliser used could save £1,464-£2,025/ha. The RBR 2008/2009 survey reported average annual water costs (across all specialist glass businesses including soft fruit) of £530-£630. This confirms that, generally speaking, the savings in expenditure on water do not justify expenditure on irrigation scheduling tools. Growers using mains water would expect to pay significantly more for water and there may then be a significant financial benefit to using less water. However, the reduction in energy use through pumping less water could be significant. If a grower could save at least £600/ha in fertiliser from the use of an irrigation scheduling tool, then a cost of at least £300/ha/annum for that scheduling tool would seem reasonable. A more complete cost benefit analysis will be carried out using data from the grower trials at New Farm Produce Ltd and S.H. Chesson Partnership and included in the 2013 Final Report for SF 136.

Action points for growers

- Employ an irrigation consultant to ensure that current and new irrigation systems are designed correctly to achieve accurate and precise delivery of water and fertilisers.
- Monitor run-off at different times throughout the day to establish which irrigation events can be reduced to save water and fertilisers.
- Consider using vapour pressure deficits (VPD) to help inform irrigation decisions.
- Use substrate moisture and EC probes to help inform irrigation decisions.
- Current industry ‘standard’, ‘best’ and ‘better’ practice must be first be established before the water and nutrient use efficiencies delivered in this project can be assessed in a commercial context. It would be helpful if substrate strawberry growers would fill out and return a questionnaire on water and fertiliser use efficiencies. Please contact Scott Raffle or Andrew Tinsley at HDC for a copy of the questionnaire.

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 the labour costs associated with picking and avoid issues associated with soil sterilisation. 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 that there are no dry patches within the bag and to reduce the build-up of potentially damaging salts in the substrate. 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.* The Water Framework Directive 2000, The Water Act 2003) will, in future, place restrictions on 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.

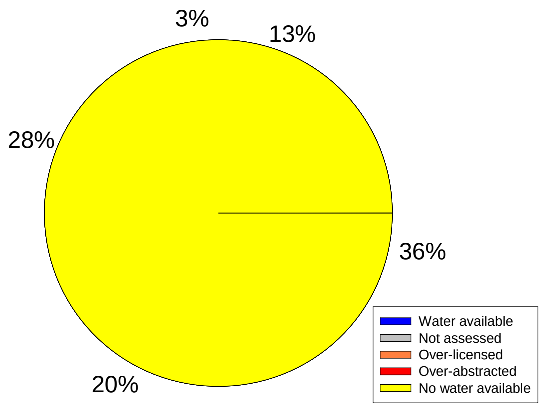

Figure 1. Assessment of water resource availability (for direct abstraction) for the soft fruit sector in 2008 (re-drawn from Knox *et al*., 2009).

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 is becoming increasingly concerned about the environmental impact of substrate production, especially in the south east. 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. It has already been 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.

Effective irrigation scheduling can be achieved using several different approaches, either alone or in combination. Adjusting the duration and frequency of irrigation events to maintain substrate or soil moisture contents within pre-determined thresholds is a very effective scheduling tool that has delivered significant water savings, good commercial yields and improvements in berry quality in work at EMR on strawberry[6,7]. The sudden and sustained increase in water demand that often occurs during cropping can easily be accounted for using this approach; the upper and lower irrigation set points remain the same but the rate of soil or substrate drying is increased. The relatively low cost of substrate moisture probes combined with improved and cost-effective telemetry options now makes remote access of 'real-time' substrate moisture contents economically viable for commercial growers.

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 a number of 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[6,7,8]. However, deficit irrigation must be applied carefully as both fruit size and quality can be compromised if the extent of substrate drying is not controlled with sufficient precision[9]. Again, the effect of the RDI regime on substrate electrical conductivity (EC) and the consequences for plant growth, Class 1 yields and fruit quality needs to be determined.

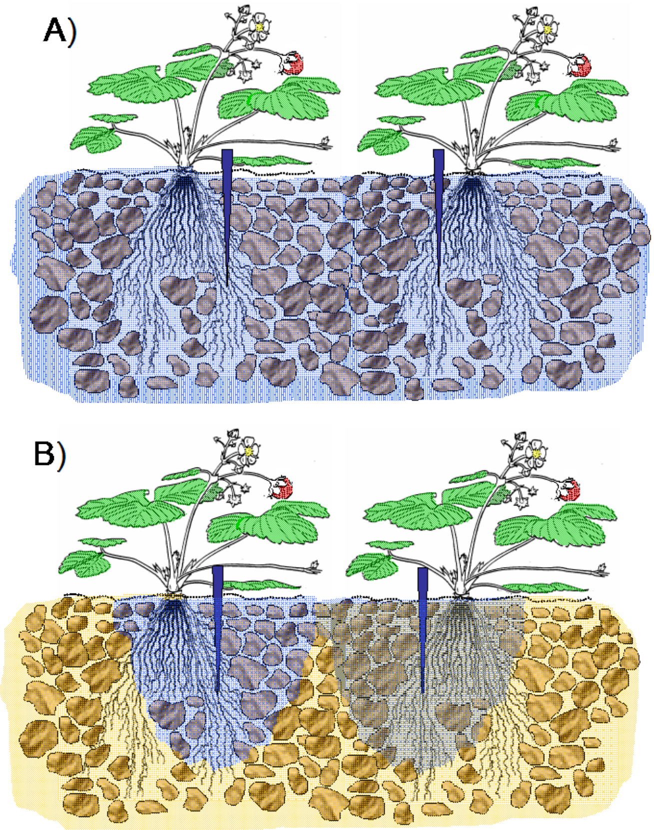

Figure 2. A) When irrigation is scheduled to achieve 'run-off', the substrate is wetted fully and all roots are able to supply water and nutrients to sustain shoot growth and fruit development. B) Under an RDI regime, gradual substrate drying occurs which triggers the production of root-sourced chemical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

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 cv.'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. The experiment was repeated on main season cv. 'Elsanta' and 'Sonata' crops in 2010.

In the third year of the project (2011), the ratios of nitrogen supplied from two different chemical forms, nitrate and ammonium, were manipulated to test the effects on berry size, firmness, soluble solids content (SSC) and shelf-life potential. In soil-less culture, NO_3-N is supplied mainly as potassium nitrate, calcium nitrate and nitric acid. Ammonium nitrate is also used to provide NH_4-N during fruit development, but is often 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[10,11]. Excessive nitrogen application can also induce albinism[12] and reduces fruit size, SSC, flavour and firmness. High nitrogen inputs can also stimulate lush vegetative growth, which often exacerbates pest and disease problems. The effects of reducing nitrogen inputs on the regulation of plant and fruit physiology by hormonal signalling have been investigated in Defra–funded work at EMR[7].

Different proportions of NH_4-N and NO_3-N in the feed solution can be obtained by using a mixture of compounds such as calcium nitrate and ammonium sulphate. Because ammonium nitrate provides both forms of nitrogen, it cannot be used to alter the proportions of NH_4-N and NO_3-N. Very recent research[10,11] suggests that manipulating the ratio of NH_4-N to NO_3-N can increase berry size and, therefore, yields of marketable fruit as well as improving firmness and SSC. Fruit numbers also increased with the proportion of NH_4-N in hydroponically-grown strawberry[13]. However, high ratios of NH_4-N to NO_3-N can limit photosynthesis and fruit quality, as well as reducing calcium uptake. The supply of potassium and calcium must be managed carefully to optimise berry flavour and firmness[14]. In other crops, mixed nitrate/ammonium fertilization can partially alleviate the negative effects of salinity on growth, compared to all-nitrate or all-ammonium fertilization[15].

Materials and Methods

Plant material

Bare-rooted grade A+ plants of cultivars ‘Elsanta’ and ‘Sonata’ were obtained from Hargreaves’ Plants Ltd on 13 June 2011 and stored at 2°C until needed. A total of 176 0.5 m-long peat bags containing a 0.5 kg m^{-3} base fertiliser (NPK 15:10:20) and a wetting agent were positioned on a newly refurbished table top system 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 29 June 2011 each substrate bag was planted with four plants of either cv. ‘Elsanta’ or ‘Sonata’; there were 88 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 the two-week establishment period. Throughout the experiment all plants received the standard EMR pest and disease spray programme (but see below).

Experimental design

Two experiments were carried out in 2011, one on each of the two cultivars. Each experiment was an extended Latin square design consisting of ten blocks and four treatments. Rows 1 and 6 served as guard rows (Figure 3). In the commercial control (CC) treatment, sufficient irrigation was applied to achieve an average of between 10-20% run-off throughout the season using an ammonium nitrogen: nitrate ratio of 1:10, i.e. 10% N supplied via ammonium. In the second treatment, 10% N was supplied via ammonium (10% NH_4-N) but irrigation was scheduled to match demand with supply (see below) so that run-off was minimised or eliminated. Twenty percent or 30% of N was supplied *via* ammonium in treatments 3 (20% NH_4-N) and 4 (30% NH_4-N), respectively, and irrigation was again scheduled to minimise or eliminate run-off.

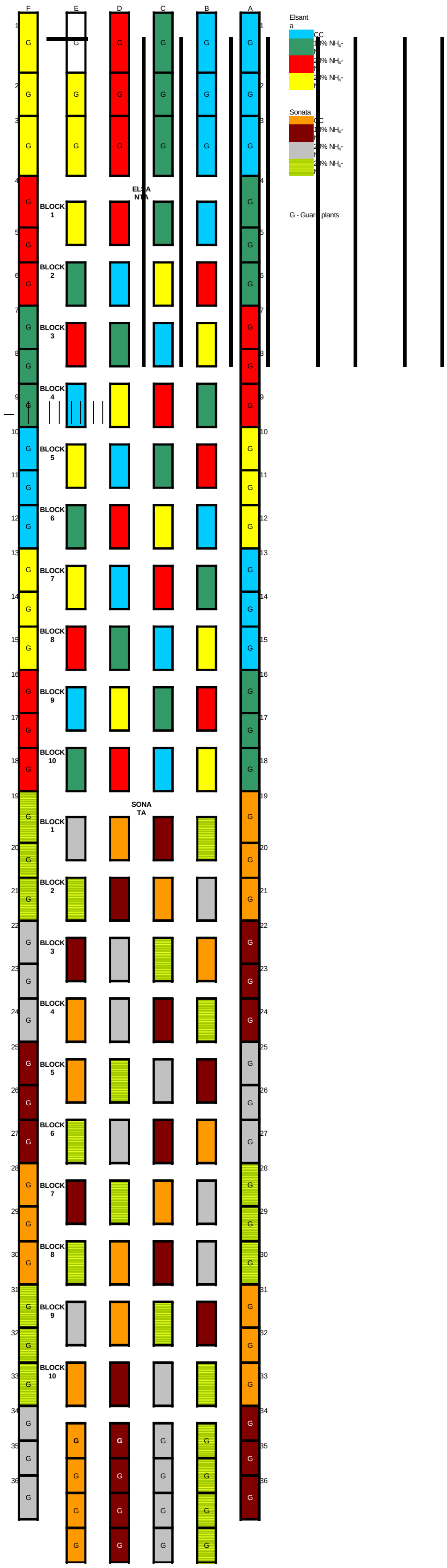

Figure 3. Plot plan showing the experimental design. Rows 1 and 6 were designated as guard rows and all measurements were made on 60-day cv. ‘Elsanta’ or ‘Sonata plants in rows 2 to 5. Each 0.5 m peat bag contained four’ plants.

Irrigation application and scheduling

Separate irrigation lines were used for each cultivar and for each treatment so that irrigation could be scheduled and applied to optimise water and nutrient use efficiencies in each treatment. During establishment, 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 eight DC-4S ¾" valves. Water was sourced from the mains supply to ensure a consistent supply (both in terms of quantity and quality) throughout the experiment. A water meter was connected to each irrigation line and measured the total volumes of water used in each treatment during different stages of crop development. Dripper outputs were tested prior to the experiment to ensure an accuracy of within 10%; outputs were then tested regularly throughout the experiment. Irrigation was pulsed throughout the day to help minimise run-off.

On 14 July 2011 SM200 substrate moisture probes (Delta-T Devices Ltd, Cambridge, UK) were inserted into the middle of a substrate bag, adjacent to a dripper and a plant, in each of the eight treatments. SM200 probes were connected to eight GP1 data loggers wired into the Galcon irrigation timers. The GP1 loggers were then programmed to trigger irrigation events when the substrate moisture content fell in each treatment bag to a pre-determined set point or to achieve the desired level of run-off. The frequency of irrigation events was determined by the rate of substrate drying in response to changes in evaporative demand throughout the day. In the commercial control (CC) treatments, the duration of irrigation events was adjusted to ensure that sufficient water was added to achieve the correct volumes of run-off. In the 10%, 20% and 30% NH_4-N treatments, the number and duration of irrigation events was adjusted to ensure that the volumetric substrate moisture content (VSMC) was maintained between upper and lower set points whilst minimising or eliminating run-off.

The accuracy with which the GP1/SM200 automatic irrigation scheduling system matched demand for water with supply was continually monitored. This was achieved by carrying out gravimetric measurements of substrate bag water loss over 24 h to obtain crop-coefficient values that could be used in conjunction with estimates of daily potential evapo-transpiration (ET_P) to estimate the volume of water lost from the substrate bags over each 24 h period. ET_P 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. The frequency and duration of irrigation events was then adjusted to ensure that irrigation was being applied to match demand with supply in the 10%, 20% and 30% NH_4-N treatments.

Following a period of establishment, irrigation scheduling regimes were first applied on 28 July 2011 when the plants were at 50% full bloom. In each treatment, run-off was channelled from three separate substrate bags into ECRN-50 rain gauges (Figure 4A) connected to Decagon EM50G data loggers with telemetry (Decagon Devices, USA). Volumes of irrigation applied at each event were also recorded by ECRN-50 rain gauges (Figure 4B). The percentage of irrigation applied that was lost via run-off was calculated each day and the irrigation set points on the GP1 data loggers were adjusted accordingly.

Figure 4. Rain gauges were used to record A) volumes of run-off and B) dripper outputs automatically throughout the season. Photos taken on 9 May 2011, the experiment shown was carried out as part of WU0110.

Volumetric substrate moisture content and electrical conductivity

Changes in volumetric substrate moisture content (VSMC) were logged continuously using Decagon 10HS probes and EM50G data loggers. Substrate electrical conductivity (EC) and temperature was also logged continuously using Decagon 5TE probes. Manual measurements of VSMC and substrate EC at several positions within each substrate bag were also made with a Delta-T Devices 'WET' sensor.

Adjusting NO_3-N to NH_4-N ratios

Fertigation regimes were formulated by Mr Michael Daly (The Agrology House, Lincs., UK) after mineral analysis of the mains water used for the experiment. Straight fertilisers were used to achieve 10%, 20% and 30% of the total nitrogen applied in the form of NH_4-N. In order to achieve this it was necessary in the 30% NH_4-N recipes to add calcium chloride in order to keep the calcium constant in each treatment. Total nitrogen was kept the same in all treatments, as were P, K, Ca, Mg and trace elements (Table 1). Calcium recipes were given from a target of 150 mg/L Ca during the vegetative stage to 125 mg/l Ca during the fruiting stage.

Table 1. Nutritional composition of the vegetative and fruiting feeds for each treatment diluted 1:100 (including background water and nitric acid).

Nutrient	Concentration in diluted feed (mg L^{-1})				
	Vegetative	Fruiting			
	All treatments	CC	10% NH_4-N	20% NH_4-N	30% NH_4-N
Total N	129	150	150	150	150
NO_3-N	125	135	135	120	105
NH_4-N	4	15	15	30	45
P	33	46	46	46	46
K	205	250	250	250	250
Ca	151	150	150	150	150
Mg	27	33	33	33	33
Cl	0.21	34	34	34	34
B	0.14	0.22	0.22	0.22	0.22
Cu	1.38	0.11	0.11	0.11	0.11
Fe	0.60	1.80	1.80	1.80	1.80
Mn	0.03	0.75	0.75	0.75	0.75
Mo	0.66	0.50	0.50	0.50	0.50
Zn	0.56	0.56	0.56	0.56	0.56
EC (mS cm^{-1})	1.74	2.01	2.01	2.25	2.42

From two weeks after planting until the small green fruit stage, a vegetative feed was used in both cultivars and all treatments. Plants were fertigated from two stock tanks, one containing 'Hortipray' calcium nitrate (19% Ca, 14.5% NO_3-N, 1.0% NH_4-N) and a second containing 'Solufeed' (6-11-37 + 4 Mg0 + trace elements) and 'Hortipray' magnesium sulphate (9.6 % Mg). Nitric acid (60%) was added to each tank to reduce the bicarbonate concentration of the water to around 50 mg L^{-1} for buffering purposes. Dosatrons were used to dilute the stock solutions 1:100 and to adjust the feed EC levels throughout the experiments. The target pH range of the solution applied to the plants was 5.8 - 6.2. At the small green fruit stage, a fruiting feed was used for the cv 'Elsanta' and cv 'Sonata' CC treatments; this was first applied on 4 August 2011. The fruiting feed was applied throughout cropping and for three weeks after cropping had finished to 'build up' the crowns for the next season. EC and pH of the diluted feed solution were measured daily at the drippers, together with the EC of any run-off.

For the 10%, 20% and 30% NH_4-N treatments, the composition of the fruiting feed was adjusted to deliver the necessary contributions of N from NO_3 and NH_4 (Table 1). 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.

Leaf tissue and substrate nutrient status

Leaf and substrate samples were taken from each of the eight treatments for nutrient analysis at the middle (18 August 2011) and towards the end (9 September 2011) of cropping to determine whether the different NH_4-N regimes affected plant mineral uptake and the accumulation of ions in the substrate.

Measurement of physiological responses

All routine measurements were carried out on one plant in each of eight replicate bags per treatment in rows 2-5 (see Figure 4). Tables in rows 1 and 6 were used as guard plants to avoid any edge effects at the sides of the polytunnel. Midday xylem 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 (g_s) of one young, fully-expanded leaf per experimental plant was measured twice-weekly with a steady-state porometer (Leaf porometer SC-1, Decagon Devices Ltd.). Rates of photosynthesis of fully expanded leaves were measured using a portable infra-red gas analyser (CIRAS-1, PP-systems) with an additional light source powered by a car battery on five occasions during fruit development and cropping.

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 three expanding leaves was measured throughout the season.

Changes in primary, secondary and tertiary fruit volume were measured twice weekly during development to determine whether the different irrigation and fertigation regimes affected the rate of fruit expansion. The diameter of labelled fruit was measured twice at diametrically opposed positions on the shoulder and combined with length measurements to estimate fruit volume; for this purpose, fruit were assumed to be conical.

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 4). Ripe fruit were first harvested on 11 August

2011 and were collected twice weekly until 19 September 2011. 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. Berry SSC was measured with a digital refractometer (Palett 100, Atago & Co. Ltd, Tokyo, Japan).

Shelf-life tests

Shelf-life tests were undertaken for secondary/tertiary fruit harvested on 2 September 2011. 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 were recorded on each of the seven days.

Calculation of water productivity and nutrient use efficiency

The total volume of water applied during the experiment from 14 July until 19 September 2011 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.

Nutrient inputs were calculated by multiplying the total amount of each nutrient applied per litre of irrigation water supplied throughout the experiment by the concentrations of individual nutrients in the diluted feed solution.

Statistical analyses

Statistical analyses were carried out using GenStat 11th Edition (VSN International Ltd.). To determine whether differences between cultivars were statistically significant, analysis of variance (ANOVA) tests were carried out and least significant difference (LSD) values for p<0.05 were calculated.

Additional experiment in 2011

Due to the issues associated with powdery mildew throughout this project (see below), an additional experiment was carried out in Spring 2011. Although the experiment was primarily designed to test the potential of a novel irrigation strategy developed at EMR (Transient Deficit Irrigation – TDI) to improve water use efficiency and fruit quality in substrate strawberry production (Defra Project WU0110), additional treatments were included to provide information about the potential of using RDI to improve water use efficiency and fruit quality. A Commercial Control (CC) treatment was included where irrigation was applied to achieve an average of 10% run-off throughout the season and the irrigation scheduling regime that was used in SF 107 experiments in 2011 was also imposed.

Results

It should be noted that throughout this project, Class 1 yields were lower than anticipated due to issues associated with powdery mildew. The subsequent reduction in transpirational leaf area of infected plants would have reduced water use and slowed the rate of substrate drying; therefore, the volumes of water applied over the season would be lower than in disease-free plants. However, since plants in all treatments were infected similarly, the relative differences between treatments in terms of water use reported below would not have been affected. The approaches developed in SF 107 have also been trialled in Defra-funded work at EMR with mildew-free main season substrate-grown cv. 'Elsanta' crops and significant savings in water and fertilisers have been achieved whilst maintaining good commercial yields of high quality fruit.

2011

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

Irrigation volumes and percent run-off

For each cultivar and for each treatment, irrigation volumes applied at each irrigation event over the season were recorded automatically using ECRN-50 rain gauges. The sum of the daily irrigation volumes applied to the CC and 10% NH_4-N regimes for 'Elsanta' are presented in Figure 5 (A and B), together with estimates of daily ET_P. The total volumes of water applied to each cultivar in each treatment are presented in Table 2. Compared to CC values, water savings of 15 to 42% were achieved over the season in cv. 'Elsanta' and of 22 to 45% in cv. 'Sonata' when irrigation was scheduled to match demand with supply. Consequently, run-off from the substrate bags was either greatly reduced or eliminated in the 10%, 20% and 30% NH_4-N treatments (Figure 6A and B), compared to the average values over the season from the CC treatments (Table 2). The effects of this approach on substrate VSMC and EC are described below.

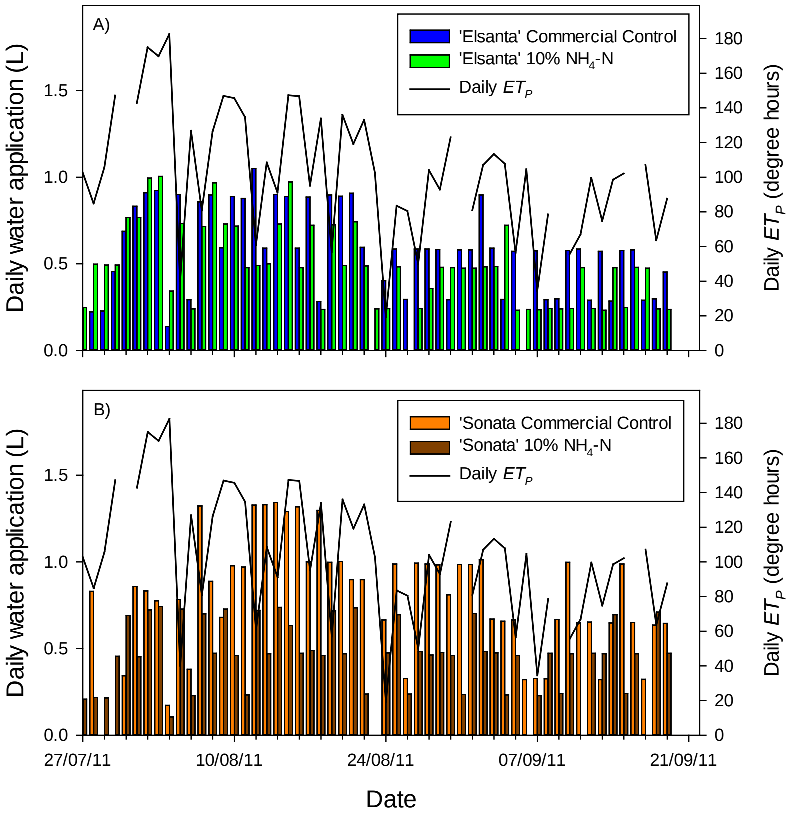

Figure 5. Daily irrigation volumes applied to 60-day A) 'Elsanta' and B) 'Sonata' plants under the Commercial Control and the 10% NH_4-N regimes. Results are means of three replicate measurements per treatment. Estimates of daily potential evaporative demand are also presented.

Table 2. Total volumes of irrigation water applied per plant (L) for 60-day cv. 'Elsanta' and cv. 'Sonata' under the irrigation and NO_3-N:NH_4-N regimes and the associated percent run-offs averaged over the over the season.

Treatment	Volume of water applied (L)		Average run off (%)	
	'Elsanta'	'Sonata'	'Elsanta'	'Sonata'
CC	31.2	42.7	22.4	19.3
10% NH_4-N	26.5	24.3	4.4	0.0
20% NH_4-N	22.3	33.4	5.6	0.2
30% NH_4-N	18.0	23.6	0.2	4.6

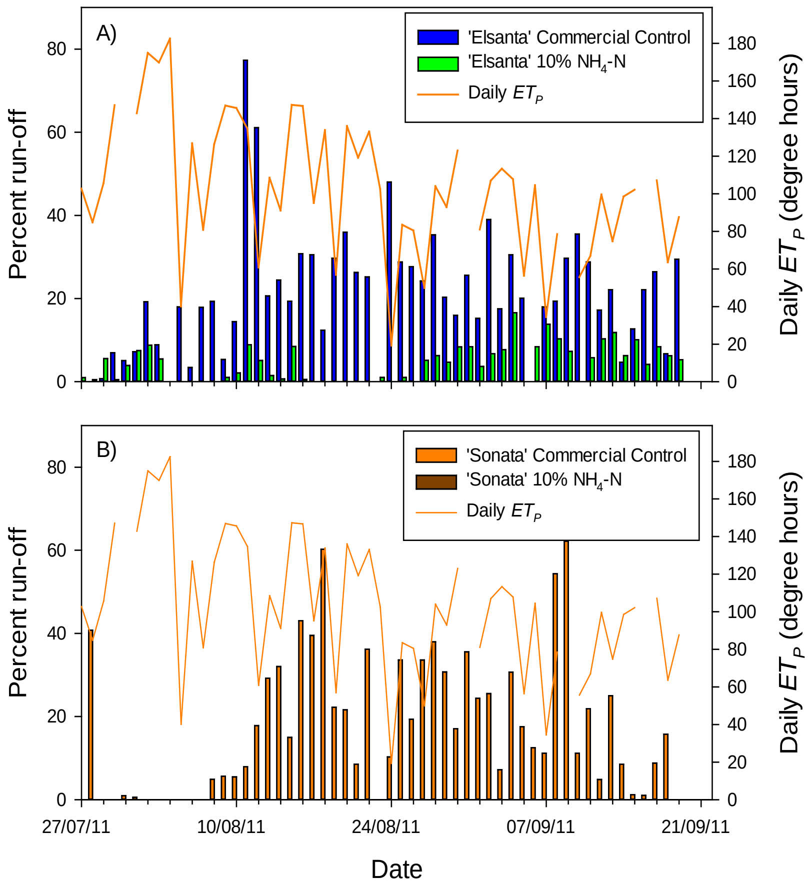

Figure 6. Daily run-off expressed as a percent of the volume of irrigation water applied to 60-day A) 'Elsanta' and B) 'Sonata' plants under the Commercial Control and the 10% NH_4-N regimes. Results are means of three replicate measurements per treatment. Estimates of daily potential evaporative demand are also presented.

Volumetric substrate moisture contents and EC

Irrigation to the CC treatments was scheduled to achieve an average value of between 10 and 20% run-off over the season (see Table 2). Consequently, the average VSMC was maintained between 0.4 and 0.5 m^3 m^{-3} in the CC treatments in both cultivars; data for cv. 'Sonata' are presented in Figure 7. Volumetric substrate moisture content was maintained above 0.47 m^3 m^{-3} for the majority of the season and since run-off was achieved at most irrigation events on most days, this value effectively represents substrate water holding capacity. Under the 10%, 20% and 30% NH_4-N regimes, VSMC was generally maintained between 0.35 and 0.4 m^3 m^{-3} during flowering and cropping (Figure 7) and was significantly lower than CC values on some measurement dates.

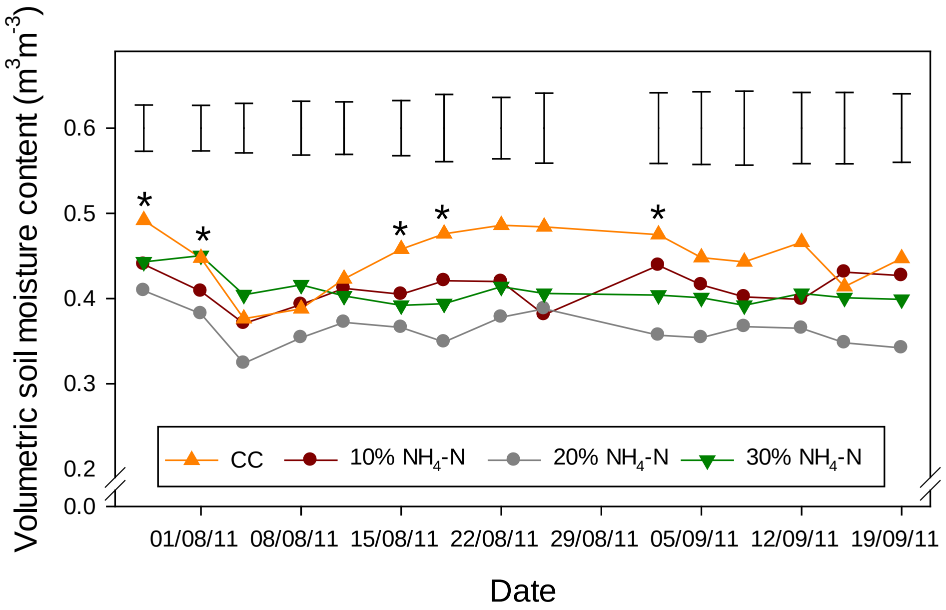

Figure 7. Changes in volumetric soil moisture content (m^3 m^{-3}) in peat bags containing 60-day 'Sonata' plants under the different irrigation and NO_3-N:NH_4-N regimes. Results are means of eight replicate measurements per treatment. Vertical bars are LSD values at p<0.05, asterisks indicate statistically significant differences.

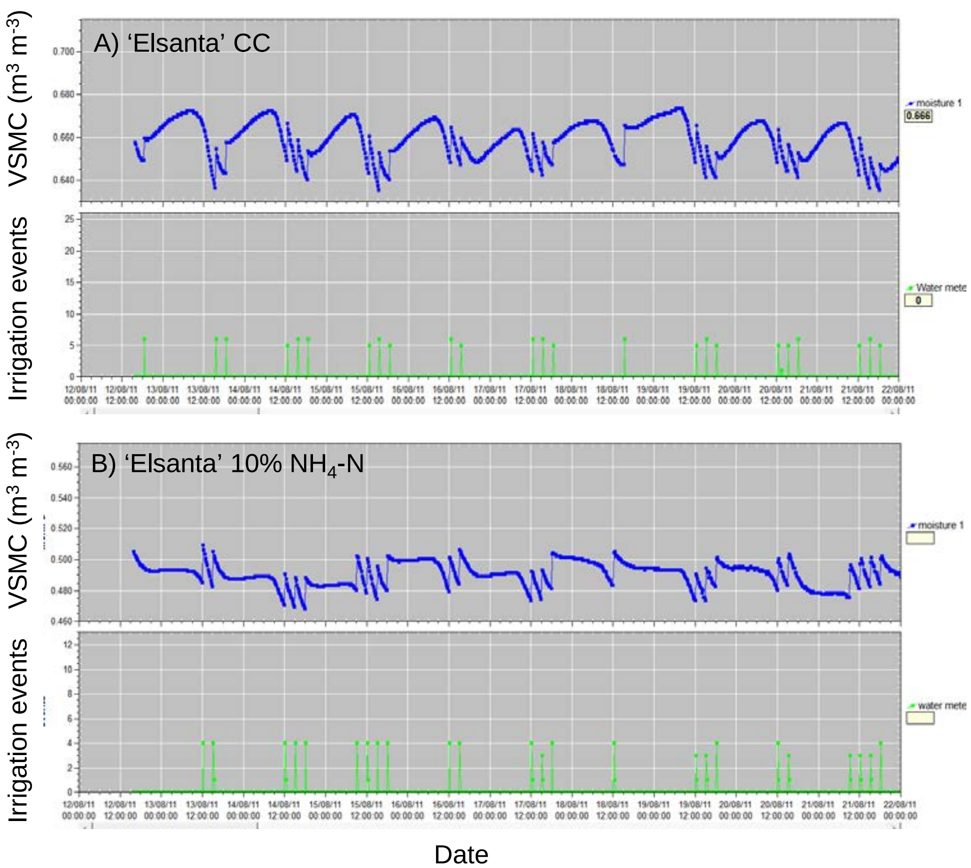

Figure 8. Changes in volumetric substrate moisture content measured continuously using Delta-T SM200 probes over a 10 day period in the middle of cropping in A) the Commercial Control and B) the 10% NH_4-N regimes in 60-day cv. 'Elsanta' plants. The number of irrigation events per day is also presented.

Continuous measurements of VSMC were also made using Delta-T Devices GP1 data loggers and SM200 probes and outputs from the water meters were also recorded (1 event = 1 L). Examples of these data sets are presented in Figure 8 for the cv. 'Elsanta' CC and 10% NH_4-N treatments during a 10 day period in the middle of cropping. In the cv. 'Elsanta' CC treatment, the irrigation set point was 0.65 m^3 m^{-3} and either one, two orthree 5 min-long irrigation events were triggered depending on daily evaporative demand. During this 10 day period, a total of 8.47 L of water was applied to each cv. 'Elsanta' CC bag and run-off averaged 29%. In the cv. 'Elsanta' 10% NH_4-N treatment, the irrigation set point was 0.485 m^3 m^{-3} and one, two, three or four 3 min-long irrigation events were triggered depending on daily evaporative demand. For example, on 18 August 2011, daily ET_P was low (56.9) and so plant water use was relatively low (8 g h^{-1}), consequently the rate of substrate drying was slow and one irrigation event was triggered. Conversely, on 15 August 2011, daily ET_P was high (146.7) resulting in high transpiration rates (17.5 g h^{-1}) and so the substrate dried more rapidly and four irrigation events were triggered. A total of 6.58 L of water was applied to each cv. 'Elsanta' 10% NH_4-N bag and run-off averaged 1.5% over the 10-day period between 12 and 22 August 2011.

Substrate EC varied from 0.5 to 1.75 mS cm^{-1} over the season and values were similar in the different treatments, despite the much reduced run-off in the 10%, 20% and 30% NH_4-N treatments, data from the CC and 10% NH_4-N regimes are shown for each cultivar in Figure 9. The increased substrate EC after 22 August 2011 was presumably due to the application of chemical sprays to try to control the mildew infection. 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 (data not shown).

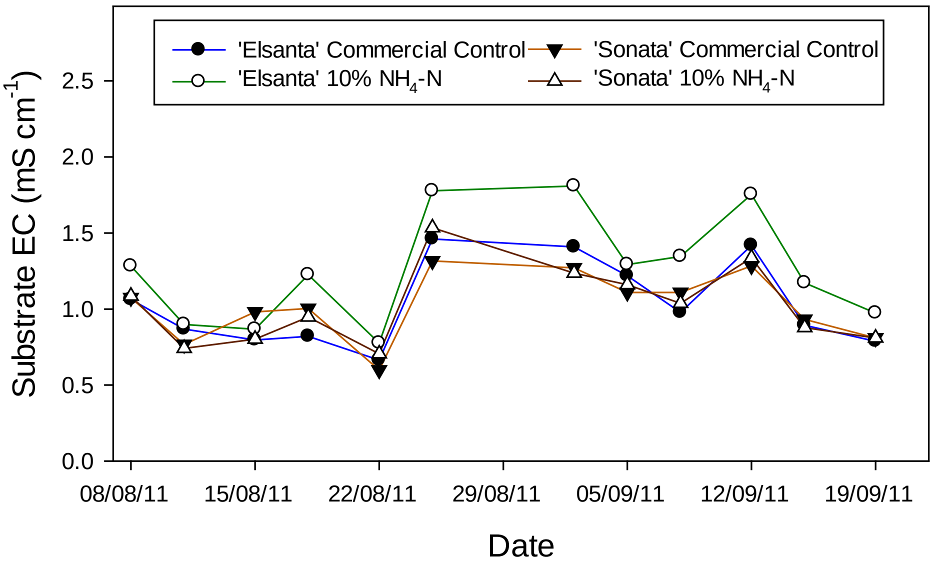

Figure 9. Changes in substrate EC (mS cm[1]) in peat bags containing 60-day cv. 'Sonata' plants under the Commercial Control and 10% NH_4-N regimes. Results are means of eight replicate measurements per treatment.

Plant physiological responses

Leaf elongation in cv. 'Elsanta' was similar in each of the four treatments during the beginning and end of cropping but was significantly slowed in the 10%, 20% and 30% NH_4-N treatments in the middle of cropping, compared to the CC value (Figure 10). Leaf elongation rates were similar in cv. 'Sonata' throughout cropping and no statistical differences were noted between the different irrigation and fertigation regimes (data not shown). No statistically significant treatment effects on g_s were detected for cv. 'Sonata' on 15 measurements dates throughout cropping and on only one occasion was g_s reduced significantly by the 20% NH_4-N treatment in cv. 'Elsanta' (data not shown). This occurred on 15 August 2011 and coincided temporally with the slowed leaf extension mentioned above. No significant treatment effects on midday ψ_L were detected for either cultivar on six measurement dates and rates of photosynthesis were also similar in each cultivar, irrespective of the irrigation and fertigation regimes applied (Figure 11A and B). Overall, these results indicate that NO_3-N to NH_4-N ratios between 10% and 30% did not affect plant physiology in either cultivar under the CC and the water-saving irrigation regimes.

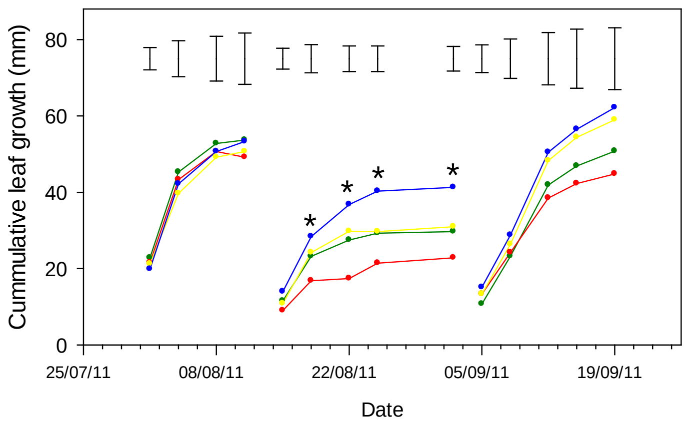

Figure 10. Cummulative leaf growth measured on expanding leaves of 60-day 'Elsanta' plants under the different irrigation and NO_3-N:NH_4-N regimes. Results are means of eight replicate measurements per treatment. Vertical bars are LSD values at *p*<0.05, asterisks indicate statistically significant differences

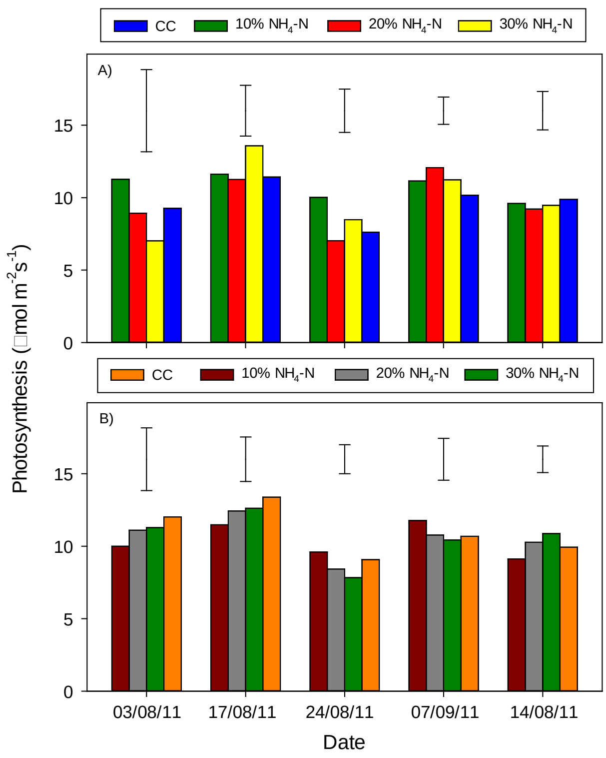

Figure 11. The effects of the irrigation and NO_3-N:NH_4-N regimes on rates of photosynthesis in 60-day A) 'Elsanta' and B) 'Sonata' plants**.** Results are means of eight replicate measurements per treatment, vertical bars are LSD values at *p*<0.05.

Foliar and substrate nutrient analysis

Leaf and coir samples were analysed for macro- and micro-nutrients at the middle and towards the end of cropping. On 18 August 2011, two weeks after the 10%, 20% and 30% NH_4-N regimes were applied, most macro and micro nutrients were within the normal ranges in leaf samples from cv. 'Elsanta' (Tables 3); the exceptions were N and S which were above their respective satisfactory ranges in all treatments. In cv. 'Sonata', N and S were also above satisfactory values and Ca was just below satisfactory values in all treatments (Table 4). Leaf Fe concentration was excessively high in the cv. 'Sonata' 30% NH_4-N regime.

Table 3. Foliar mineral analysis for 60-day 'Elsanta' leaf samples collected on 18 August 2011 in the middle 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			
		CC	10% NH_4-N	20% NH_4-N	30% NH_4-N
N	(%)	*4.0*	*3.9*	*4.1*	*4.0*
P	(%)	0.5	0.4	0.4	0.4
K	(%)	2.5	2.2	2.1	2.2
Mg	(%)	0.4	0.5	0.5	0.4
Ca	(%)	1.3	1.34	1.21	1.1
Mn	(mg kg^{-1})	207	216	204	190
Cu	(mg kg^{-1})	6.1	5.3	4.9	4.7
Fe	(mg kg^{-1})	172.2	176.2	140.2	128.2
Zn	(mg kg^{-1})	29.2	27.6	25.6	27.6
B	(mg kg^{-1})	45.5	43.8	40.0	42.0
S (%)	(%)	*0.3*	*0.3*	*0.3*	*0.3*
N:S ratio	-	14.3:1	14.6:1	15.1:1	15.7:1

Table 4. Foliar mineral analysis for 60-day 'Sonata' leaf samples collected on 18 August 2011 in the middle 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			
		CC	10% NH_4-N	20% NH_4-N	30% NH_4-N
N	(%)	*3.9*	*3.8*	*4.1*	*3.9*
P	(%)	0.5	0.5	0.4	0.5
K	(%)	2.1	2.1	1.9	2.0
Mg	(%)	0.3	0.3	0.4	0.3
Ca	(%)	**0.8**	**0.8**	**1.0**	**0.9**
Mn	(mg kg^{-1})	135	126	149	138
Cu	(mg kg^{-1})	*4.3*	*4.3*	*3.9*	*4.7*
Fe	(mg kg^{-1})	157.0	111.5	122.6	**1317.4**
Zn	(mg kg^{-1})	29.6	28.8	25.5	29.8
B	(mg kg^{-1})	*28.1*	*24.5*	*29.8*	*23.8*
S (%)	(%)	*0.3*	*0.3*	*0.3*	*0.3*
N:S ratio	-	15.7:1	14.7:1	15.9:1	15.3:1

At the end of cropping, macro and micro nutrients were at similar levels to those measured previously in cv. 'Elsanta' although N concentrations were lower and Cu concentrations had fallen slightly below the satisfactory value (Table 5). In cv. 'Sonata', N concentrations were within the satisfactory range, with the exception of the CC treatment where it was still higher (Table 6). Leaf Ca concentrations remained below the satisfactory range, however, this was unlikely to be due to the increasing proportion of NH_4-N since values were also low in the 10% NH_4-N treatment which received the same fertigation regime as the CC. This effect was more likely due to the reduced Ca inputs resulting from the water-saving irrigation scheduling regime used in the 10%, 20% and 30% NH_4-N treatments (see Table 9). However, the reduced Ca input did not affect 'Sonata' fruit firmness or shelf-life potential (see below).

Table 5. Foliar mineral analysis for 60-day 'Elsanta' leaf samples collected on 19 September 2011 at the end 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			
		CC	10% NH_4-N	20% NH_4-N	30% NH_4-N
N	(%)	*3.6*	*3.7*	*3.8*	*3.9*
P	(%)	0.5	0.4	0.5	0.5
K	(%)	2.2	1.7	1.9	2.0
Mg	(%)	0.46	0.4	0.5	0.5
Ca	(%)	1.3	1.4	1.5	1.4
Mn	(mg kg^{-1})	190	194	222	219
Cu	(mg kg^{-1})	5.0	**4.1**	**4.5**	**4.2**
Fe	(mg kg^{-1})	133.2	*647.1*	200.4	147.9
Zn	(mg kg^{-1})	25.9	23.2	26.0	26.1
B	(mg kg^{-1})	*54.8*	42.0	47.6	49.3
S (%)	(%)	*0.2*	*0.3*	*0.2*	*0.3*
N:S ratio	-	15.1:1	14.4:1	15.8:1	15.1:1

Table 6. Foliar mineral analysis for 60-day 'Sonata' leaf samples collected on 19 September 2011 at the end 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			
		CC	10% NH_4-N	20% NH_4-N	30% NH_4-N
N	(%)	*3.8*	3.5	3.5	3.5
P	(%)	0.5	0.5	0.5	0.5
K	(%)	2.0	1.8	1.7	1.7
Mg	(%)	0.32	0.3	0.3	0.3
Ca	(%)	**0.9**	**0.7**	**0.7**	**0.6**
Mn	(mg kg^{-1})	131	118	114	120
Cu	(mg kg^{-1})	**4.4**	**4.1**	**3.6**	**3.7**
Fe	(mg kg^{-1})	101.4	146.9	132.5	89.0
Zn	(mg kg^{-1})	25.9	30.1	28.0	32.7
B	(mg kg^{-1})	30.9	**27.8**	**26.6**	**23.6**
S (%)	(%)	*0.3*	*0.2*	*0.2*	*0.2*
N:S ratio	-	14.2:1	15.0:1	15.1:1	13.2:1

Substrate mineral analyse were also carried out at the middle and towards the end of cropping. In cv. 'Elsanta', increasing the proportion of NH_4-N caused acidification of the rhizosphere within two weeks of treatment application and by the end of cropping, substrate pH values were lower in the 20% and 30% NH_4-N treatments in both cultivars, compared to the CC values (Table 7). This was expected due to the release of hydrogen ions during the conversion of NH_4-N to NO_3-N.

Table 7. Substrate pH values at the end of cropping following six weeks under the irrigation scheduling and NO_3-N:NH_4-N regimes in 60-day 'Elsanta' and 'Sonata'.

Cultivar	Substrate pH			
	CC	10% NH_4-N	20% NH_4-N	30% NH_4-N
'Elsanta'	5.95	5.81	5.62	5.69
'Sonata'	5.79	5.73	5.67	5.66

The substrate EC was consistent with a liquid-fed crop without excess nutrients being applied (ADAS Index 1 [151-300 µS/cm]to ADAS index 2 [300-400 µS/cm]); there was a general increase in EC between the two sampling dates suggesting that nutrients may have been accumulating as crop growth progressed (data not shown). Ammonium-N did not generally increase in the substrate with increasing proportions of NH_4-N in the feed, presumably due to the rapid breakdown of NH_4-N into NO_3-N

Class 1 yields

Total yields of Class 1 fruit were only around 150 g per plant, rather than the 250 g expected, due to the effects of mildew on fruit ripening, rates of expansion and the increase in waste fruit. Average yields of Class 1 fruit per plant were not significantly affected by the 10%, 20% and 30% NH_4-N regimes in either cv. 'Elsanta' or cv. 'Sonata' compared to the CC regimes (Figure 12A and B). As expected, non-destructive estimates of fruit volume during development and ripening were similar in cv. 'Elsanta', irrespective of irrigation or fertigation regime (data not shown). Significant differences in estimated fruit volume were detected between CC and 30% NH_4-N treatments in primary fruit and between CC and 10% NH_4-N treatments in secondary fruit (data not shown). However, these differences were not large enough to significantly reduce Class 1 yields.

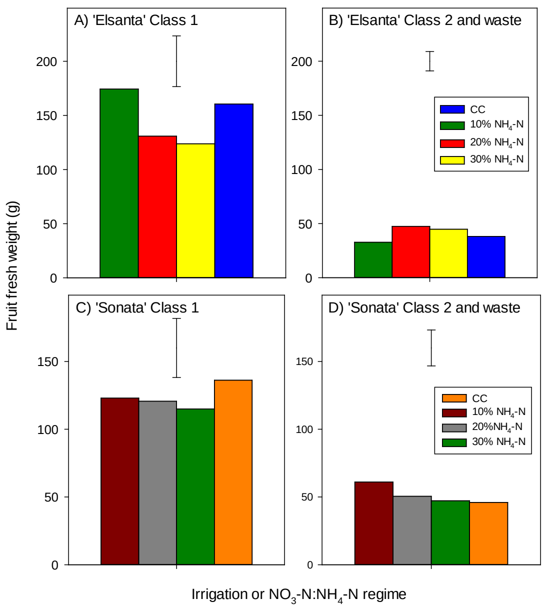

Figure 12. The effects of the irrigation and NO_3-N:NH_4-N regimes on yields in 60-day A) 'Elsanta' and B) 'Sonata' plants. Results are means of eight replicate plants per treatment, vertical bars are LSD values at *p*<0.05.

Fruit quality and shelf-life potential

Berry firmness was unaffected in either cultivar by the irrigation and fertigation regimes (Figure 13) and no treatment effect on berry SSC was detected (Figure 14), although SSC were higher in tertiary fruit.

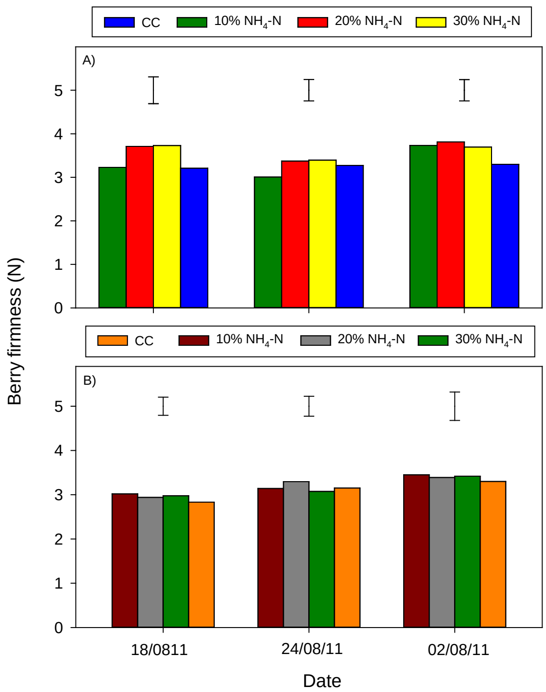

Figure 13. The effects of the irrigation and NO_3-N:NH_4-N regimes on berry firmness in 60-day A) 'Elsanta' and B) 'Sonata'. Results are means of eight replicate plants per treatment, vertical bars are LSD values at *p*<0.05.

Due to the low numbers of suitable Class 1 fruit, only two shelf-life assessments were carried out in 2011. Rates of water loss from cv. 'Elsanta' berries harvested from the 20% and 30% NH_4-N regimes were slowed compared to CC values in the second shelf-life test; no significant treatment effects were detected in the first shelf-life test (data not shown). Berry susceptibility to bruising and the development of rots were similar, irrespective of irrigation or fertigation regime, in both shelf-life tests (data not shown). No significant treatment effects were detected in either shelf-life test with cv. 'Sonata' (data not shown).

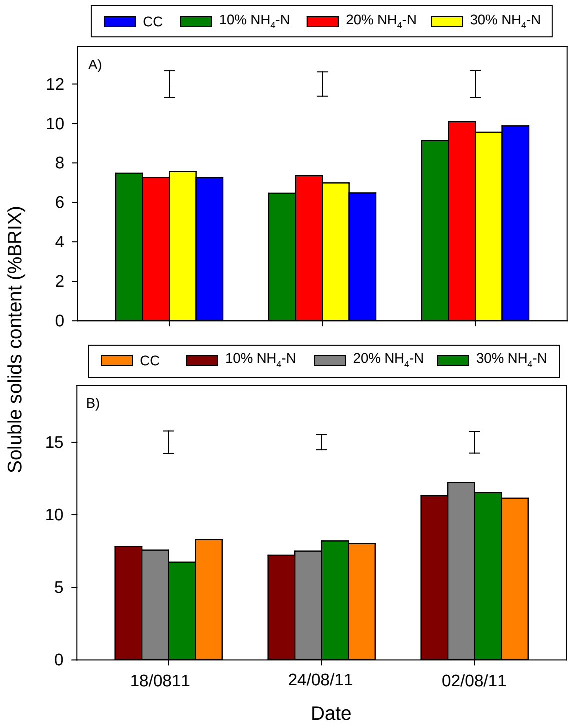

Figure 14. The effects of the irrigation and NO_3-N:NH_4-N regimes on soluble solids content (BRIX) in 60-day A) 'Elsanta' and B) 'Sonata'. Results are means of eight replicate plants per treatment, vertical bars are LSD values at $p<0.05$.

Water and fertiliser use

The volume of irrigation applied to each plant under each of the three irrigation regimes is presented in Table 2. Scheduling irrigation to match demand with supply so that run-off was minimised or eliminated resulted in water savings of up to 42% and 45% for cv. 'Elsanta' and cv. 'Sonata' respectively, compared to the CC treatments where run-off averaged 20% over the season.

Water productivity values were also calculated for each irrigation regime and for each cultivar (Table 8). The volume of water applied was first recorded from Day 0 (27 July 2011) 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. Typical grower WP values are not yet known for substrate-grown strawberries but will be measured on two grower sites during 2012 in HDC project SF 136.

Table 8. Water productivity values associated with irrigation and NO_3-N:NH_4-N regimes for 60-day cv. 'Elsanta' and cv. 'Sonata'

Cultivar	Water productivity (L per kg class 1 fruit)			
	CC	10% NH_4-N	20% NH_4-N	30% NH_4-N
'Elsanta'	48.6	38.0	42.6	36.3
'Sonata'	78.4	49.4	69.2	51.3

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 15% and 45% were achieved using the irrigation scheduling regimes to reduce or eliminate run-off. The total amounts of N, P, K, Ca and Mg applied during the season to cv. 'Elsanta' and cv. 'Sonata' plants under the CC regime are presented in Table 9. Under water-saving irrigation regimes, feed recipes will have to be modified to compensate for the reduced inputs.

Table 9. Total mass of macro nutrients applied via fertigation per plant for 60-day cv. 'Elsanta' and cv. 'Sonata' under the different irrigation and NO_3:NH_4 regimes

Element	Total mass of nutrient applied per plant (g)							
	'Elsanta'				'Sonata'			
	CC	10% NH_4-N	20% NH_4-N	30% NH_4-N	CC	10% NH_4-N	20% NH_4-N	30% NH_4-N
Total N	4.7	4.0	3.3	2.7	6.4	3.7	5.0	3.5
NO_3 - N	4.2	3.6	2.7	1.9	5.8	3.3	4.0	2.5
NH_4 - N	0.5	0.4	0.7	0.8	0.6	0.4	1.0	1.1
P	1.4	1.2	1.0	0.8	2.0	1.1	1.5	1.1
K	7.8	6.6	5.6	4.5	10.7	6.1	8.4	5.9
Ca	4.7	4.0	3.3	2.7	6.4	3.7	5.0	3.5
Mg	1.0	0.9	0.7	0.6	1.4	0.8	1.1	0.8

Additional experiment in 2011

Water and fertiliser savings of 6%, 33% and 9% were delivered by the irrigation scheduling, RDI and TDI treatments, respectively. Class 1 yields per plant were similar in main season plants under the Commercial Control, the irrigation scheduling and the TDI regimes (~512 g per plant). However, yields of Class 1 fruit were reduced by 19% in RDI-treated plants, due to a reduction in fruit size rather than fruit number. Berry organic acid, glucose and fructose concentrations and the sugar:acid ratio were significantly increased by the irrigation scheduling and TDI regimes, compared to CC values and although SSC values were generally higher, the differences were not statistically significant (data not shown). The percentage of berries developing rots during shelf-life tests was also reduced by the irrigation scheduling, RDI and TDI treatments (data not shown).

Discussion

Experiments in 2009 and 2010

In the first two years of the project, irrigation scheduling and RDI regimes were imposed on 60-day and main season cv. 'Elsanta' and cv. 'Sonata' plants. An irrigation scheduling regime that matches demand with supply and so minimises or eliminates run-off was developed using irrigation set points based on volumetric substrate moisture contents (VSMC). In 2009 with 60-day crops, water and fertiliser savings of up to 45% were achieved without reducing yields of Class 1 fruit, although total yields were low due to the effect of the x10 strength potassium bicarbonate spray applied in error.

Despite the reduced nutrient inputs, foliar concentrations of N, P, K, Mg, Mn, Fe, Zn, B and S were within satisfactory ranges in each cultivar under each irrigation regime ,although concentrations of Ca and Cu were just below satisfactory values by the end of the cropping season. RDI reduced total leaf areas by 20% and 39% in cv. 'Elsanta' and cv. 'Sonata', respectively, and the percentage of cv. 'Sonata' fruit that developed bruising over a 6-day shelf-life test was reduced from 45% in Commercial Controls to 15% by RDI. However, substrate EC was increased by 20% under the RDI regime by the end of the growing season.

In 2010, RDI regimes were imposed successfully on main season cv. 'Elsanta' and cv. 'Sonata' plants and physiological responses to substrate drying such as lowered stomatal conductances, transpiration rates, leaf growth and photosynthetic rates were detected. Total canopy areas were reduced by up to 58% and 62% in RDI-treated cv. 'Elsanta' and cv. 'Sonata', respectively. However, Class 1 yields were also significantly reduced in RDI-treated plants compared to CC values (449 g vs 231 g). Although these strategic experiments have shown that RDI has the potential to deliver significant water and fertiliser savings, as well as improvements in fruit quality, the technique would be difficult to implement in commercial production. Maintaining the substrate within the target upper and lower VSMC thresholds under high evaporative demand would be challenging due to the limited substrate volumes (3-4 L per plant) and this would increase the risk of shoot water deficits and associated reductions in Class 1 yields and quality.

Although run-off was eliminated and water and fertiliser savings of 50% were achieved by implementing the irrigation scheduling technique, main season cv. 'Elsanta' and cv. 'Sonata' Class 1 yields were reduced by 27% and by 13%, respectively, compared to the Commercial Control regime. This was due to a reduction in fruit size rather than fruit number, and presumably resulted from temporary limitations in substrate water availability under high evaporative demands. Therefore, the VSMC irrigation set points were adjusted for the 2011 experiments (see below).

Developing approaches to help improve irrigation scheduling

The new irrigation scheduling regime that has been developed in SF107 (and WU0110) has great potential to further improve the economic and environmental sustainability of substrate soft fruit production in the UK. Managing the volume of run-off throughout the fruit development under changeable evaporative demands in crops of different ages is challenging for commercial growers. Manually collecting and measuring run-off volumes in each block of substrate crop in time to inform irrigation decisions can be time consuming and an automated system that enabled irrigators to react quickly to differing evaporative demands would help to deliver significant water and fertiliser savings. The system developed in this project enables data on water inputs and outputs to be accessed remotely so that the percent run-off after each irrigation event can be calculated. This information can then be used to highlight times of the day when run-off is excessive and the duration of these events can then be adjusted to reduce water and fertiliser losses.

Feed regimes may need to be adjusted in some cultivars to account for the reduced input of fertilisers when irrigation is scheduled to match demand with supply. Continuous monitoring of VSMC also ensures that water availability does not become limiting once run-off volumes have been reduced. The potential build-up of salts under these water- and fertiliser-saving strategies can also be monitored using EC probes, and managed by flushing through with acidified water or dilute calcium nitrate solutions if needed. During these scientific trials equipment from three different manufactures has been used to build an automated irrigation system that enables precise control of run-off. For commercial exploitation these systems need to be integrated into a single controller unit. The necessary components of this system are currently being identified in a new follow-on

HDC project (SF 136).

Scheduling irrigation based on estimates of evaporative demand can be a very effective way of irrigation scheduling and much of EMR's work over the last twelve years has been developed using this approach. If ET_P is calculated for the previous 24 h period, as was done here, and irrigation is applied to replace the estimated volume of water lost during that time, significant variations in VSMC can result if ET_P is very different on successive days. For example, if a cloudy day (low ET_P) is followed by a very hot and sunny day (high ET_P), the volume of water applied to replace that lost on the cloudy day will be insufficient to match demand on the sunny day and VSMC will fall temporarily until the next day. The converse is also true in that significant run-off may result on a cloudy day where the ET_P on the previous day has been very high. These issues can be largely overcome if daily irrigation events are scheduled to replace the water estimated to have been lost since the last irrigation event. This, albeit time-consuming, approach was done in our earlier strategic Defra-funded work (HH3609TX) and allows precise control over irrigation scheduling. The potential to use measurements of VPD to deliver volumes of irrigation using a commercial rig that matches demand throughout the day will be tested in the trial at New Farm Produce Ltd in HDC project SF 136.

Manipulating N nutrition

The aim of this work was to test the potential of manipulating ammonium-N ($N\text{-}NH_4$) and nitrate-N ($N\text{-}NO_3$) ratios to try to improve berry firmness and shelf-life potential, particularly in cultivars such as 'Sonata' where berries can be soft and vulnerable to bruising. In this experiment, changing the percentage of ammonium-N from 10% to either 20% or 30% did not significantly affect plant physiology or fruit quality. In previous work[10,11], higher ratios of NO_3-N:NH_4-N have been needed to elicit physiological responses (*e.g.* 50%:50%, 25%:75%) but during the preparation of the original proposal, industry representatives felt that ratios greater than 70%:30% would limit fruit yields and quality. In the 60-day crop in 2011, the different NO_3-N:NH_4-N regimes were applied for only six weeks but during that time, no significant treatment differences were observed. More work is needed to determine the potential of manipulating N nutrition in this way to improve aspects of fruit quality and flavour.

Increasing the NO_3-N:NH_4-N ratio has also been shown to improve tolerance to high salinities in hydroponically-grown tomato[15]. Interestingly, a NO_3-N:NH_4-N ratio of 70:30 (as used in HDC project SF 107) did not affect growth and other parameters under control conditions but improved shoot and root biomass and maintained leaf photosystem II (PSII) efficiency under high salinity. These changes were induced via effects on plant hormone status in response to high salinity.

The impact of substrate soft fruit production on 'blue water' quality

The proportion of soft fruit growers moving from soil to substrate production is increasing rapidly and current industry practice is to irrigate to between 10 and 20% run-off to prevent the accumulation of potentially damaging salts (*e.g.* Na^+, Cl^-) within the substrate. Since many growers add fertiliser at each irrigation event, this practice results in large losses of both water and fertilisers and, in fact, exacerbates the build-up of salts within the substrate. Some water bodies are failing to achieve the environmental objectives of the Water Framework Directive. Diffuse water pollution is now a bigger threat to water quality than point source pollution. The EA is concerned about the effects of substrate-grown soft fruit production on groundwater quality in the south east and have recently commissioned ADAS to help identify current issues and promote 'best practice'. Defra- and HDC-funded research at EMR has demonstrated the potential to deliver water and fertiliser savings of 45%, compared to current industry practice, without reducing Class 1 yields and aspects of fruit quality have been improved. EMR's work has been highlighted by ADAS as part of the promotion of best practice (Robert Irving, personal communication). Nevertheless, there is a risk that grower concerns over perceived problems associated with adequate uptake of essential nutrients and increased EC in both soils and substrates (due to the accumulation of 'ballast ions' *e.g.* Na^+, Cl^-, SO_4^{++}) will limit industry uptake of the new water-and fertiliser saving techniques. Research to identify the critical concentrations of 'ballast ions' that limit yield and quality will enable fertigation to be targeted more precisely and help growers gain confidence in reducing water and fertiliser inputs.

Benchmarking grower water use efficiency

It is important to be able to relate the volumes of water used to obtain 1 kg of marketable fruit (the WP value) in these scientific experiments to those achieved by growers under commercial conditions. This sort of information is vital to establish baseline water use in the UK soft fruit industry and to identify areas where a relatively minor change of practice could lead to rapid and significant improvements in water use efficiency. However, experience has shown that it is very difficult to glean this information from a sufficient number of growers. Data of this sort will be collected from our two growers partners in HDC project SF 136 for substrate-grown cv. 'Elsanta' and an irrigation questionnaire designed for substrate soft fruit growers will be prepared. Gathering and collating information more widely from the UK soft fruit industry on water and fertiliser use efficiencies could form the basis of a separate HDC Concept Note; this possibility will be discussed with the HDC Soft Fruit Research Manager and the HDC Soft Fruit Panel Chairman.

Cost benefit analysis

In these experiments water and nutrients were delivered to the substrate around each plant by using four dripper stakes per 0.5-m bag to ensure an even distribution, prevent dry spots from developing and minimise the likelihood of run-off. However, in commercial production with 1-m bags, costs associated with doubling the number of dripper spikes to eight per bag may be prohibitive. These extra costs must be set against the water and fertiliser savings (see below) to decide whether this approach would be financially viable. The approach being used in both commercial trials in HDC project SF 136 is to use five 1.2 L per hour drippers per 1-m substrate bag. Some growers are beginning to switch to this system instead of using a 6 L per hour dripper with four irrigation spikes per 1-m bag since water would still be supplied to the majority of the substrate should individual drippers become blocked; these could then be readily and inexpensively replaced. Clearly, the economics of this approach are justifiable for commercial production systems.

The reduction in fertiliser use of between 15% and 45% could be expected to deliver significant cost savings to growers. The Rural Business Research (RBR) 2008/2009 Farm Business Survey for Horticulture Production in England reported average annual fertiliser costs (across all specialist glass businesses including soft fruit) of £3,250-£4,500/ha. On this basis, a 15% reduction in fertiliser used could, on average, save £488-£675/ha while a 45% reduction in fertiliser used could save £1,464-£2,025/ha. The RBR 2008/2009 survey reported average annual water costs (across all specialist glass businesses including soft fruit) of £530-£630. This confirms that, generally speaking, the savings in expenditure on water do not justify expenditure on irrigation scheduling tools. Growers using mains water would be expected to pay significantly more for water and there may then be a significant financial benefit to using less water.

However, the reduction in energy use through pumping less water could be significant. If a grower could save at least £600/ha in fertiliser from the use of an irrigation scheduling tool, then a cost of at least £300/ha/annum for that scheduling tool would seem reasonable. A full cost benefit analysis will be carried out using data from the grower trials at New Farm Produce Ltd and S.H. Chesson Partnership in HDC project SF 136.

Further research

One aim of this project SF 107 was to try to improve berry firmness and shelf-life potential by manipulating ammonium-N (N-NH_4) and nitrate-N (N-NO_3) ratios. Although this strategy could help to improve fruit quality for those growers who prefer to continue with 'insurance irrigation', berry quality could best be improved by judicious irrigation scheduling. This work has developed a new irrigation strategy that has successfully eliminated run-off, delivered water and fertiliser savings of up to 45%, compared to Commercial Controls.

The irrigation/fertigation strategy now needs to be tested in commercial grower trials to help ensure relevance to the industry and to take account of differences in water quality and background EC. This work is being carried out in a newly commissioned HDC project, SF 136 at two grower sites, SH Chesson Partnership and New Farm Produce Ltd. The irrigation scheduling approach is readily transferable to raspberry and blueberry crops, where improvements in water and fertiliser use efficiencies are also needed. A Concept Note that addresses these issues will be prepared for consideration by the HFC Soft Fruit Panel in 2012.

Concerns over perceived problems associated with increased EC could limit substrate growers' uptake of the new water- and fertiliser-saving techniques being developed in Defra- and HDC-funded work at EMR. New strategic research is needed to identify substrate EC values above which fruit yields and quality are reduced and to identify opportunities to improve fruit quality. Manipulating NO_3-N:NH_4-N ratios has been reported to improve tolerance to salinity stress. An outline proposal for strategic R&D that addresses these issues has been discussed with Defra and the HDC with a view to submission of a full proposal to Defra in 2012.

Main Conclusions

- Irrigation scheduling and deficit irrigation regimes were imposed successfully on 60-day and main season cv. 'Elsanta' and cv. 'Sonata' plants
- A new irrigation scheduling strategy has been developed for substrate-grown strawberries that enables demand to be matched with supply. In this strategy, irrigation inputs and outputs are monitored continuously using rain gauges and data loggers with telemetry. This information is used to adjust the timing and frequency of irrigation so that run-off is eliminated and demand is matched with supply. Volumetric substrate moisture content and EC are also measured

continuously to ensure that irrigation is scheduled effectively and substrate EC levels are controlled adequately once run-off has been eliminated.

- Water savings of between 15% and 45% were delivered using the new irrigation scheduling strategy, without reducing Class 1 yields. Since nutrients were added at each irrigation event, fertiliser savings of up to 45% have also been delivered, without affecting foliar nutrient concentrations or fruit quality
- An RDI regime was developed that limited excessive canopy growth and improved berry shelf-life potential in 60-day crops. However, Class 1 yields were reduced by 17% in the main season crops, due to temporary losses of shoot turgor at high evaporative demands when substrate water availability was limited.
- RDI would be difficult to implement in some commercial production systems where the accuracy and consistency of water delivery may not be sufficient to maintain VSMCs between upper and lower set points. Under these circumstances, the limited substrate volumes (3-4 L per plant) would increase the risk of shoot water deficits and associated reductions in Class 1 yields and quality
- An automated system has been developed that triggers irrigation automatically once the VSMC has fallen to a pre-determined lower set point. By adjusting the frequency and duration of irrigation events, the volume of run-off can be fine-tuned at different stages of crop development. The system is currently being tested in commercial grower trials in HDC project SF 136
- Altering the contribution of NH_4-N from 10% to either 20% or 30% did not alter plant physiology or aspects of fruit quality in either cv. 'Elsanta' or cv. 'Sonata'. Further strategic work is needed to identify the NO_3-N:NH_4-N ratio that affects plant physiology and fruit quality attributes. The potential of altering N nutrition to improve tolerance to salinity stress in substrate soft fruit production should also be investigated
- Fertiliser savings of between £448 and £2,025 per ha per annum could be achieved by scheduling irrigation so that run-off was minimised or eliminated
- The potential of using the new irrigation scheduling strategy to reduce water and fertiliser inputs in commercial strawberry production is currently being tested in HDC project SF 136
- New fertigation regimes need to be developed for to optimise plant nutrition under water-saving irrigation strategies

Knowledge exchange and technology transfer events

2009-2010

- Presentation of the work to the HDC Board on 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 on 20 July 2009
- An overview of the work was presented during the farm tours at Fruit Focus on 22 July 2009
- Presentation of the work to Sainsbury's food technologists on 16 October 2009
- Presentation of the work to a delegation from ICAR on 4 December 2009
- Presentation of work to West Sussex Fruit Group on 9 December 2009
- Presentation of work to Prof. Ian Crute, AHDB Chief Scientist on 18 December 2009
- Presentation of work at EMRA Pear Day on 25 February 2010
- Regional news broadcasts: BBC South East and Meridian South East
- BBC National News and BBC Breakfast

2010-2011

- Presentation of work to School of Biological Sciences, University of Reading in May 2010
- Presentation of work to Sainsbury's / BBSRC in May 2010, EMR
- Presentation of work at Fruit Focus on 20 July 2010, EMR
- Presentation of work to Dr Jerry Knox et al., Cranfield University on 11 August 2010, EMR
- Presentation of work at Warwick-HRI Water Day II on 2 September 2010, Warwick-HRI
- Presentation of work to Dr Sue Popple, Defra in October 2010, EMR
- Presentation of work to Defra Food and Farming Group in October 2011, EMR
- Presentation of work to Board of Directors, EMR and Stockbridge Technology Centre on 11 February 2011
- Presentation of work to BBSRC on 15 February 2011, EMR
- Presentation of work at Sainsbury's / AG Thames Pear Day on 16 February 2011, EMR

2011-2012

- Presentation of work at Sainsbury's / AG Thames Pear Day on 16 February 2011, EMR
- An overview of the work was presented at the HDC SF Agronomy Day in Feb 2011, EMR
- Presentation of the work to The Abu Dhabi Food Control Authority, Abu Dhabi in April 2011, UAE
- Presentation of the work at a Waitrose Innovation Forum in June 2011, Aylesford, Kent
- Demonstration of work during 5 field tours at Fruit Focus 2011 in July 2011, EMR
- Presentation of the work to the EMR Science Committee in September 2011, EMR
- Poster presentation at the BerryGardens Annual Technical Conference, Ashford in Nov 2011
- Presentation of work to a Sainsbury's soft fruit grower group, Dartford in November 2011
- Presentation of work to BBSRC during visit to EMR in December 2011
- Presentation at the SSCR / Bulrush Grower Information Day in February 2012, Dundee

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