Project title:	Irrigation scheduling of raspberry as a tool for improving cane management
Project number:	SF 118
Project leader:	Dr Mark A. Else, East Malling Research
Report:	Annual Report, March 2012
Previous reports:	Annual Report 2011
Key staff:	Mr Mike Davies Mrs Helen Longbottom Mrs Fiona Wilson
Location of project:	East Malling Research, East Malling, Kent
Project co-ordinators:	John Clark, Laurie Adams and Stephen McGuffie
Date project commenced:	1 April 2010
Date completion due:	31 March 2013
Keywords:	Floricanes, fruit quality, growth control, irrigation, labour costs, primocanes, substrate management, water

DISCLAIMER

AHDB, operating through its HDC division seeks to ensure that the information contained within this document is accurate at the time of printing. No warranty is given in respect thereof and, to the maximum extent permitted by law the Agriculture and Horticulture Development Board accepts no liability for loss, damage or injury howsoever caused (including that caused by negligence) or suffered directly or indirectly in relation to information and opinions contained in or omitted from this document.

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.

Mr Michael J. Davies
Project Manager
East Malling Research

Signature .... Date ....

Dr Mark A. Else
Senior Research Leader
East Malling Research

Signature .... Date ....

Report authorised by:

Dr Christopher J. Atkinson
Programme Leader, Resource Efficiency for Crop Production
East Malling Research

April 2012

Signature .... Date ....

Contents

GROWER SUMMARY

Headline

- Progress is being made towards developing an irrigation scheduling system for soilless substrate grown raspberry.

Background and expected deliverables

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

Irrigation of substrate-grown raspberries 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 and to reduce the accumulation of salts. However, Defra, the Environment Agency (EA) and the soft fruit industry are all becoming increasingly concerned about the future availability of abstracted water for trickle irrigation. At the time of writing (March 2012), the south east is already officially under drought and other major soft fruit growing regions are at high risk of drought in 2012 (Figure GS 1).

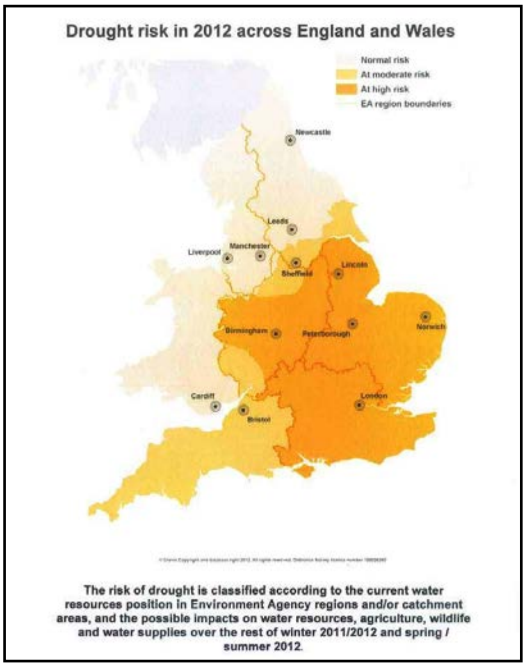

Figure GS 1 Assessment of drought risk across England and Wales for 2012. Source: the Environment Agency.

Current abstraction rates in the major soft fruit-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. Future legislation will require that drip/trickle irrigators demonstrate an efficient use of water, and current EA concerns about the impact of horticulture on groundwater quality in the south east will focus attention on improving NUE in soft fruit production. 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. In addition to saving water, altered root-sourced hydraulic and chemical signalling can prevent excessive shoot growth without reducing yields of marketable 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.

There are two aims to this project:

1. To use RDI as a tool to control cane vigour without reducing marketable yields
2. To improve water and nutrient use efficiencies in substrate-grown raspberry production

Expected deliverables from this work will include:

- Reduced production costs per tonne of marketable fruit
- Improved cane management
- Reduced water and fertiliser usage by up to 40%
- Reduced environmental impact
- Improved economic sustainability
- Demonstration of compliance with legislation

Summary of the project and main conclusions

Three experiments were conducted simultaneously during 2011. Two of these, one on the summer fruiting variety 'Tulameen' and the second on the primocane variety 'Autumn Treasure', were carried out to determine the effects of RDI on growth and cropping. Tulameen was grown in 7.5 litre pots and Autumn Treasure in 10 litre pots. Both contained washed coir as a substrate. Twenty-four experimental plants were included in each experiment and three irrigation treatments were applied: 1) well-watered (Ww) control where plants were given 110% of plant daily water use; 2) 80-70% RDI treatments (RDI-70%) where plants were initially given water at 80% of daily water use which was then reduced to 70%; 3) 70-60% RDI treatments (RDI-60%) where plants were initially given water at 70% of daily water use which was then reduced to 60%. The more severe RDI treatments were imposed on 24 June 2011 to try to limit cane height more effectively. Both experiments were set up as a complete randomised block design, with one of each treatment in each experimental block; there were eight blocks for each experiment, however only six blocks were used for routine measurements.

The third experiment was an additional one set up to test the effectiveness with which the crop coefficients developed in year 1 could be used to schedule irrigation. Although in the original proposal it was planned to test this approach in commercial trials at Belks Farm in 2011, it was thought prudent to first test the regime in a scientific experiment at EMR. Two different approaches to irrigation scheduling were tested on 'Tulameen', 'Autumn Treasure' and 'Polka'; the first was based on the actual amount of water used by the plant ('Actual' treatment) where the frequency and duration of irrigation events was scheduled to match the volume of water transpired during the previous 24 h. The second approach was to apply irrigation to replace the volume of water that was predicted to have been transpired each day using the derived crop coefficients for each variety ('Predicted' treatment). This experiment was set up as a split plot design, with five blocks, each block containing pairs of each variety, each pair consisted of plants receiving the 'Actual' or the 'Predicted' treatment. Like the first two experiments, washed coir was used as a substrate. Tulameen was planted in 7.5 litre pots, with Autumn Treasure and Polka in 10 litre pots.

Effects of RDI regimes on cane extension growth and yields

Regulated Deficit Irrigation regimes were developed and imposed on two-year-old cropping 'Tulameen' and Autumn Treasure' plants. Some shoot physiological responses to drying substrate were detected in both varieties which confirmed that the mild shoot water deficits developed under the RDI regimes due to limited substrate water availability. These shoot responses were not consistently altered over the whole season due to the need to periodically flush through to reduce substrate EC or pH. However, cane extension growth of 'Autumn Treasure' was effectively limited by both RDI-70% and RDI-60% regimes whilst that of 'Tulameen' was limited only by the RDI-60% regime.

Yields of marketable fruit were generally reduced under the RDI regimes; these differences were statistically significant for 'Autumn Treasure' (Figure GS 2) but not for 'Tulameen'. The yield penalties were due to a combination of fewer fruit and a lower average berry fresh weight. Components of berry quality were not affected by the RDI regimes, with the exception of inconsistent effects on berry redness.

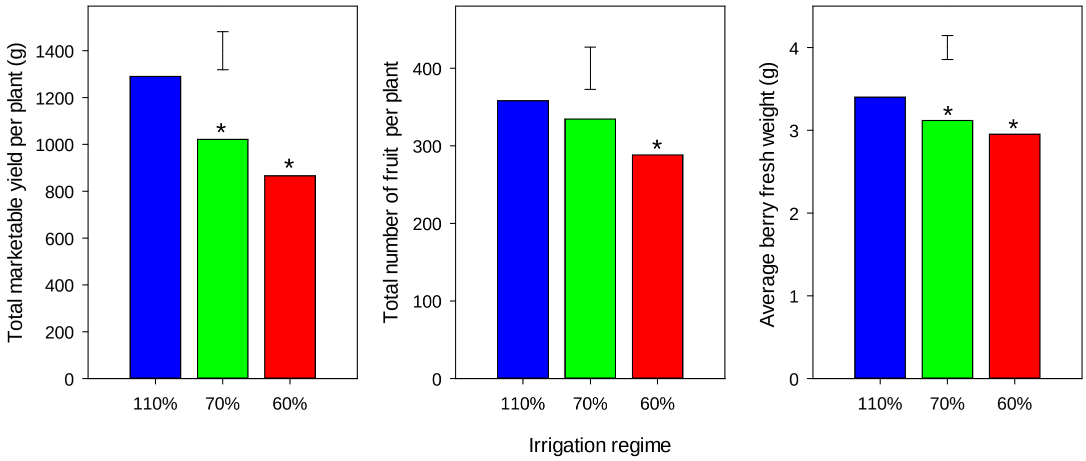

Figure GS 2. RDI-70% and RDI-60% regimes reduced marketable yields of 'Autumn Treasure due to reductions in fruit number and average fruit size. Results are means of six replicate plants per treatment.

Given the losses of marketable yields that occurred when RDI was imposed throughout the season, further developmental work will be carried out in scientific experiments at EMR (see plans for 2012). Although the RDI regimes imposed in our 2011 experiments were based on estimates of daily evapotranspiration, the VSMC at which shoot responses to soil drying were triggered in each of the three cvs was identified. These VSMC values will be used to derive lower irrigation set points for use in RDI experiments in 2012.

A comparison of irrigation scheduling methods

Table GS 1 Volumes of water applied to, and per cent run-through from, 'Autumn Treasure' and 'Tulameen' plants when irrigation was scheduled using 'Predicted' or 'Actual' crop co-efficients

Cultivar	Total volume of water applied (L)		Per cent run through (% of applied)	
	'Predicted'	'Actual'	'Predicted'	'Actual'
'Autumn Treasure'	218	98	27.6[1]	0.4
'Tulameen'	203	94	34.5	1.2

Crop coefficients derived from gravimetric estimates of plant water loss were used in conjunction with daily estimates of potential evapotranspiration (ET_P) to schedule irrigation very effectively in our experiments. However, this was achieved by ensuring that values of crop coefficients were calculated frequently. Accurate estimates of total transpirational leaf area can also be used to derive crop coefficients that can be used to schedule irrigation efficiently. Much less certain is the accuracy of this approach when proxy measures of plant water loss are used. Our data show that crop coefficients calculated using the best proxy measures of transpirational leaf area derived in year 1 for each variety (cane length for 'Tulameen', plant height for 'Autumn Treasure') were 2- to 3-fold greater than those derived using gravimetric estimates of plant water loss. Consequently, scheduling irrigation using proxy measures of plant transpirational leaf area (the 'Predicted' regime) resulted in significant over-irrigation, increased cane vigour in 'Tulameen' and 'Autumn Treasure' and significant wastage of water and fertilisers. The lack of a significant effect of the 'Predicted' regime on cane extension in 'Polka' was probably due to the poor vigour of this variety in our experiments; the 'Polka' plants were obtained in 2010 and didn't establish very well (see SF 118 Annual Report 2010). Coir Volumetric Moisture Content (VMC) was maintained at or near to full water-holding capacity under the 'Predicted' regime which led to average run-offs of between 27 and 59% of the volumes of water applied throughout the season. In contrast, scheduling irrigation using estimates of daily degree hours and crop coefficients derived from gravimetric measurements of plant water loss ('Actual' regime) effectively maintained VSMC within the optimum range and run-through averaged only 1% of the total volume of water applied.

Yields of marketable fruit were increased by 37%, 28% and 23% under the 'Predicted' regime in 'Tulameen', 'Polka' and 'Autumn Treasure', respectively. This was due to a greater number of larger fruit; the excessive fertigation using this strategy resulted in very vigourous plants. Despite the high marketable yields, the excessive application of water and fertilisers and the very vigourous cane growth suggest that this approach would be unsustainable and it is questionable whether this strategy merits further experimental or development work.

Conclusions

- Irrigation was scheduled effectively to well watered plants of each variety using gravimetric estimates of plant water use to calculate daily plant water demand.

- Two RDI regimes were imposed successfully and the VSMC set points that triggered shoot physiological responses were determined for 'Tulameen' and Autumn Treasure'.

- The RDI-60% regime effectively limited cane length in 'Tulameen' without significantly reducing marketable yields or fruit quality. The RDI-70% regime did not reduce cane height or yields.

- Although both RDI regimes inhibited cane growth of 'Autumn Treasure', significant reductions in marketable yield occurred under both regimes although fruit quality was generally unaffected.

- Scheduling irrigation using proxy measures of plant transpirational leaf area (the 'Predicted' regime) resulted in over-irrigation, increased cane vigour in 'Tulameen' and 'Autumn Treasure' and significant wastage of water and fertilisers.

- Yields of marketable fruit were increased by 37%, 28% and 23% under the 'Predicted' regime in 'Tulameen', 'Polka' and 'Autumn Treasure', respectively. This was due to both an increase in fruit number and in fruit size, presumably a consequence of excessive fertiliser applications under the 'Predicted' regime.

- Marketable yields of 'Polka' were low (379 – 526 g per plant) compared to the other two cvs (1108 – 1750 g per plant).

- The project will continue for a further season in 2012.

Financial benefits

The project aims to improve the economic sustainability of substrate raspberry production by improving both water and nutrient use efficiencies and reducing labour costs associated with cane management. 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. A partial cost-benefit analysis of implementing the new irrigation 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

- 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 raspberry growers would fill in and return a questionnaire on water use efficiency.

- 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 raspberry 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. There are further economic incentives to grow raspberry in containers (despite the initial cost): yields are more regular and higher, the crop can be more easily managed, and there are no soil-borne disease problems. 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 container and to reduce the build-up of potentially damaging salts. 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]. At the time of writing (March 2012), the EA are expecting a severe drought in the spring and summer of 2012.

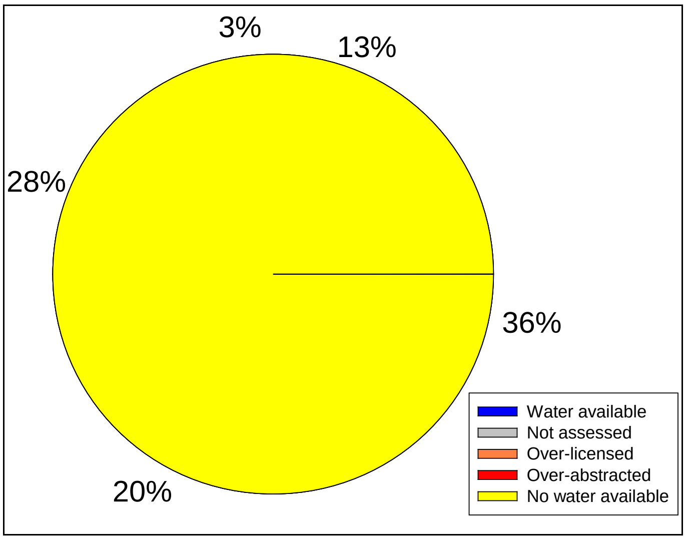

Figure 1. Assessment of water resource availability (for direct abstraction) for the soft fruit sector in 2008 (re-drawn from Knox *et al*., 2009).

Legislation designed to safeguard limited water resources and minimise 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.

Feeding continuously with every irrigation event is recommended[2] but this approach is also unsustainable. The major soft fruit growing regions are, or will soon be, designated as Nitrate Vulnerable Zones (NVZs) and, although diffuse pollution from soft fruit production is perceived as being low[5], the EA are becoming increasingly concerned about the environmental impact of soft fruit production. Some water bodies are failing to achieve the new environmental objectives of the Water Framework Directive. Diffuse water pollution is now a bigger threat to water quality than point source pollution. To help reduce the impacts of horticulture on water abstractions and diffuse pollution, new more sustainable ways of using water and fertilisers must be developed. 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 efficiencies could also be expected to improve the consistency of supply of high quality, healthy fruit with good shelf-life. 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 strawberry 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, although it is recognised that raspberry is less sensitive than strawberry to rising substrate EC.

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 on-going HDC-funded work on strawberry[8,9]. 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.

For some crops irrigation is scheduled based on estimates of evaporative demand. Crop coefficients are used with estimates of potential evapotranspiration (ET_P) to calculate 'actual evapotranspiration' *i.e.* the amount of water used by that specific crop. For pot- or substrate-grown crops, the most accurate way of determining crop coefficients is to measure weight (water) loss directly over a period of 24 h and divide this value by the number of degree hours recorded over the same period. The resulting crop coefficient (g of water lost per degree hour) can then be used in conjunction with daily estimates of ET_P to estimate plant water loss in any 24 h period. Provided the crop coefficient is recalculated regularly (*i.e.* weekly) to account for increases in canopy leaf area or increasing crop load, irrigation can be scheduled very effectively. However, the routine weighing of cropping plants is not feasible in commercial production systems and other, proxy measures of plant water use based on easily measurable plant variables must be developed.

Plant water use is proportional to total leaf area and when this latter parameter can be measured accurately, crop coefficients based on leaf area when combined with ET_P can be used to schedule irrigation effectively throughout plant and crop development[6,7,10]. But again, making repeat measurements of total leaf area of several plants within a commercial crop is not practical. However, if total leaf area could be estimated quickly and accurately, it may be possible to develop a generic system that would enable crop coefficients to be calculated for any floricane or primocane cultivar (cv).

Other plant variables, such as plant height or total cane length that are easily measured but correlate with whole plant water use, could also be used to establish crop coefficients for floricane and primocane raspberry cultivars (cvs). Work at EMR relating canopy density and plant height to water use has established coefficients for a range of ornamental crops[10], although the approach has not been extensively taken up by the industry to improve irrigation scheduling to hardy nursery stock (HNS) crops. Therefore, an initial aim put forward in the original project proposal was to identify suitable proxy measures of plant water use and test the potential of these crop coefficients to schedule irrigation to a commercial crop at Belks Farm, Kent.

Some raspberry cultivars (particularly ‘Tulameen’ and new primocane cvs) are very vigorous and excessive vegetative growth substantially increases labour costs associated with tying and cutting canes and fruit picking. Furthermore, dense canopies can lead to high relative humidity around the berries which can encourage rots and reduce fruit firmness. Regulated Deficit Irrigation (RDI), whereby plants are given less than 100% of the water they use so that a mild rootzone stress develops, has been used to control vegetative growth in several fruit crops without reducing yields, including raspberry[11,12] and strawberry[6,7] . Potential benefits in terms of cane management and control of excessive vigour need to be determined for raspberry. However, the appropriate percentage deficit must first be determined to avoid potentially deleterious effects, such as lower yields or increasing substrate EC above acceptable levels. It may also be necessary to apply RDI only at certain stages of crop development to avoid yield penalties.

Materials and Methods

Plant material and experimental location

One hundred bare-rooted short canes of cvs ‘Tulameen’ and ‘Autumn Treasure’ were obtained from R W Walpole Ltd in mid-March 2010 and the roots were placed immediately into moist compost and stored at 2°C until needed. Ten rooted cuttings of cv ‘Polka’ were supplied in 9 cm pots from Hargreaves Plants Ltd on 1 April 2010 and potted into 10 L pots containing coir on 21 April 2010.

Figure 2. Arrangement of plants within the polytunnel at EMR . Photo taken on 9 July 2010

The plants of each cultivar (cv.) were placed into pots with washed coir supplied by Mr Tim Chambers, Belks’ Farm, on 21 April 2010. Cv ‘Tulameen’ was planted into 7.5 L pots whilst the cvs ‘Autumn Treasure’ and ‘Polka’ were planted into 10 L pots. All canes of cv ‘Autumn Treasure’ were cut back to coir level. The plants were then positioned on battens laid on the floor in a polytunnel at EMR (Figure 2). The cvs ‘Tulameen’ and ‘Autumn Treasure’ plants that were used in the experiments in 2011 were previously placed in the outer two rows of the tunnel and served as guard plants during 2010. The crop management of the guard rows and experimental plant rows in 2010 for each of the cvs. was identical and was reported in the first annual report (March 2011).

During March 2011, these cvs ‘Autumn Treasure’ and ‘Tulameen’ plants were moved from the outer rows and positioned in the middle two rows of the polytunnel. The experimental plants used in 2010 were moved to the guard rows in 2011. Each row was 1.4 m apart and the distance from pot centre to pot centre within rows was 37 cm. The cv ‘Polka’ plants used in 2010 experiment were used again in 2011. Cv ‘Tulameen’ plants with four floricanes were selected for experiments and arranged in experimental blocks according to size. On 12 April 2011, the number of canes in each cv ‘Autumn Treasure’ and cv ‘Polka’ plant was reduced to four. The vegetative feed regime began on 16 April 2011 (see fertigation details below) and irrigation scheduling, initially, at 100% of the estimated potential daily evapotranspiration (ET_P) began on 18 April 2011. On 29 April 2011, irrigation was scheduled to each cv according to the requirements of the experimental treatments (see below).

Experimental design

Three experiments were conducted simultaneously during 2011. Two experiments, one on the floricane cv ‘Tulameen’ and the second on the primocane cv ‘Autumn Treasure’, were carried out to determine the effects of RDI on growth and cropping of these two cvs. Twenty-four experimental plants were included in each experiment and three irrigation treatments were applied: 1) well-watered (Ww) control where plants were given 110% of plant daily water use; 2) 80-70% RDI treatments (RDI-70%) where plants were initially given water at 80% of daily water use which was then reduced to 70%; 3) 70-60% RDI treatments (RDI-60%) where plants were initially given water at 70% of daily water use which was then reduced to 60%. The more severe RDI treatments were imposed on 24 June 2011 to try to limit cane height more effectively. Both experiments were set up as a complete randomised block design, with one of each treatment in each experimental block (Figure 3). There were eight blocks for each experiment, however only six blocks were used for routine measurements.

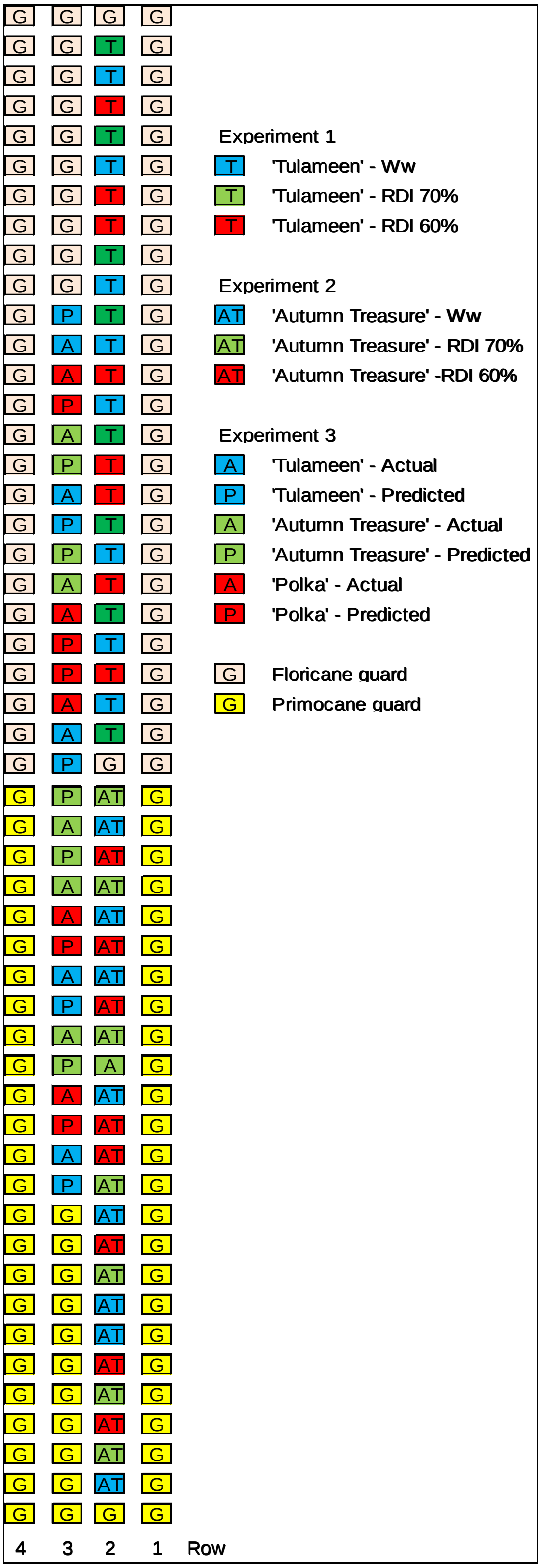

Figure 3. The experimental design used in 2011. All routine measurements were made on experimental plants in rows 2 and 3. Rows 1 and 4 were designated as guard rows.

The third experiment was an additional one set up to test the effectiveness with which the crop coefficients developed in year 1 could be used to schedule irrigation. Although in the original proposal it was planned to test this approach in commercial trials at Belks Farm in 2011, it was thought prudent to first test the regime in a scientific experiment at EMR. Two different approaches to irrigation scheduling were tested on cvs ‘Tulameen’, ‘Autumn Treasure’ and ‘Polka’; the first was based on the actual amount of water used by the plant (‘Actual’ treatment) where the frequency and duration of irrigation events was scheduled to match the volume of water transpired during the previous 24 h. The second approach was to apply irrigation to replace the volume of water that was predicted to have been transpired each day using the derived crop coefficients for each cv. (‘Predicted’ treatment). This experiment was set up as a split plot design, with five blocks, each block containing pairs of each cv., each pair consisted of plants receiving the ‘Actual’ or the ‘Predicted’ treatment (Figure 3).

Irrigation application and scheduling

The timing and duration of irrigation events was controlled using three Galcon DC-4S units (supplied by City Irrigation Ltd, Bromley, UK) connected to a manifold housing 11 DC-4S ¾” valves. Water was sourced from the mains to ensure a reliable supply throughout the experiment (but see below). Dripper outputs were tested prior to the experiment to ensure an accuracy of within 5% of the mean. Irrigation was pulsed throughout the day and was generally applied at 09:00, 12:00, 15:00 and 18:00.

Daily potential evapotranspiration values were obtained using an SKTS 500/PRT Evaposensor and SEM 550 Evapometer (Skye Instruments Limited, Llandrindod Wells, Powys, UK). The Evaposensor was positioned at canopy height amongst the experimental plants (Figure 4). The method used to determine *ET* °h^{-1} (g water loss per degree hour) values for Experiments 1 and 2, and the ‘Actual’ treatment in Experiment 3 is described below.

Figure 4. The Skye Evapo-sensor and Evapometer used to estimate daily potential evapo-transpiration. Photo taken on 15 July 2010

Determining ETp and irrigation application

To calculate the appropriate amount of water to apply to each cv, the relationship between gravimetric estimates of plant water use and the accumulated degree hours over 24 h were calculated each week (the *ET* $°h^{-1}$ value). In Experiments 1 and 2, Ww guard plants of cvs ‘Tulameen’ and ‘Autumn Treasure’ were used to avoid foliar damage to the experimental plants that inevitably occurs from the frequent lifting and moving of plants to record weight losses. Water loss per degree hour for each cv was determined and used in conjunction with the number of daily degree hours in the previous 24 h to determine the average daily volume of water used by plants of each cv. Thus, the sum total volume of the four daily irrigation events replaced the volume estimated to have been lost on the previous day. Correction factors of either 1.1. 0.8, 0.7 or 0.6 were used to schedule irrigation to the Ww, RDI 80%, RDI 70% and RDI 60% treatments, respectively. Thus, the sum total volume of the daily irrigation events replaced 110%, 80%, 70% or 60% of the volume estimated to have been lost over the previous 24 h. A correction factor of 1.1 was used to calculate daily irrigation requirements to plants under the ‘Actual’ regime in Experiment 3 to accommodate variations in plant size and therefore, daily water requirement. For plants under the ‘Predicted’ regime, the volumes of irrigation needed were estimated using the crop coefficient formulae derived in year 1:

For ‘Tulameen’:

$$log(\text{water use}) = -1.81 + 0.683*log(\text{total cane length [cm]} \qquad \text{[eq. 1]}$$

For ‘Autumn Treasure’ and ‘Polka’:

$$log(\text{water use}) = -\ 2.16 + 1.005*log(\text{plant height [cm]}) \qquad \text{[eq. 2]}$$

Plants under the ‘Predicted’ regime were supplied with 100% of calculated irrigation requirements (*i.e.* no correction factor was used). Total cane lengths and cane heights were measured weekly and average values for each cv were used in equations 1 and 2 to calculate the weekly *ET* $°h^{-1}$ value. The volume of water supplied to individual plants of each cv was then calculated by multiplying the estimated *ET* $°h^{-1}$ value by the measured daily degree hours recorded on the Skye Evapometer.

Fertigation

Two different nutrient regimes were applied to the cvs, depending on whether the plants were in the vegetative or fruiting stage of growth. These nutrient feeds were formulated by Mr Michael Daly (The Agrology House, Lincs., UK) after mineral analysis of the mains water used for the trial. Plants were fertigated from two stock tanks, one containing calcium nitrate (Hortipray, 19% Ca, 14.2% NO_3-N, 1.3% NH_4-N) and a second for the Solufeed (Solufeed 'F' 9:7:37 and, 4.6% MgO, and trace elements) and magnesium sulphate (Hortipray, 16% MgO). 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. The target pH range of the solution applied to the plants was 5.8 - 6.2. Dosatrons were used to adjust the feed EC levels. The nutritional composition of the two feeds when diluted 1:100 (including background water and nitric acid) is given in Table 1. During August 2011, it was noted that the plants were beginning to suffer from nutrient deficiency, and after further investigation, it seemed likely that this was due to an increase in the pH of the coir, which when tested had risen to 7.2 from the initial value of pH 6 when plants were potted up in March 2010. The pH of the coir was reduced to 6.2 by flushing through with acidified water (pH 5.4) during the week commencing 9 September 2011. To limit any further increases in coir pH, the volume of nitric acid in the feed solutions was increased from 15 September 2011 to lower the pH of the solution at the dripper to 5.4-5.8.

Table 1. Nutrient content of vegetative and fruiting feeds used for the 2011 experiments after a 1:100 dilution (including irrigation water ion content and nitric acid).

	Concentration in diluted feed (mg L^{-1})	
Nutrient	Vegetative	Fruiting
NO_3-N	141	143
NH_4-N	5	4
P	21	25
K	207	253
Ca	147	132
Mg	29	33
B	0.24	0.27
Cu	0.14	0.13
Fe	0.57	0.70
Mn	0.34	0.42
Mo	0.01	0.01
Zn	0.08	0.10

To keep the concentration of nitrogen applied to the plants constant, the amount of calcium nitrate in the stock solution was reduced. Consequently the concentration of Ca applied to the plants was reduced to 144 and 129 mg L^{-1} for the vegetative and fruiting feeds respectively, and the concentrations of all other nutrients were the same (Table 1). The vegetative fertiliser mix was applied to all plants on 16 April and switched to a fruiting mix between 25 May and 22 July 2011 for 'Tulameen', after which the vegetative feed mix was applied until 20 October. Fruiting mix was applied to the primocane cvs from 12 July to 10 October 2011.

The EC and pH of the diluted feed solution were measured weekly at the drippers along with the volume of water emitted; the volume and EC of any run-off from the pots was also measured twice weekly.

Coir volumetric moisture content, pH and EC

Volumetric substrate moisture content and substrate EC were measured twice weekly, using a Delta-T 'WET' sensor calibrated for coir. To determine the average coir moisture content within each pot, four sets of holes were drilled into the side of the pots to allow the horizontal insertion of the 'WET' sensor probe. Coir moisture content was measured one third and two thirds down from the top of the pot on the north and south side of each pot. This approach generated a detailed profile of changes in coir moisture content around the developing root system within each pot.

For both the 'cvs Tulameen' and 'Autumn Treasure' RDI experiments, VSMC was also monitored continuously on nine plants within each experiment (three for each treatment) with Decagon 10HS sensors connected to Decagon EM50 data loggers. The sensors were inserted horizontally through slits in the plastic wall of the pots into the middle of the root system at a depth of 8 cm. The sensors were calibrated for coir substrate and the resulting regression equation was used to convert raw probe counts into VSMC (Figure 5)

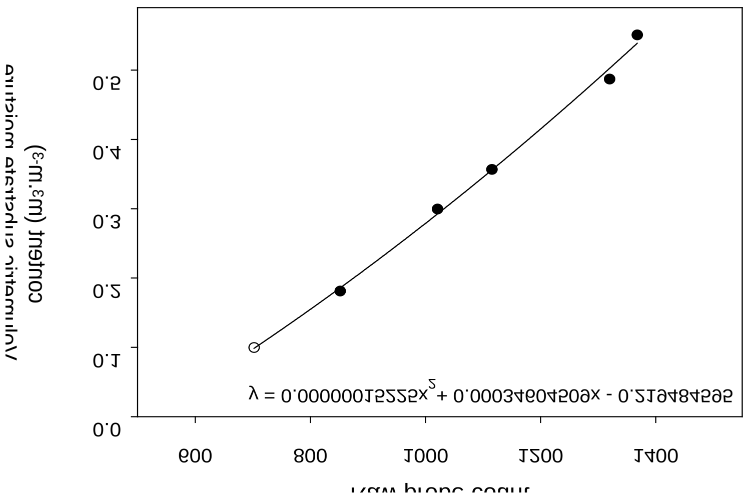

Figure 5. Calibration equation derived to enable the conversion of raw 10HS sensor counts into volumetric substrate moisture contents for coir.

Coir EC was measured twice weekly with a Delta-T WET sensor (see below); when values reached 350 mS m^{-1}, all pots were flushed through with either calcium nitrate solution (as on 20 July) to flush out ‘ballast’ ions and lower substrate EC, or with acidified water (as on 8 August and 9 September 2012).

Measurement of physiological parameters

Routine measurements in the RDI experiments (Experiments 1 and 2) were carried out on six replicate plants per cv in each irrigation treatment and on five replicate plants of each cv in each irrigation treatment in Experiment 3. Measurements were first made on 24 April 2011 and continued weekly thereafter for Experiments 1 and 2, and fortnightly for Experiment 3; final measurements in each experiment were made on 29 September 2011. Stomatal conductance (g_s) of one young, fully-expanded leaf per experimental plant was measured with a steady-state porometer (Leaf porometer SC-1, Decagon Devices) and leaf chlorophyll content was measured with a SPAD meter. Midday water potential (ψ_L) of one young, fully-expanded leaf on each experimental plant was determined using a Skye SKPM 1400 pressure bomb (Skye Instruments Ltd, UK); leaves were sealed inside the pressure chamber within 30 s of excision. 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 eleven occasions for the RDI experiments and on six occasions for the ‘Actual’ and ’Predicted’ scheduling experiment.

Table 2. Raspberry quality attributes, graded on a scale of 1-5

Grade	Redness	Brightness	Outline	Uniformity of size	Texture	Cohesion	Skin strength	Flavour
5	pale	very bright	very even	very uniform	very firm	all fruit whole	robust	very good, aromatic
4	fairly pale	bright	even	uniform	firm	most fruit whole	fairly robust	good
3	medium	medium	medium	medium	medium	slightly crumbly	moderate	slightly acid, moderate, bland
2	dark	dull	uneven	variable	soft	crumbly	fairly fragile	poor, acid, weak
1	very dark	very dull	very uneven	very variable	very soft	very crumbly	fragile	very poor, very acid, foreign

For all experiments, leaf extension was determined by measuring the length of the leaf blade of young, expanding leaves twice-weekly until maturity; newly expanding leaves were then labelled and measured. In total, leaf extension of four expanding leaves per experimental plant was measured throughout the season for the primocane cultivars and seven leaves were measured for cv 'Tulameen'. Cane height was measured weekly on each of the four primocanes of experimental cvs 'Polka' and 'Autumn Treasure' plants, while for experimental cv 'Tulameen' plants, heights of the four fruiting canes and the four strongest new vegetative canes were measured. On seven occasions, excess canes were removed from each pot and their number and weight were recorded.

Fruit yields and quality

Ripe berries were harvested from fruiting plants twice a week. Fruit number and berry fresh weight for marketable fruit from each plant was recorded, along with the weight of waste fruit. The quality of the fruit was assessed weekly using eight criteria: fruit redness, brightness, uniformity of size, outline, texture, cohesion, skin strength and flavour (Table 2). Berries from plants within the same cv and treatment were bulked to ensure a sufficient number of berries in each sample. Juice was also extracted from three ripe fruit from each sample and soluble solids content (SSC [%BRIX]) was measured with a digital refractometer (Palett 100, Atago & Co. Ltd, Tokyo, Japan). Shelf life assessments were also carried out weekly over the peak picking times; again berries from plants within the same cv and treatment were bulked to ensure there was a sufficient number of berries within a sample. Raspberries were placed three fruit deep into a punnet, the punnet weighed and the fruit assessed for brightness and redness. The punnet was cooled at 4 °C for 4 h before being placed in a shelf-life room at 18 °C. After 48 and 72 hours, all punnets were re-weighed to determine the extent of berry water loss and the fruit were assessed for redness, brightness, uniformity of colour, texture, drupelet collapse and the percentage of fruit in each punnet that had developed rots (Table 3).

Statistical analyses

Statistical analyses were carried out using GenStat 10th Edition (VSN International Ltd). To determine whether differences between cvs were statistically significant, analysis of variance (ANOVA) tests were carried out and least significant difference (LSD) values for p<0.05 were calculated.

Results

Evapotranspiration per degree hour

Evapotranspiration per degree hour (*ET* °h^{-1}) was calculated weekly for each cv. in each experiment by measuring gravimetric water loss and then dividing that value by the number of degree hours recorded over the same time period; *ET* °h^{-1} values calculated for each cv. under the 'Actual' regime in Experiment 3 are presented in (Figure 6A).

Table 3. Raspberry quality attributes, graded on a scale of 1-5, for assessment of shelf-life

Grade	**Redness**	**Brightness**	**Uniformity of colour**	**Texture**	**Rots**
5	pale	very bright	very uniform	as picked	0%
4	fairly pale	bright	uniform	almost as good	2-10%
3	medium	medium	medium	slightly collapsed	11-30%
2	dark	dull	variable	moderately collapsed	31-50%
1	very dark	very dull	very variable	very collapsed	51-100%

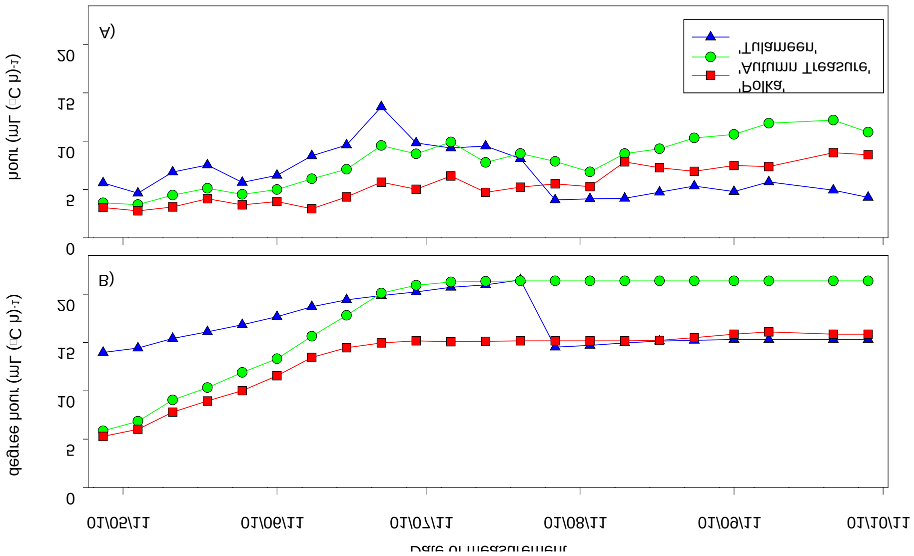

Figure 6. Changes in crop evapotranspiration (ET_P) for the three cvs over the course of a season when scheduling according to A) gravimetric measures of actual water loss and B) ETp based on crop coefficients using cane length as a prediction of crop water needs, for plants in experiment 3. Results are means of six replicate plants per cv for A) and five for B)

Values of *ET* °h^{-1} for each cv. under the 'Predicted' regime were calculated using regression equations 1 and 2 following weekly measures of either total cane length ('Tulameen') or plant height ('Polka' and 'Autumn Treasure') (Figure 6B). The *ET* °h^{-1} values were multiplied by the number of degree hours recorded for each day to calculate the volume of water needed for each cv under the different irrigation regimes.

Values of *ET* °h^{-1} generally increased for each cv during May and June as the plants grew and leaf area increased (Figure 6A). During July values of *ET* °h^{-1} for cv 'Autumn Treasure' remained relatively stable since cane extension rate had slowed (see below) but values increased again from August onwards, presumably due to the increased water demand associated with cropping and/or the growth of lateral side shoots. Similar variations in values of *ET* °h^{-1} were evident in cv 'Polka'. cv 'Tulameen' the fall in *ET* °h^{-1} towards the end of July coincided with the removal of the spent fruiting canes, after which values remained stable over the remainder of the season as the extension growth of the current season's canes slowed (see Figure 12).

The values of *ET* °h^{-1} calculated for plants under the 'Predicted' regime were between 2- and 3-fold greater than those under the 'Actual' regime (compare Figure 6A and B) which resulted in over-irrigation so that the volumes of water applied to these plants were far in excess of their requirements (Table 4).

Table 4. The amount of water applied to each plant (27 April-29 September) under the various scheduling regimes

	Total volume of water applied (L)				
	Ww	RDI-70%	RDI-60%	'Predicted'	'Actual'
'Tulameen'	94	63	54	203	94
'Autumn Treasure'	106	70	61	218	98
'Polka'	N/A	N/A	N/A	165	85

Volumes of irrigation water applied between May and September to plants under the 'Predicted' regime were double those given to plants under the 'Actual' regime, and this was the case for all three cvs. Since fertiliser was applied at each irrigation event (fertigation), plants under the 'Predicted' regime also received twice as much fertiliser as those under the 'Actual' regime.

Volumetric substrate moisture contents under the different irrigation regimes

Scheduling irrigation using estimates of daily degree hours and crop *ET* °h^{-1} derived from gravimetric measurements of plant water loss generally maintained VSMC between 0.4 and 0.55 m^3 m^{-3} for Ww cvs 'Autumn Treasure' and 'Tulameen' plants in Experiments 1 and 2 (Figure 7). Within two weeks of the RDI treatments being applied to cv 'Tulameen', VSMC fell to 0.3 and 0.27 m^3 m^{-3} in the RDI-70% and RDI-60% regimes, respectively (Figure 7A), and VSMC remained significantly lower than in Ww plants throughout most of the season, although differences in VSMC between the RDI-70% and RDI-60% treatments were not statistically significant. Similar changes in VSMC in the different irrigation regimes were noted for cv 'Autumn Treasure' (Figure 7B).

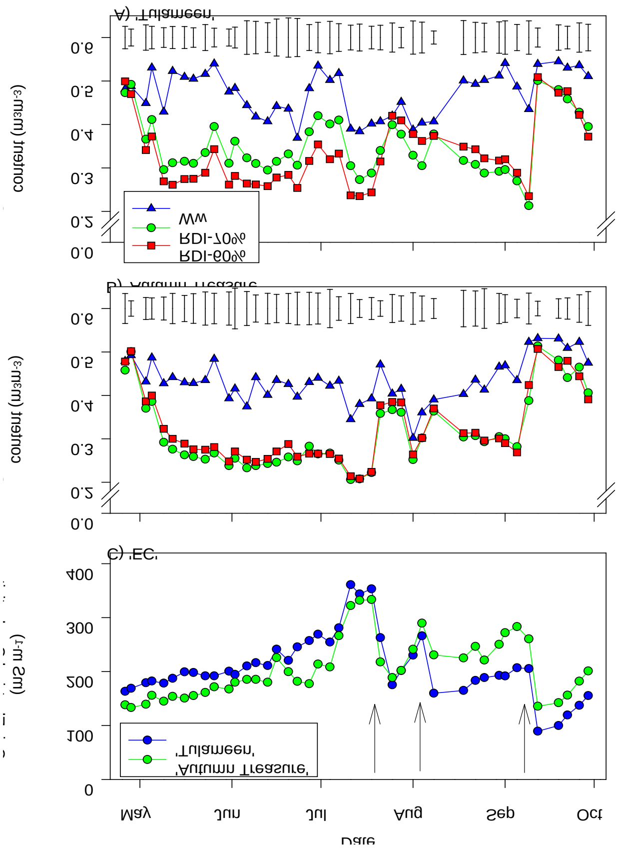

Figure 7. Changes in average pot VSMC for A) 'cv Tulameen' and B) cv 'Autumn Treasure' for Ww, RDI-70% and RDI-60%. Results are means of six replicate plants per treatment; vertical bars are LSD values at *p*<0.05. Changes in EC for Ww 'cv Tulameen' and cv 'Autumn Treasure' are shown in C, results are means of six replicate plants for each cv. Arrows indicate flushing of coir to lower EC or pH

In cv 'Tulameen' plants, VSMC rose in each irrigation treatment at the end of June, a consequence of the temporary and erroneous increase in calculated *ET* °h^{-1} for one week (see Figure 6) which resulted in more water than was necessary being applied. In both cvs under Ww conditions, substrate EC increased gradually during May and June (Figure 7C), before increasing rapidly to over 300 mS m^{-1} during early August.

Diurnal fluctuations in VSMC in Experiment 2 were monitored continuously using 10HS Decagon sensors inserted horizontally in the middle of the rooting zone. Changes in VSMC following irrigation events and subsequent substrate drying were detected in all three irrigation regimes; representative data are presented in Figure 8A & B. The difference between the peak and trough, the wettest and driest part of the daily cycle, for the majority of the days was less than 0.05 m^3 m^{-3} (Figure 8A). Coir volumetric moisture content for Ww plants was maintained above 0.4 m^3 m^{-3}, VSMC under the RDI-60% regime fluctuated between 0.2 and 0.3 m^3 m^{-3}, whilst VSMC of RDI-70% treated plants remained between 0.3 and 0.4 m^3 m^{-3}. These trends in VSMC were similar to those obtained from the bi-weekly measurements made using the 'WET' sensor. Following flushing of the substrate to reduce EC and pH in July, the gradual daily decline of VSMC in the RDI-70% and RDI-60% treatments as the coir dried can be seen clearly (Figure 8B).

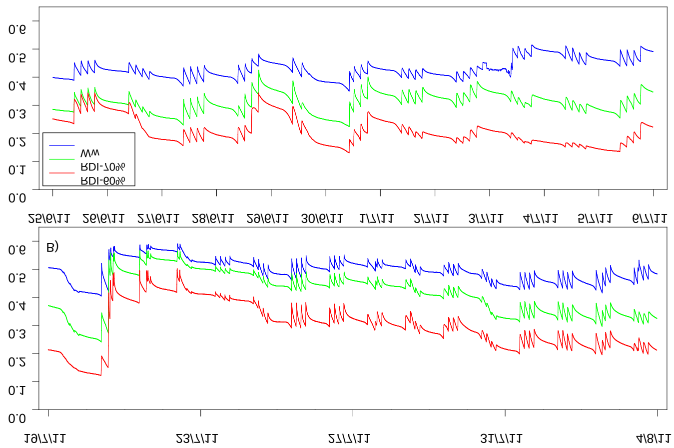

Figure 8. *VSMC* of cv 'Autumn Treasure' plants when continuously monitored using 10HS Decagon sensors A) 25 June – 6 July and B) 19 July – 4 August. Measurements were recorded every five minutes

Volumetric substrate moisture contents under the 'Predicted' regime in Experiment 3 were consistently higher than those in the 'Actual' regime in all three cvs (Figure 9), although differences were not statistically significant. Nevertheless, the VSMC data suggest that the 'Predicted' regime resulted in coir being maintained very near to substrate moisture holding capacity while the VSMC under the 'Actual' regime was optimal in terms of WUE. The temporary drop in VSMC of the cv 'Autumn Treasure' plants under the 'Actual' regime at the beginning of August was due to the incorrect *ET* °h^{-1} value being used to schedule the irrigation for that week.

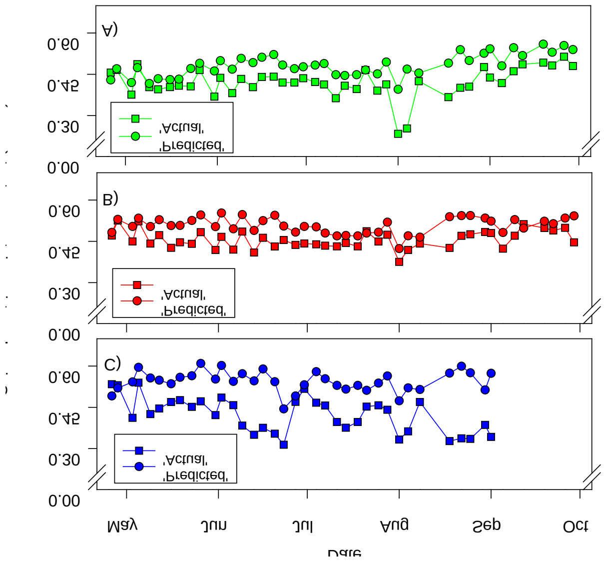

Figure 9. Changes in coir volumetric moisture content for experiment 3, for A) cv 'Autumn Treasure', for B) cv 'Polka', and for C) cv 'Tulameen' and for those scheduled using gravimetrically calculated ET_P 'Actual' and those scheduled using ET_P calculated using the crop coefficients 'Predicted'. Results are means of five replicate plants per treatment

Coir electrical conductivity and pH

The sudden rise in substrate EC seen in Ww plants also presumably occurred to a greater extent in RDI-treated plants but it was not possible to measure EC accurately in the drier coir under the RDI regimes. Although raspberry is known to be more tolerant of higher substrate EC than strawberry, the potentially greater build-up of EC under the RDI regimes could have complicated the interpretation of yield and fruit quality data and so the decision was taken to flush all pots with dilute calcium nitrate solution to restore substrate EC levels to below 200 mS m^{-1}; this action resulted in the temporary increase in VSMC measured in the RDI-70% and RDI-60% plants. In early August 2011, signs of foliar iron deficiency were apparent and it was confirmed that compost pH levels had risen to 7.2. To restore a favourable coir pH, all pots were flushed with acidified water which again raised the VSMC in RDI-treated plants (Figure 7) although substrate moisture deficits were rapidly re-established by the middle of August 2011. A second flushing event was carried out in mid-September 2011 to reduce substrate pH.

Run-through

The volume of water running through the pots of Ww cv 'Autumn Treasure' was less than 2% of the volume applied, indicating that the irrigation scheduling approach effectively matched demand with supply (Table 5) and minimised wastage. As expected, there was no run-through from plants under the RDI-70% and RDI-60% regimes (Table 5). For Ww cv 'Tulameen', the per cent run through averaged 16% in Experiment 1 but only 1% in Experiment 3. Over-irrigation of Ww cv 'Tulameen' in Experiment 1 was probably due to the guard plants that were used to calculate *ET* °h^{-1} having a larger leaf area and, therefore, using more water than the experimental plants. Limited and transient run-through was recorded in RDI-treated cv 'Tulameen' plants at the end of July which occurred for several days after the flushing through of the coir. Run-through in plants under the 'Predicted' regime ranged from 25% to 60% of the volume applied (Table 5), again suggesting that these plants were over-irrigated.

Table 5. The volume of water that ran-through as a % of the volume applied for the various scheduling regimes. Each value (except [1] – see foot note) is based on the average of 35 measurements taken between 3 May and 9 September with 5-6 reps per treatment per cultivar. Actual plants given 110% ETp.

	% Run through				
	RDI Experiments			'Actual' vs 'Predicted' methods of scheduling	
Cultivar	Ww	RDI-70%	RDI-60%	'Actual'	'Predicted'
'Tulameen'	15.8	0.3	0.8	1.2	34.5
'Autumn Treasure'	1.7	0	0	0.4	27.6[1]
'Polka'	N/A	N/A	N/A	7.6	59.4

[1] Cv 'Autumn Treasure' predicted the value is the average of only 6 measurements taken between 22 August and 9 September.

Plant physiological responses

Rates of photosynthesis of cvs 'Autumn Treasure' and 'Tulameen' plants averaged across the eleven measurements taken during the season did not significantly differ between plants under the Ww, RDI-70% and RDI-60% regimes (Figure 10A and B). Although g_s was occasionally reduced in RDI-treated cv 'Autumn Treasure' plants, g_s was similar under the three irrigation regimes when averaged across all nineteen measurement dates (Figure 10C). No significant treatment differences in g_s of cv 'Tulameen' plants were detected in Experiment 1 (Figure 10D). There were also no treatment effects on *A* or g_s between plants under the 'Actual' and 'Predicted' regimes in the three cvs (data not presented).

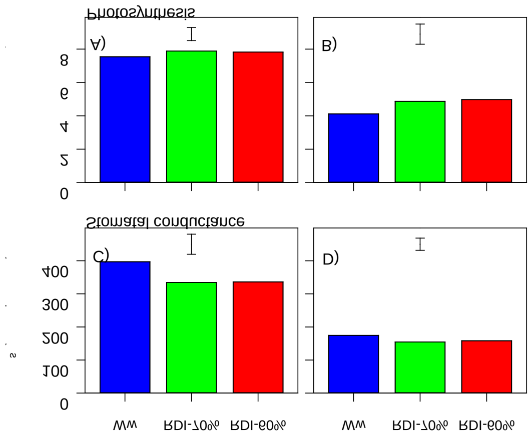

Figure 10. Average values of photosynthesis for A) cv 'Autumn Treasure' and B) cv 'Tulameen' and stomatal conductance for C) cv 'Autumn Treasure' and D) cv 'Tulameen' receiving irrigation at Ww, RDI-70% and RDI-60% of calculated ET_P. Results presented are averages across the season for six plants for each treatment within each cv, for photosynthesis the measurements were carried out on 11 occasions and for stomatal conductance on 19 occasions. Vertical bars are LSD values at $p<0.05$

Midday leaf water potential for cv 'Tulameen' plants under the RDI regimes was more negative than Ww values on seven measurement dates (Figure 11), indicating that mild shoot water deficits developed in RDI-treated plants. Although ψ_L of RDI-treated cv 'Autumn Treasure' plants was significantly lowered on four occasions, average ψ_L over the season was not significantly influenced by the irrigation regimes.

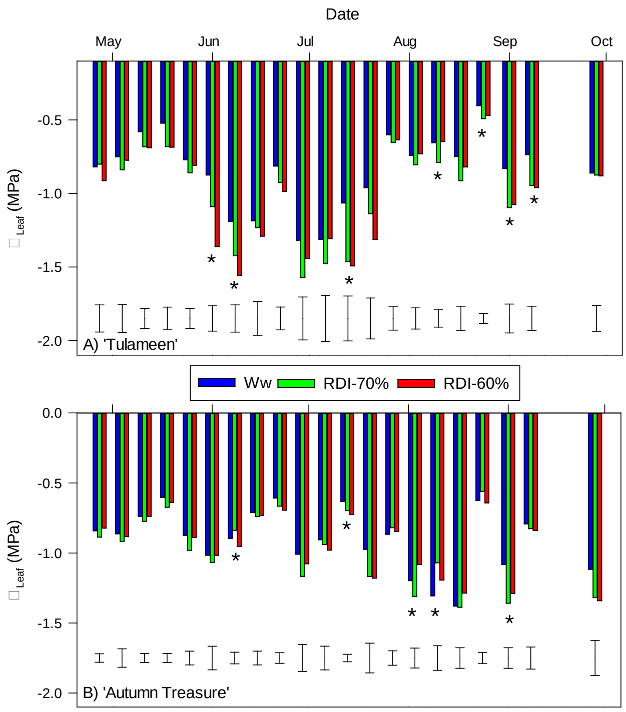

Figure 11. Midday leaf water potential for plants of 'Tulameen' (top graph) and 'Autumn Treasure' (bottom graph) for Ww, RDI-70% and RDI-60%. Results presented are averages for six plants for each treatment. Astericks (*) show days where significant differences between the treatments occurred. Vertical bars are LSD values at $p<0.05$.

Leaf water potential was significantly lowered in cv ‘Tulameen’ plants under the ‘Actual’ regime, compared to that under the ‘Predicted’ regime (Table 6).

Table 6. Midday leaf water potential for plants of cvs ‘Autumn Treasure’, ‘Polka’ and ‘Tulameen’ for ‘Actual’ and ‘Predicted’ treatments. Results presented are averages across the season for 5 plants per cultivar per treatment. Measurements were taken on 11 occasions (Significance levels, SED (df =12) and LSD at 5% are shown)

	Leaf water potential (MPa)		
Cultivar	‘Actual’	‘Predicted’	
‘Tulameen’	-1.09	-0.91	
‘Polka’	-0.90	-0.89	
‘Autumn Treasure’	-0.99	-0.98	
	F.prob	SED	LSD
Cultivar	0.002	0.021	0.048
Treatment	0.024	0.025	0.055
Cult.Treat	0.033	0.043	0.095

Cane extension in cv ‘Autumn Treasure’ was limited under both RDI regimes, compared to Ww plants, and this difference was statistically significant from the 1 June 2011 until fruiting began in mid-July (Figure 12). Leaf elongation was also slowed by both RDI treatments during the period 17 May to 24 June (data not shown). In cv ‘Tulameen’, the growth of the four measured canes in plants under the RDI-60% regime was reduced compared to Ww plants and this difference was statistically significant from the 6 July to 3 August 2011, after which it was just below significance until the end of September. The RDI-70% regime did not limit cane length. Measurements of LER showed that there was a reduction in leaf growth in both RDI treatments, compared to Ww plants, between 15 July and 4 August (data not shown), indicating that some aspects of shoot physiology were affected by RDI.

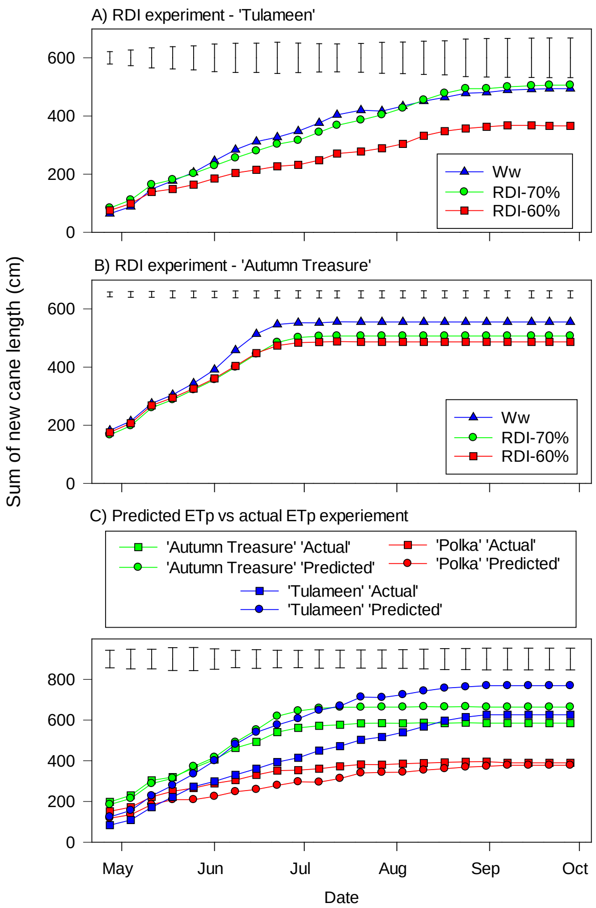

Figure 12. Sum of new cane length for plants of A) cv 'Tulameen' and B) cv 'Autumn Treasure' for Ww, RDI-70% and RDI-60%. Results presented are averages for six plants for each treatment. Also for 'Predicted' ET_P vs 'Actual' ET_P, for cvs 'Autumn Treasure', 'Polka' and 'Tulameen' for those scheduled using 'Actual' water requirements and those scheduled according to 'Predicted' water requirements. Results are means of five replicate plants per treatment. Vertical bars are LSD values at $p<0.05$

Cane growth of cv 'Tulameen' was significantly increased under the 'Predicted' regime from 8 June 2011 onwards and so the total length of cane in these plants increased by 20%, compared to that of plants in the 'Actual' regime. Cane lengths of cv 'Tulameen' were similar in Experiments 2 and 3 when irrigation was scheduled to match demand with supply and this confirms that the 'Predicted' regime resulted in excessively vigorous plants. Leaf elongation was also greater under the 'Predicted' regime between 2 and 23 July 2011 (data not shown). There were no significant differences in total cane length between the scheduling methods for the other two cvs in Experiment 3. There was, however, an increase in the LER of the cv 'Autumn Treasure' plants in the 'Predicted' scheduling regime from 17 May to 23 June 2011 (data not shown).

Fruit yield, quality and shelf life

Ripe fruit were first picked from cv 'Tulameen' plants in Experiment 1 on 9 June 2011, cropping peaked between 20 June and 4 July 2011 and continued until the end of July 2011 (Figure 13). The fruiting canes were then removed. Yields of marketable fruit were higher from Ww plants but the differences were not statistically significant (Table 7). Total fruit number, total waste and mean berry weight were similar, irrespective of irrigation treatment. Berry SSC, brightness, cohesion, flavour, outline, skin strength, texture and uniformity were unaffected by irrigation regime (Table 8), although there was a statistically significant difference in the redness of fruit harvested from plants under the RDI-70% and RDI-60% regimes. There were no treatment differences in rates of berry water loss during the shelf-life tests and aspects of fruit quality were similarly unaffected at the end of the shelf-life period (data not shown).

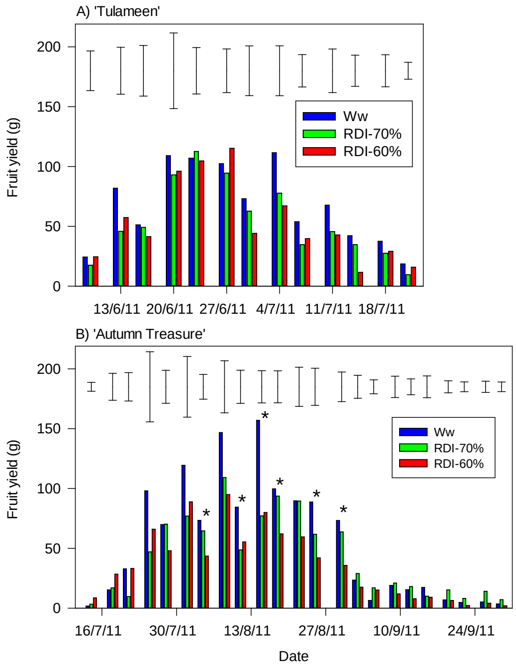

Figure 13. Fruit yield for plants of A) cv 'Tulameen' and B) cv 'Autumn Treasure' for Ww, RDI-70% and RDI-60% plants on days harvesting was carried out. Results presented are averages for 6 plants for each treatment. Asterisks (*) show days where significant differences between the treatments occur. Vertical bars are LSD values at p<0.05

Table 7. Total yield, fruit number, fruit waste and mean berry weight per plant for cvs ‘Tulameen’ and ‘Autumn Treasure’ for Ww, RDI-70% and RDI-60%. Results presented are averages of 6 plants for each treatment. (Significance levels, SED (df 10) and LSD at 5% are shown)

‘Tulameen’

	Total yield (g)	Total fruit number	Total fruit waste (g)	Mean Fruit weight (g)
Ww	880	225	42	3.9
RDI-70%	705	204	44	3.4
RDI-60%	689	205	26	3.5
F.prob	n.s.	n.s.	n.s.	n.s.
SED	88.0	21.8	8.6	0.25
LSD	196.1	48.6	19.2	0.55

‘Autumn Treasure’

	Total yield (g)	Total fruit number	Total fruit waste (g)	Mean Fruit weight (g)
Ww	1290	358	44	3.4
RDI-70%	1021	335	34	3.1
RDI-60%	866	288	29	3.0
F.prob	<0.001	0.047	0.025	0.02
SED	71.8	24.1	4.6	0.13
LSD	162.4	54.6	10.4	0.29

Table 8. Measures of fruit quality and Brix at harvest for cvs ‘Tulameen’ and ‘Autumn Treasure’ for Ww, RDI-70% and RDI-60%. Results presented are averages across all fruit picks and average for the 6 plants of each treatment. (Significance levels, SED (df = 10) and LSD at 5% are shown).

‘Tulameen’

	Brix	Brightness	Cohesion	Flavour	Outline	Redness	Skin strength	Texture	Uniformity
Ww	11.7	3.5	4.5	3.2	2.9	2.8	4.4	3.3	3.2
RDI-70%	11.6	3.5	4.4	3.1	3.1	3.0	4.3	3.5	2.6
RDI-60%	11.7	3.3	4.5	3.2	3.2	2.7	4.1	3.5	2.7
F.prob	n.s.	n.s.	n.s.	n.s.	n.s.	0.041	n.s.	n.s.	n.s.
SED	0.44	0.17	0.19	0.18	0.31	0.14	0.24	0.22	0.34
LSD	0.99	0.37	0.42	0.39	0.69	0.31	0.54	0.50	0.76

‘Autumn Treasure’

	Brix	Brightness	Cohesion	Flavour	Outline	Redness	Skin strength	Texture	Uniformity
Ww	9.1	3.9	4.3	2.6	2.6	3.1	3.7	3.7	3.2
RDI-70%	9.3	3.8	4.5	2.7	2.9	2.8	3.3	3.2	3.4
RDI-60%	9.3	3.6	4.3	2.6	2.9	2.7	3.3	3.5	3.3
F.prob	n.s.	n.s.	n.s.	n.s.	n.s.	0.042	n.s.	n.s.	n.s.
SED	0.50	0.09	0.20	0.14	0.31	0.11	0.40	0.17	0.39
LSD	1.39	0.24	0.54	0.40	0.87	0.30	1.00	0.48	1.09

In Experiment 2, fruit were first harvested from cv ‘Autumn Treasure’ on 14 July 2011, cropping peaked between 25 July and 30 August 2011 with approximately 80% of the total yield being picked during this time; fruit production declined during September and October. Statistically significant reductions in marketable yields occurred on two and six occasions under the RDI-70% and RDI-60% regimes, respectively, during peak cropping (Figure 13). Consequently, total marketable yields per plant were also significantly lowered by the two RDI regimes (Table 7). Under the RDI-70% regime, lower yields resulted from a reduction in berry size while both berry number and size were reduced by the RDI-60% treatment.

Berry SSC, brightness, cohesion, flavour, outline, skin strength, texture and uniformity were unaffected by irrigation regime (Table 8), although there was a statistically significant difference in the redness of fruit harvested from plants under the RDI-70% and RDI-60% regimes. In shelf-life tests, although the number of fruit with rots was generally low (between 2 and 10% of fruit developed rots), there was a significant increase in the number of berries with rots from the RDI-70% and RDI-60% regimes (data not shown). Other aspects of fruit quality were similar, irrespective of irrigation regime (data not shown).

Table 9. Total marketable yield, fruit number, fruit waste and mean fruit weight per plant for cvs 'Autumn Treasure', 'Polka' and 'Tulameen' for 'Actual' and 'Predicted' treatments. Results presented are the mean of 5 plants per treatment. (Significance levels, SED (Cultivar df=8, Treatment df=12, Cult.Treat df =19) and LSD at 5% are shown).

Cultivar	Treatment	Total yield (g)	Total fruit number	Total fruit waste (g)	Mean berry weight (g)
'Autumn Treasure'	'Actual'	1108	336	47	3.5
	'Predicted'	1750	444	46	4.1
'Polka'	'Actual'	379	114	20	3.4
	'Predicted'	526	144	25	3.8
'Tulameen'	'Actual'	1237	317	69	3.9
	'Predicted'	1608	365	61	4.4
F.prob	Cultivar	<0.001	<0.001	n.s.	0.019
	Treatment	0.01	n.s.	n.s.	0.005
	Cult.Treat	n.s.	n.s.	n.s.	n.s.
SED	Cultivar	144.3	31.4	15.8	0.15
	Treatment	124.0	33.4	7.8	0.15
	Cult.Treat	214.7	57.8	13.5	0.26
LSD	Cultivar	332.8	73.5	36.4	0.34
	Treatment	272.9	72.4	17.2	0.33
	Cult.Treat	472.7	127.3	29.8	0.57

Marketable yields were significantly higher under the 'Predicted' regime, compared to the 'Actual' regime, in both cvs 'Tulameen' and 'Autumn Treasure' (Table 9). Yield increases of 58% in 'Autumn Treasure' were due to a greater number of larger fruit whereas the 30% increase in cv 'Tulameen' was due mainly to increase in the weight of individual berries. Cv 'Polka' yields were low compared to the other two cvs and the higher yield under the 'Predicted' regime was not statistically different from that under the 'Actual' regime; comp-onents of berry quality were also similar between the two irrigation scheduling regimes (data not shown). Skin strength of cv 'Autumn Treasure' was reduced in the 'Actual' treatment. Cv 'Tulameen' berry SSC was significantly higher under the 'Actual' regime but berry brightness was significantly reduced under the 'Actual' compared to the 'Predicted' regime. Fruit quality after 72 h at 18 °C was not influenced by the irrigation scheduling regime in either cv. (data not shown)

The volume of water used to produce 1 kg of marketable fruit (the Water Productivity value) was calculated for each cv under each irrigation regime (Table 10). A lower WP value indicates a more efficient use of water and values were lower under the RDI regimes for both cvs. Water Productivity values were very much higher under the 'Predicted' regime in all three cvs, despite the higher marketable yields, due to the significant over-irrigation that resulted from using crop coefficients to schedule irrigation. In cv 'Tulameen', WP was lower in the 'Actual' treatment (Experiment 3) than in the Ww treatment in Experiment 1, despite irrigation being scheduled similarly (essentially, both sets of plants were well-watered). This was due to the higher yields achieved in Experiment 3 (compare Tables 7 and 9).

Table 10. Volume of water applied to produce one kg of fruit, for cvs 'Tulameen' and 'Autumn Treasure' for Ww, RDI-70% and RDI-60%, and also for these cultivars and cv 'Polka' for 'Actual' and 'Predicted' treatments

	Volume of water applied per Kg of fruit				
	RDI Experiments			Actual vs predicted methods of scheduling experiment	
Cultivar	110%	70%	60%	Actual	Predicted
'Tulameen'	106	89	79	76	126
'Autumn Treasure'	82	68	71	89	124
'Polka'	N/A	N/A	N/A	225	314

Discussion

Over the course of the first two years of this project, it has been necessary to make some amendments to the original work plan that was devised by a former colleague at EMR. The current project leader's successful work with strawberry over the last seven years has been achieved by first developing effective irrigation scheduling regimes and deficit irrigation regimes under carefully controlled scientific conditions over several seasons. Only when plant physiological and cropping responses to these regimes were consistently predicted could a 'low risk' irrigation scheduling strategy be developed for testing under commercial conditions. In SF 118, the original intention was to schedule irrigation to a commercial crop of cv 'Polka' at Belks' Farm in Year 2 using the appropriate regression equations developed in Year 1 (equations 1 and 2). However, it was thought prudent to first test the accuracy of this approach to irrigation scheduling under scientific conditions and so an additional experiment was carried out at EMR in 2011. In the original proposal, imposing an RDI treatment on a commercial cv 'Polka' crop at Belks' Farm was also due to be carried out in Year 2. However, since RDI regimes were developed and effects of marketable yields and quality tested for the first time in 2011, it was again thought prudent to first analyse and interpret results from 2011 before testing RDI under commercial conditions.

A comparison of irrigation scheduling methods

Crop co-efficients derived from gravimetric estimates of plant water loss can be used in conjunction with daily estimates of ET_P to schedule irrigation very effectively[6,7,8,9], provided that values of ET °h^{-1} are calculated frequently. Accurate estimates of total transpirational leaf area can also be used to derive ET °h^{-1} values that can be used to schedule irrigation efficiently. Much less certain is the accuracy of this approach when proxy measures of plant water loss are used. Our data show that values of ET °h^{-1} calculated using the best proxy measures of transpirational leaf area for each cv. (equations 1 & 2) were 2- to 3-fold greater than those derived using gravimetric estimates of plant water loss. Consequently, scheduling irrigation using proxy measures of plant transpirational leaf area (the ‘Predicted’ regime) resulted in significant over-irrigation, increased cane vigour in cvs ‘Tulameen’ and ‘Autumn Treasure’ and significant wastage of water and fertilisers.

The lack of a significant effect of the ‘Predicted’ regime on cane extension in cv ‘Polka’ was probably due to the poor vigour of this cv. in our experiments; the cv ‘Polka’ plants were obtained in 2010 and didn’t establish very well (see SF 118 Annual Report 2010). Coir VMC was maintained at or near to full water-holding capacity under the ‘Predicted’ regime which led to average run-offs of between 27 and 59% of the volumes of water applied throughout the season. In contrast, scheduling irrigation using estimates of daily degree hours and crop ET °h^{-1} derived from gravimetric measurements of plant water loss (‘Actual’ regime) effectively maintained VSMC within the optimum range and run-through averaged only 1% of the total volume of water applied.

Yields of marketable fruit were increased by 37%, 28% and 23% under the ‘Predicted’ regime in cvs ‘Tulameen’, ‘Polka’ and ‘Autumn Treasure’, respectively. This was due to a greater number of larger fruit; the excessive fertigation using this strategy resulted in very vigourous plants. Despite the high marketable yields, the excessive application of water and fertilisers and the very vigourous cane growth suggest that this approach would be unsustainable and it is questionable whether this strategy merits further experimental or development work.

Effects of RDI regimes on cane extension growth and yields

Regulated Deficit Irrigation regimes were developed and imposed on two-year-old cropping cvs 'Tulameen' and Autumn Treasure' plants. Some shoot physiological responses to drying substrate were detected in both cvs, which confirmed that the mild shoot water deficits developed under the RDI regimes were due to limited substrate water availability. These shoot responses were not consistently altered over the whole season due to the need to periodically flush through to reduce substrate EC or pH. However, cane extension growth of cv 'Autumn Treasure' was effectively limited by both RDI-70% and RDI-60% regimes whilst that of 'Tulameen' was limited only by the RDI-60% regime.

Yields of marketable fruit were generally reduced under the RDI regimes; these differences were statistically significant for cv 'Autumn Treasure' but not for cv 'Tulameen'. The yield penalties were due to a combination of fewer fruit and a lower average berry fresh weight. Components of berry quality were not affected by the RDI regimes, with the exception of inconsistent effects on berry redness.

Given the losses of marketable yields that occurred when RDI was imposed throughout the season, further developmental work needs to be carried out in scientific experiments at EMR (see plans for 2012). Although the RDI regimes imposed in our 2011 experiments were based on estimates of daily evapotranspiration, the VSMC at which shoot responses to soil drying were triggered in each of the three cvs was identified. These VSMC values will be used to derive lower irrigation set points for use in RDI experiments in 2012.

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. In order to be able to begin this analysis, a grower water use questionnaire was prepared early in 2011 and sent to several key raspberry growers. The intention was to incorporate their suggestions for improvements to layout and clarity into a revised version that would then be distributed to a target group of substrate raspberry growers to gain important information on water use efficiencies. However, no replies were received. The project leader has experienced similar difficulties in trying to glean this information from strawberry growers, despite repeated attempts by the HDC Soft Fruit Research Manager, SF Knowledge Transfer Manager, Panel Chairperson and key personnel of Producer Organisations to encourage strawberry growers to complete the short and straightforward questionnaire. This sort of information is vital to establish baseline water use in the 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, it may be more productive to develop a separate HDC Concept Note to obtain this information from soft and top fruit growers.

Experimental plans for 2012

RDI was applied throughout the growing and cropping season in 2011 to each of the three cvs and the effects of a second season of RDI on cvs 'Autumn Treasure' and 'Tulameen' on cane extension growth, fruit yields and quality will be determined. Additional experiments will also be carried out to try to determine the optimum time to apply RDI to floricanes and primocanes; RDI regimes will be imposed at different developmental stages to determine whether cane vigour can be controlled without reducing yields of marketable fruit.

To try to avoid any negative effects of RDI on floricane yields, RDI-70% and RDI-60% regimes will be applied only after fruiting to determine whether new cane growth can be controlled effectively. Irrigation to Ww controls will be scheduled either by reference to daily ET_P (110%) or by using the VSMC irrigation set points derived in the first two years of this project; this comparison will enable us to evaluate the feasibility of using the coir irrigation set points to schedule irrigation in commercial trials. In primocanes, a RDI-60% regime will be imposed until flowering to limit cane extension growth but then plants will be well-watered during cropping to try to maximise marketable yields and plants will remain well-watered thereafter. A second RDI-60% treatment will be applied in which early RDI will be followed by a Ww treatment during flowering and cropping and then a second period of RDI 60% will be imposed after cropping until leaf fall to try to limit late season cane extension and alter resource partitioning between roots and shoots. Irrigation to Ww controls will be scheduled by reference to daily ET_P (110%).

Five Decagon 10HS sensors will be installed within the rooting zone of five containerised floricane or primocane plants at Belks Farm and connected to a Decagon EM50G data logger with telemetry. Changes in VSMC will be monitored throughout the season under the commercial irrigation regime to provide information on current practice and to identify opportunities to deliver water and fertiliser savings in future commercial trials. The data logger and sensors being used at Belk's Farm has been kindly supplied by South East Water.

Conclusions

- Irrigation was scheduled effectively to Ww plants of each cultivar using gravimetric estimates of plant water use to calculate daily plant water demand
- Two RDI regimes were imposed successfully and the VSMC set points that triggered shoot physiological responses were determined for cvs 'Tulameen' and 'Autumn Treasure'
- The RDI-60% regime effectively limited cane length in cv 'Tulameen' without significantly reducing marketable yields or fruit quality. The RDI-70% regime did not reduce cane height or yields
- Both RDI regimes inhibited cane growth of cv 'Autumn Treasure' but significant reductions in marketable yield occurred under both regimes although fruit quality was generally unaffected
- Scheduling irrigation using proxy measures of plant transpirational leaf area (the 'Predicted' regime) resulted in over-irrigation, increased cane vigour in cvs 'Tulameen' and 'Autumn Treasure' and significant wastage of water and fertilisers
- Yields of marketable fruit were increased by 37%, 28% and 23% under the 'Predicted' regime in cvs 'Tulameen', 'Polka' and 'Autumn Treasure', respectively. This was due to both an increase in fruit number and in fruit size, presumably a consequence of excessive fertiliser applications under the 'Predicted' regime
- Marketable yields of cv 'Polka' were low (379 – 526 g per plant) compared to the other two cvs (1108 – 1750 g per plant)

Technology transfer and knowledge exchange

- Poster presentation at Fruit Focus 2011, July 2011, EMR
- Presentation of the work to the EMR Science Committee, September 2011, EMR
- Poster presentation at the Berry Gardens Annual Technical Conference, November 2011, Ashford
- Presentation of work to BBSRC during visit to EMR, December 2011

References

1) **Knox JW, Kay MG, Weatherhead EK, Burgess C, Rodriguez-Diaz JA** (2009) Development of a Water Strategy for Horticulture. HDC Technical Report
2) **HDC Factsheet 06/0:** Principles of strawberry nutrition in soil-less substrates, 2007
3) **ADAS**: Irrigation Best Practice Grower Guide – Top and Soft Fruit (2003)

4) **WU0102:** A study to identify baseline data on water use in agriculture. ADAS Final Report 2006.
5) **HH3696:** Sustainability of UK strawberry crop. Final Report. www.defra.gov.uk/science/project_data/DocumentLibrary/HH3606NSF/HH3606NSF_3194_FRP.doc.
6) **HH3609TX:** Partial rootzone drying: delivering water saving and sustained high quality yield into horticulture. Lancaster University, East Malling Research, Unversity of Dundee, 2004-2009. Final Report 2009.
7) **Defra WU0110**: Developing novel water-saving irrigation strategies to produce fruit with more consistent flavour and quality and an improved shelf-life. EMR, 2007-2012. Annual Report 2009.
8) **SF 83 / HL0187**: Improving water use efficiency and fruit quality in field-grown strawberry. EMR, 2007-2012. Annual Report March 2010.
9) **HDC SF 107**: Managing water, nitrogen and calcium inputs to optimise flavour and shelf-life in soil-less strawberry production. EMR, 2009-2012
10) **HNS 97b**: Lancaster University, University of Dundee, EMR (2005-2009)
11) EU, University of Dundee, Çukurova University, Instituto Superior de Agronomia *et al*. (2000-2003)
12) **Grant *et al*.** (2004) *Journal of Horticultural Science and Biotechnology* 79, 125-130; 12)

Acknowledgements

We are grateful to Mr Tim Chambers for providing the substrate and the pots as 'in-kind' contributions and to Mr Michael Daly (The Agrology House) for helpful advice on fertigation of substrate-grown raspberries.

