Project title: Irrigation scheduling of raspberry as a tool for improving cane management

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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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Report authorised by:

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GROWER SUMMARY

Headlines

- Irrigation scheduling using coir volumetric moisture contents as set points delivered good marketable yields, reduced or eliminated run-through and optimised water and fertiliser inputs
- This approach could be readily implemented into commercial production using the ‘closed loop’ system developed in SF 136 and now needs to be evaluated on growers’ sites
- Regulated Deficit Irrigation regimes applied throughout the season did not consistently limit cane extension growth in ‘Autumn Treasure’ and ‘Tulameen’ but yields of marketable fruit were reduced although fruit quality was not affected

Background and expected deliverables

More efficient use of inputs including labour, water and fertilisers is vital to the future success of the UK soft fruit industry. Recent droughts, particularly affecting the south east and east regions (Figure GS1) have highlighted the need for growers to use water (and fertilisers) more efficiently. Trickle irrigation has been exempt from legislation until now but it is envisaged that drip irrigators will require an abstraction licence in future and growers must be able to demonstrate an efficient use of water to comply with legislation. There is also concern about the effects of intensive soft fruit production on groundwater quality in the south east and the Environment Agency commissioned ADAS to promote ‘best practice’ in a series of grower workshops in 2012.

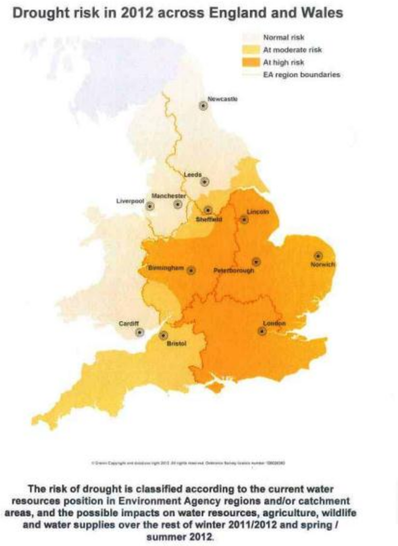

Figure GS1. Assessment of drought risk across England and Wales for 2012. Source: the EA.

However, there are few practical guidelines for growers on how best to schedule irrigation, and matching demand with supply can be difficult in changeable summer weather. Many substrate strawberry growers are advised to irrigate to achieve 10-20% run-off, in part to avoid dry spots within the substrate but mainly to prevent the accumulation of potentially damaging 'salts' within the substrate. This approach can lead to excessive vegetative growth, increased disease, and fruit with a reduced shelf-life and associated increases in waste fruit. Berry eating quality can also be reduced because key flavour compounds are diluted by the high water content. If soft fruit growers are to maintain or increase yields against a backdrop of increasing summer temperatures, dwindling water supplies, and governmental demands for greater environmental protection, new production methods that improve water and nutrient use efficiency and utilise 'best practice' are needed.

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 limit 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. However, the potential of using RDI to control cane vigour without reducing marketable yields is not yet known.

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 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

In 2012, four experiments were conducted on the floricane cultivar ‘Tulameen’ and two on the primocane ‘Autumn Treasure’. The first pair of experiments (1 A&B) tested the effect of continuing the RDI regimes first imposed in 2011 on marketable yields and cane vigour of ‘Tulameen’ and ‘Autumn Treasure’ in the second year of production. The second pair of experiments (2 A&B) investigated the potential of applying RDI at different stages during development and cropping of ‘Tulameen’ and ‘Autumn Treasure’ to determine whether cane vigour could be controlled without reducing marketable yields.

Irrigation treatments

All experiments were carried out in a polytunnel at EMR (Figure GS2). Eighteen experimental plants were included in Experiments 1A&B. Three treatments were applied: 1) Well-watered (Ww) control where plants were given 110% of their daily water use; 2) 70% RDI (RDI-70%) where plants were given 70% of their daily water use; 3) 60% RDI (RDI-60%) where plants were given 60% of their daily water use. The same irrigation regimes were applied to the same plants in both 2011 and 2012 so that longer-term effects of the RDI regimes on yields and cane vigour could be determined.

Figure GS2. ‘Tulameen’ plants used in Experiment 2B. Photo taken on 12 May 2012.

Although cane vigour of ‘Tulameen’ was effectively reduced by a RDI-60% treatment imposed throughout the growing season in 2011, marketable yields were also lowered. In 2012, Experiments 2A&B were carried out on ‘Tulameen’ and ‘Autumn Treasure’ to determine whether applying RDI at specific stages during plant growth and crop development could be used to control cane vigour without reducing marketable yields. All plants were irrigated to match demand with supply and so were kept well watered until the

21 June 2012 when the first fruit started to ripen. Four treatments were imposed in Experiment 2A: Ww, where plants were given 110% of their daily water use; 2) early RDI-70% where plants were given 70% of their daily water use for most of the growing season; 3) early RDI-60% where plants were given 60% of their daily water needs for most of the growing season; 4) late RDI-60% where plants were given 60% of their daily water use towards the end of fruiting for the remainder of the growing season. In Experiment 2B, three treatments were imposed: Ww, where plants were given 110% of their daily water use; 2) early RDI-60% where plants were given 60% of their daily water use for most of the growing season; 3) early RDI-60% followed by a return to Ww conditions at the beginning of fruiting.

Fertigation

Two different nutrient regimes were applied to each cultivar 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 experiment. Plants were fertigated from three stock tanks, one containing calcium nitrate and potassium nitrate, the second containing potassium nitrate, monopotassium phosphate, magnesium sulphate and a Hortifeed trace element mix and the third containing 60% nitric acid. The target pH range of the solution applied to the plants was 5.4 - 5.6; dosatrons were used to adjust the feed EC

Effects of RDI on plant growth and yields in the second cropping year

Experiment 1A – 'Tulameen': The growth of individual canes did not differ between the plants in the different irrigation regimes (Figure GS3A). Leaf elongation was reduced between 14 June and 21 July 2012 in plants in the RDI-60% treatment when compared to those in the Ww treatment, which suggests that in 'Tulameen', leaf growth is more sensitive to limited substrate water availability than cane growth.

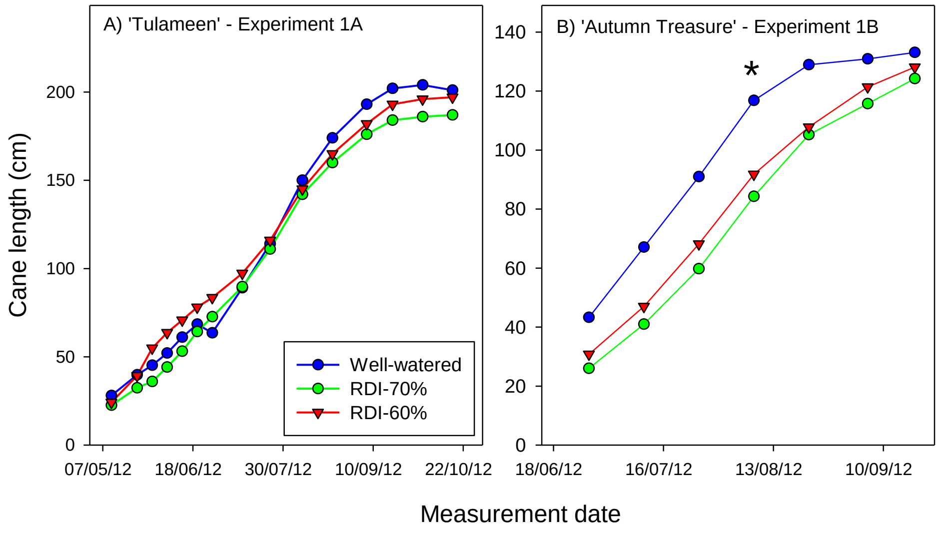

Figure GS3. The effects of different irrigation treatments on the growth of new canes in A) 'Tulameen' and B) 'Autumn Treasure' plants in Experiment 1. Results are means of six plants for each treatment; asterisks indicate statistically significant differences between treatments (*p*<0.05)

Ripe fruit were first picked from 'Tulameen' plants on 14 June 2012, cropping peaked between 25 June to 16 July 2012 and continued until the middle of August 2012. The average yield of marketable fruits per plant in the Ww, RDI-70% and RDI-60% treatments were 1100 g, 808 g and 659 g, respectively (Table GS1). Although these differences were not statistically significant due to high sample variability, a potential loss of yield of between 27 and 40% would be unacceptable to commercial growers. These lowered yields resulted largely from an effect of the RDI regimes on berry size and although fruit number was not significantly affected due to high sample variability, fruit number was reduced by 20% by the RDI-60% regime. Berry brightness, cohesion, flavour, outline, skin strength, texture, SSC and uniformity were unaffected by the different irrigation regimes. There were no treatment differences in rates of berry water loss during the shelf-life tests and aspects of fruit quality were unaffected at the end of the shelf-life period.

Table GS1. Effects of RDI treatments on fruit number, marketable yields per plant and average fruit fresh weight for 'Tulameen' in Experiment 1A. Results are means of six plants for each treatment; asterisks indicate a statistically significant difference from the Ww (control) value (*p*<0.05).

Irrigation regime	Fruit number	Yield (g)	Mean fruit weight (g)
RDI-60%	202	659	3.3*
RDI-70%	225	808	3.5*
Ww	256	1100	4.1

Experiment 1B – 'Autumn Treasure': The RDI-70% and RDI-60% treatments significantly reduced cane extension growth in 'Autumn Treasure' plants during August 2012 compared to Ww plants (Figure GS3B). However, canes under both RDI regimes continued to grow throughout August and September whereas cane extension in Ww plants had slowed by the end of August, so values were similar in all treatments by the end of September 2012. Leaf elongation of 'Autumn Treasure' was not affected by the RDI regimes.

Fruit were first harvested from 'Autumn Treasure' on 13 August 2012 and cropping peaked between 10 September and 8 October 2012, with approximately 60% of the total yield being picked during this time. Fruit production declined during October and the final harvest was on 13 November 2012. The yield of fruit harvested on individual days was significantly greater for plants in the Ww treatment than for those receiving RDI and consequently, total marketable yields per plant were significantly lowered by the two RDI regimes (Table GS2). This was largely due to reductions in fruit numbers rather than to significantly smaller

Figure GS4. The effects of different irrigation treatments on the growth of new canes in A) 'Tulameen' and B) 'Autumn Treasure' plants in Experiment 2. Results are means of six plants for each treatment; asterisks indicate statistically significant differences from the Ww (control) value (*p*<0.05)

berries. There were no statistically significant effects of the RDI treatments on components of berry quality, rates of berry water loss or deterioration in berry quality at the end of the shelf-life period.

Table GS2. Effects of RDI treatments on fruit number, marketable yields per plant and average fruit fresh weight for 'Autumn Treasure' in Experiment 1B. Results are means of six plants for each treatment; asterisks indicate a statistically significant difference from the Ww (control) value (*p*<0.05).

Irrigation regime	Fruit number	Yield (g)	Mean fruit weight (g)
RDI-60%	129*	462*	3.8
RDI-70%	101*	358*	3.8
Ww	318	1280	4.2

Effects of RDI applied at different developmental stages on plant growth and yields

Experiment 2A – 'Tulameen': Leaf elongation was significantly reduced in plants receiving RDI-60% when compared to plants in the other three treatments during the period 14 June and 21 July 2012 (data not shown). Individual cane extension was also reduced by approximately 20% in those plants (Figure GS4A) but this effect was not statistically significant due to high sample variability.

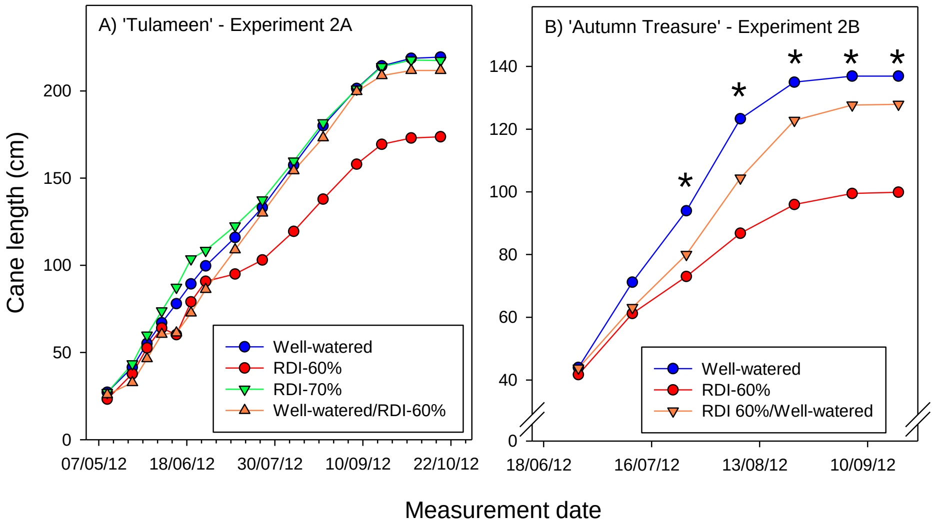

Figure GS4. The effects of different irrigation treatments on the growth of new canes in A) 'Tulameen' and B) 'Autumn Treasure' plants in Experiment 2. Results are means of six plants for each treatment; asterisks indicate statistically significant differences from the Ww (control) value (*p*<0.05)

Ripe fruit were first harvested from 'Tulameen' plants on 14 June 2012, cropping peaked between 25 June and 16 July and continued until the middle of August 2012. Yields of marketable fruit from Ww plants averaged 1,632 g per plant and although not statistically significant, average yields were reduced by between 20 and 29% in RDI-treated plants (Table GS3). Although fruit size was reduced by the RDI-60% and RDI-70% treatments compared to those in the Ww or Ww / RDI-60% treatments, this effect was just outside statistical significance. Berry brightness, cohesion, flavour, outline, skin strength and texture were unaffected by the different irrigation treatments but berry uniformity was significantly reduced in RDI-60% and RDI-70% treatments. Berry SSC was significantly improved by the RDI-60% when compared to the other three treatments. 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.

Table GS3. Effects of RDI treatments on fruit number, marketable yields per plant and average fruit fresh weight for 'Tulameen' in Experiment 2A. Results are means of six plants for each treatment; there were no statistically significant treatment effects on fruit number, yield or size.

	Fruit number	Yield (g)	Mean fruit weight (g)
RDI-60%	299	1252	4.3
RDI-70%	268	1160	4.4
Ww/RDI-60% 60%	266	1309	4.8
Ww	326	1632	4.9

Experiment 2B – 'Autumn Treasure': Within one month of the application of RDI-60%, cane length was significantly reduced compared to Ww values (Figure GS4B). However, when the early RDI treatment was returned to a Ww regime (RDI-60% / Ww) at the beginning of August 2012, the rate of cane extension growth increased so that final cane length was similar to that of Ww plants. Leaf elongation was slowed by the continuous RDI-60% treatment but only temporarily.

Fruit were first harvested from 'Autumn Treasure' on 6 August 2012 and cropping patterns and duration were similar to those described for experiment 1B. The yield of fruit harvested on individual days was significantly greater for plants in the Ww treatment than for those receiving RDI and consequently, total marketable yields per plant were significantly lowered by the RDI regimes, due to an effect on fruit number (Table GS 4). Yields from the RDI-60% / Ww plants were significantly lower than those from Ww plants, even though over the fruiting period both sets of plants were effectively being well watered. There were no statistically significant effects of irrigation treatment on fruit quality or shelf-life potential.

Table GS4. Effects of RDI treatments on fruit number, marketable yields per plant and average fruit fresh weight for 'Autumn Treasure' in Experiment 2B. Results are means of six plants for each treatment; asterisks indicate a statistically significant difference from the Ww (control) value (p<0.05).

Irrigation regime	Fruit number	Yield (g)	Mean fruit weight (g)
RDI-60%	194*	749*	4.0
RDI-60%/Ww	168*	664*	4.0
Ww	330	1326	4.1

Main Conclusions

- A new irrigation scheduling regime has been developed using irrigation set point based on coir volumetric moisture contents. This approach has the potential to deliver significant water and fertiliser savings in commercial 'Tulameen' and 'Autumn Treasure' raspberry production without reducing marketable yields or quality
- Water productivities obtained using this approach were 89 and 96 L of water used to produce 1 kg of marketable fruit for Ww 'Tulameen and 'Autumn Treasure', respectively
- The scheduling approach now needs to be tested in experiments on commercial growers' sites with a high background EC in the irrigation water. This work would help to determine whether the reduced water inputs and associated loss of 'flushing' causes EC to rise in the substrates to the extent that plant growth and marketable yields are affected
- Although irrigation can be scheduled effectively using estimates of ET, gravimetric water losses and crop co-efficients in scientific experiments, this approach is not practical for use in commercial raspberry production
- RDI-60% and RDI-70% regimes did not limit cane growth in 'Tulameen' and marketable yield was reduced by up to 40%
- RDI-60% applied to 'Tulameen' at the beginning of the fruiting phase did not limit extension growth of new canes but marketable yields were reduced by 20%
- The severity of RDI needed to limit cane extension growth in 'Autumn Treasure' also reduced marketable yields
- Applying an early RDI-60% regime to 'Autumn Treasure' and then switching to a Ww regime during fruiting did not limit cane extension growth but did reduce marketable yields
- The use of RDI is not recommended for the control of cane vigour in substrate-grown 'Tulameen' or 'Autumn Treasure'
- The effects of very short-term 'wilting' treatments on cane extension, fruit yields and

quality need to be determined and incorporated into the water-and fertiliser-saving irrigation strategy developed in SF 118

Knowledge exchange and technology transfer activities

- The project aims, objectives and results were presented to BIFGA during a visit to EMR, 25 April 2012
- Project aims, objectives and results were presented in a feature article for the HDC News in June 2012
- The project aims, objectives and results were presented at the Kent Water Summit: Water security for Farmers and Growers, 12 November 2012, EMR
- The project aims, objectives and results were discussed during a visit to Angus Soft Fruit Ltd, 7 February 2013, Dundee

Financial benefits

The project aims to provide the potential to improve the economic and environmental sustainability of soil-less raspberry production by improving both water and nutrient use efficiencies. However, current industry 'standard', 'best' and 'better' practice must be first be established before the water and nutrient use efficiencies and productivities delivered in this project can be assessed in a commercial context.

Given the lack of information regarding current water and fertiliser use in soil-less raspberry production, it is difficult to estimate the potential financial benefits that might be achieved by adopting the irrigation scheduling approach developed in this project. 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 £3250-£4500/ha. On this basis, a 20% reduction in fertiliser used could on average therefore save £650-£900/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 on average 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.

Unlike strawberry, there seems to be a paucity of information on the average marketable yields obtained from commercial plantings of substrate-grown raspberry cultivars. Collection and collation of this data would help to set the yields obtained in the current work (Ww 'Tulameen' = 1,632 g and Ww 'Autumn Treasure' = 1,326 g per plant) into a commercial context.

Action points for growers

- Employ an irrigation consultant to ensure that 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
- Use substrate moisture and EC probes to help inform irrigation scheduling decisions
- Consider using the coir volumetric moisture content set points developed in this project to optimise water and fertiliser inputs and reduce or eliminate run-through without affecting marketable yields or fruit quality
- Assess the impact of the transient wilting treatment (used to control cane vigour) on marketable yields
- 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

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].

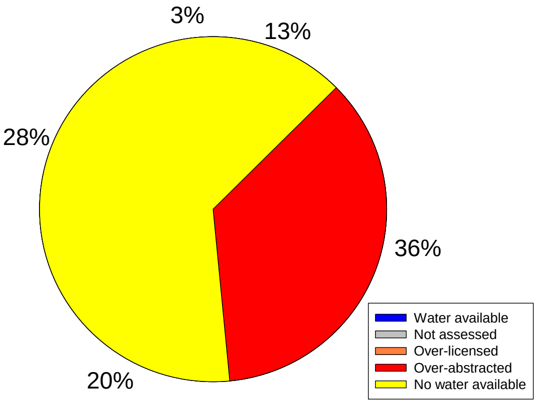

Figure 1. Assessment of water resource availability (for direct abstraction) for the soft fruit sector in 2008 (re-drawn from Knox *et al*., 2009).

Legislation 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. We have already 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 our 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 one aim of this project was to determine whether other, proxy measures of plant water use based on easily measurable plant variables could be used to schedule irrigation effectively.

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 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 varieties (particularly ‘Tulameen’ and new primocane varieties) 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 ‘Tulameen’ and ‘Autumn Treasure’ were obtained from R.W. Walpole Ltd in mid-March 2010 and the roots were placed immediately in to moist compost and stored at 2°C until needed. The plants of each cv. were placed into pots with washed coir supplied by Mr Tim Chambers (Belks’ Farm), on 21 April 2010. ‘Tulameen’ was planted into 7.5 L pots whilst the ‘Autumn Treasure’ was planted into 10 L pots. All canes of ‘Autumn Treasure’ were cut back to coir level. The plants were then positioned on batons laid on the floor in a polytunnel at EMR (Figures GS2 and 3). There were 4 rows of plants, each row was 1.4 m apart and the distance from pot centre to pot centre was 37 cm.

Figure 3. ‘Autumn Treasure’ plants in Experiment 1B showing emergence of the second flush of growth, the first flush of growth was removed on 1 May 2012 due to premature anthesis. Photo taken on 18 May 2012.

In 2012, the RDI experiment carried out in 2011 was continued for both ‘Tulameen’ (Experiment 1A) and ‘Autumn Treasure’ (Experiment 1B) using the same plants, to determine the impact of RDI over two cropping seasons on fruit production and cane vigour in the second year of production. In 2012, two additional experiments were carried out, one with ‘Tulameen’ (Experiment 2A) and the other with ‘Autumn Treasure’ (Experiment 2B). The plants used in Experiment 2 were the former guard plants in the outer two rows of the tunnel. These plants remained well-watered throughout 2010 and 2011 and they were moved to the central two rows of the tunnel in February 2012. Plants previously used for experiments in 2010 and 2011 were moved to the outer rows and acted as guard plants in 2012.

On 12 April 2012, the number of canes in each ‘Autumn Treasure’ was reduced to four. The vegetative feed regime began on 5 April 2012 (see fertigation details below) for all ‘Tulameen’ and ‘Autumn Treasure’ plants. The irrigation treatments were first applied to ‘Tulameen’ on 11 May 2012 but the imposition of the irrigation treatments to ‘Autumn Treasure’ was delayed until 24 June 2012. These plants began to flower unusually early in mid-April, on stems less than 30 cm high, presumably as a consequence of the warm temperatures experienced in March followed by cold temperatures in April, which caused the early initiation of flowers. The stems of all ‘Autumn Treasure’ plants were cut back to coir level on 1 May 2012, to encourage a new flush of stems and this delayed cropping by approximately one month.

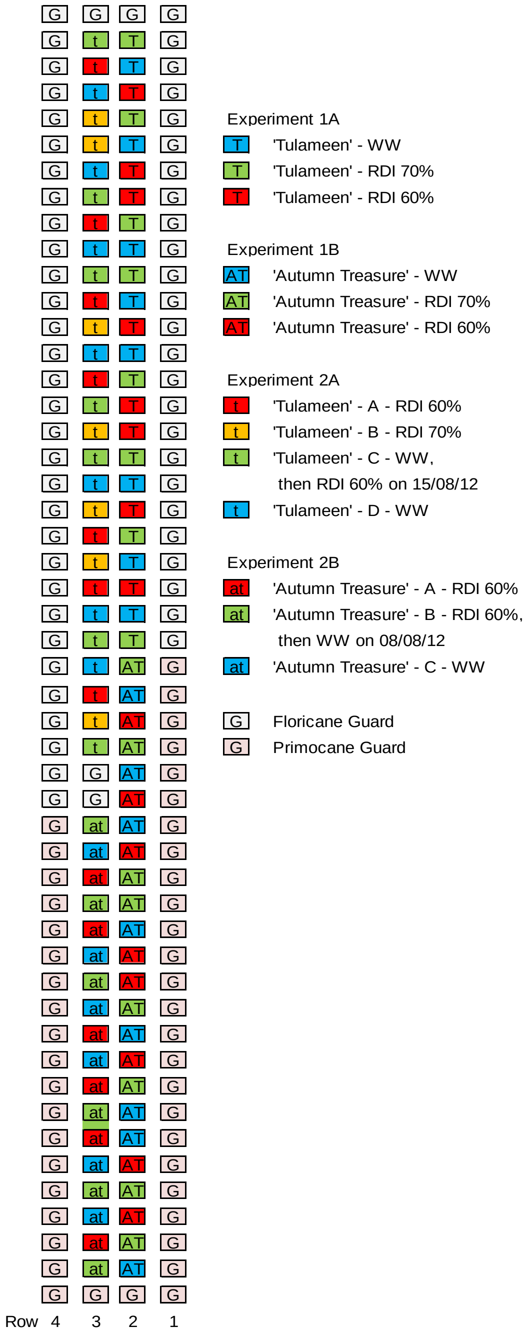

Figure 4. The experimental design used in 2012 experiments. All routine measurements were made on experimental plants in rows 2 (Experiment 1 A&B) and 3 (Experiment 2 A&B). Rows 1 and 4 were designated as guard rows.

Experimental design

Four experiments were conducted simultaneously during 2012 (Figure 4). Experiments 1 A (‘Tulameen’) and B (‘Autumn Treasure’), were a continuation of the experiments started in 2011 to determine the effects of RDI on growth and cropping of these two cvs. The experimental set-up in 2012 was the same as in 2011, with individual plants having the same treatment applied in each year. In both ‘Tulameen’ (Experiment 1A) and ‘Autumn Treasure’ (Experiment 1B), twenty-four plants were included in the experiment with three irrigation treatments being applied: 1) a Well-watered (Ww) control where plants were given 110% of estimated plant daily water use; 2) 70% RDI treatments (RDI-70%) where plants were given 70% of estimated daily water use 3) 60% RDI treatments (RDI-60%) where plants were given 60% of estimated daily water use. The irrigation treatments were first imposed on the 11 May 2012 for ‘Tulameen’ and 22 June 2012 for ‘Autumn Treasure’. To calculate daily irrigation volumes, plants within the guard rows, rather than in the experimental blocks, were used to calculate average water use for each of the two cvs. This was necessary to avoid repeated handling of the experimental plants and the attendant damage to shoots.

There were eight blocks for each experiment, however only six blocks were used for routine measurements.

In 2011, the imposition of RDI throughout the growing season to control cane vigour resulted in lower marketable yields. We hypothesised that if short-term RDI was applied at specific stages during the cropping cycle, these yield penalties might be avoided, despite achieving adequate control of cane growth. In 2012, two additional experiments were carried out, one on each cv., to test this hypothesis. In Experiment 2A, 24 experimental plants were used and four irrigation treatments were applied: 1) Ww throughout the growing season, where plants were given 110% of their daily water use; 2) early 70% RDI where plants were given 70% of their daily water needs from the start of fruiting (22 June 2012); and throughout the rest of the growing season; 3) early 60% RDI where plants were given 60% of their daily water needs from the start of fruiting and throughout the rest of the growing; 4) late 60% RDI where plants were given 60% of their daily needs towards the end of fruiting (16 August 2012) for the rest of the growing season. For Experiment 2B with 'Autumn Treasure', eighteen plants were used, all were kept well watered until 22 June 2012, when three irrigation treatments were imposed: 1) Ww throughout the growing season, where plants were given 110% of their daily water use; 2) early 60% RDI where plants were given 60% of their daily water needs from 22 June 2012 until the start of fruiting (10 August 2012), after which they were well-watered; 3) continuous 60% RDI where plants were given 60% of their daily water needs from 22 June 2012 throughout the rest of the growing season. Both experiments were set up as a complete randomised block design, with one of each treatment in each experimental block (Figure 4). There were six blocks for each experiment.

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. 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 5). The method used to determine *ET* $°h^{-1}$ (g water loss per degree hour) values is described below.

Figure 5. The Skye Evapo-sensor and Evapometer used to estimate daily potential evapo-transpiration. Photo taken on 15 July 2010.

Determining ET_P 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 all experiments, Ww guard plants of 'Tulameen' and 'Autumn Treasure' were used to avoid foliar and fruit damage to the experimental plants that inevitably occurred from the frequent lifting and moving of plants to record weight losses. Water loss per degree h for each cv. was determined and used in conjunction with the number of 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 over the previous 24 h. Correction factors of either 1.1. 0.7 or 0.6 were used to schedule irrigation at 110%, 70% and 60% daily water use respectively. Thus, the sum total volume of the daily irrigation events replaced 110%, 70% or 60% of the volume estimated to have been lost over the previous 24 h.

Whilst using the guard plants to determine the water use of experimental plants worked well for 'Tulameen', it was more problematic for irrigation scheduling to the experimental 'Autumn Treasure' plants. The coir volumetric moisture content (CVMC) of the Ww experimental 'Autumn Treasure' plants in both experiments began to fall at the start of irrigation scheduling, suggesting that the guard plants were using less water than the experimental plants. In Experiment 1B, plants within the Ww regime had a lower CVMC than those in both RDI regimes during July (see Figure 8). The CVMC of the plants in all three irrigation treatments in Experiment 2B also declined, indicating that the Ww plants in this experiment were not getting enough water and that the deficit on the RDI treatment was too severe. On 25 July 2012, Ww experimental plants were given 125% of the water use of the guard plants and plants under the RDI-60% regime were given 60% of this new higher value.

Subsequently CVMC began to increase, whilst run-off from the Ww plants in both experiments, averaged across the rest of the season, remained low at 9% and 2% for Experiments 1B and 2B respectively, indicating that the approach adopted to rectify the problem was effective.

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. In 2012, a new feed formulation was used due to signs of nutrient deficiency towards the end of the 2011 season (see Annual Report 2011). Plants were fertigated from three stock tanks, one containing calcium nitrate and potassium nitrate, the second containing potassium nitrate, monopotassium phosphate, magnesium sulphate and 'Hortifeed' trace element mix and the third containing 60% nitric acid. The target pH range of the solution applied to the plants was 5.4 - 5.6. 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. The vegetative fertiliser mix was applied to all plants on 5 April 2012 and switched to a fruiting mix between 31 May and 31 July 2012 for 'Tulameen', after which the vegetative feed mix was applied until 17 October. Fruiting mix was applied to 'Autumn Treasure' plants from 31 July to 14 November 2011.

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

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).

Nutrient	Concentration in diluted feed (mg L^{-1})	
	Vegetative	Fruiting
NO_3-N	136	143
NH_4-N	4	3
P	42	42
K	180	253
Ca	150	126
Mg	25	30
B	0.17	0.17
Cu	0.10	0.10
Fe	1.80	1.80
Mn	0.75	0.75
Mo	0.05	0.05
Zn	0.56	0.23

Coir volumetric moisture content and EC

Coir volumetric 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 volumetric 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 and EC around the developing root system within each pot.

Measurement of physiological parameters

Routine measurements in all experiments were carried out on six replicate plants per cv. in each irrigation treatment. Measurements were first made on the 9 May 2012 for 'Tulameen' plants in Experiments 1A and 2A and on the 11 July for 'Autumn Treasure' plants in Experiments 1B and 2B; subsequent measurements were carried out on a fortnightly basis. Final measurements were made on 3 October 2012 for 'Tulameen', and on 31 October 2012 for 'Autumn Treasure'. 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). Midday leaf 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. From the 31 July 2012, measurements of midday stem water potential (ψ_S) replaced those of leaf water potential since the former measure is less affected by fluctuations in the aerial environment. Leaves were wrapped in tin foil sleeves for 2-3 h prior to measuring water potential. 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 for 'Tulameen' and three occasions for 'Autumn Treasure'.

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 seven expanding leaves per experimental plant was measured throughout the season for 'Tulameen' and five leaves were measured for 'Autumn Treasure'. Cane height was measured on each of the four primocanes of experimental 'Autumn Treasure' plants from 27 June 2012, and of the four strongest new vegetative canes in 'Tulameen' from 11 May 2012; measurements were made weekly for 'Tulameen' until 27 June 2012 and then fortnightly for both cvs. Fruiting cane length in 'Tulameen' plants were measured when spent fruiting canes were removed on 14 August 2012.

Fruit yields and quality

Ripe berries were harvested from fruiting plants twice-weekly. 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 developed at EMR by the raspberry breeding team: fruit redness, brightness, uniformity of size, outline, texture, cohesion, skin strength and flavour (see SF 118 Annual Report 2012). 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 for each cv. 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 were 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 h, 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 (see SF 118 Annual Report 2012).

Statistical analyses

Statistical analyses were carried out using GenStat 11th 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. Repeated measure ANOVA tests were also carried out when measurements were repeated on a number of days.

Results

Evapotranspiration per degree hour

Evapotranspiration per degree hour (*ET* °h^{-1}) was calculated weekly by measuring gravimetric water loss of eight guard plants for each cv. 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. are presented in Figure 6. 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 both 'Autumn Treasure' and 'Tulameen' from May until August (Figure 6) as the plants grew and leaf area increased. However, for both cvs, the value of ET_P measured initially at the beginning of May was far higher than the values calculated for the rest of May/June. One possibility for this anomaly was that the evaporative demand on the day the measure was conducted was low (the number of degree hours recorded at less than 30); on such days the accuracy of the calibration is reduced and plant water use is overestimated. At the beginning of August, following the removal of the spent fruiting canes, *ET* °h^{-1} values for 'Tulameen' declined sharply. Values for both cvs decreased gradually during September and October due to a slowing in cane growth (see Figure GS 3&4) and the beginning of leaf senescence.

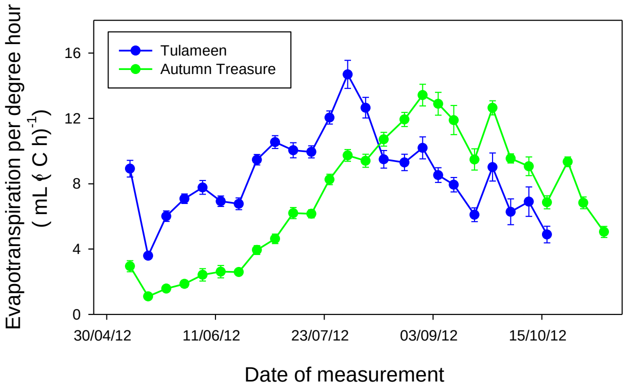

Figure 6. Changes in crop evapotranspiration (*ET_P*) for the two cvs over the 2012 season calculated by gravimetric measures of water loss of eight guard plants for each cv.

Coir volumetric moisture contents under the different irrigation regimes

Scheduling irrigation using estimates of daily degree h 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 'Tulameen' in Experiment 1A (Figure 7A). Within two weeks of the RDI treatments being applied, VSMC fell to 0.25 m^3 m^{-3} and 0.37 m^3 m^{-3} in the RDI-60% and RDI-70% regimes respectively, and continued to fall in the latter over the following month until a value of 0.29 m^3 m^{-3} was reached. The VSMC was significantly lower for the plants in the

RDI regimes than for Ww plants from the beginning of June and throughout the rest of the growing season. In Experiment 2A, the VSMC was generally maintained above 0.4 m^3 m^{-3} until the imposition of the RDI treatments on 22 June 2012, at which point CVMC for the RDI-60% and RDI-70% regimes began to fall, reaching 0.3 m^3 m^{-3} within two weeks (Figure 7C). Coir volumetric moisture contents were maintained between the target range of 0.3 and 0.4 m^3 m^{-3} until early October. The CVMC for the well watered plants (Ww) remained relatively stable between 0.4 and 0.55 m^3 m^{-3} throughout the growing season, whilst for plants in the Ww / RDI-60% regime, CVMC began to fall in early August as the plants were switched from the Ww to the RDI-60% regime.

In Experiments 1B and 2B with 'Autumn Treasure', VSMC declined unexpectedly under the Ww regime in the weeks following the start of irrigation scheduling on 22 June 2012 (Figure 7B and D). The CVMC of plants in the RDI regimes fell to below 0.2 m^3 m^{-3}; the lower target CVMC for RDI-60% was 0.3 m^3 m^{-3} in 2011. This indicated that WW plants in Experiments 1B and 2B were not receiving adequate amounts of water, and that the deficit in RDI treatments in Experiment 2B was too severe. This was due to the disparity between the volumes of water transpired by the guard plants and the experimental plants mentioned earlier. At the beginning of fruiting (10 August 2012), irrigation of the plants in treatment RDI-60%/Ww of Experiment 2B was switched from RDI 60% to well watered,

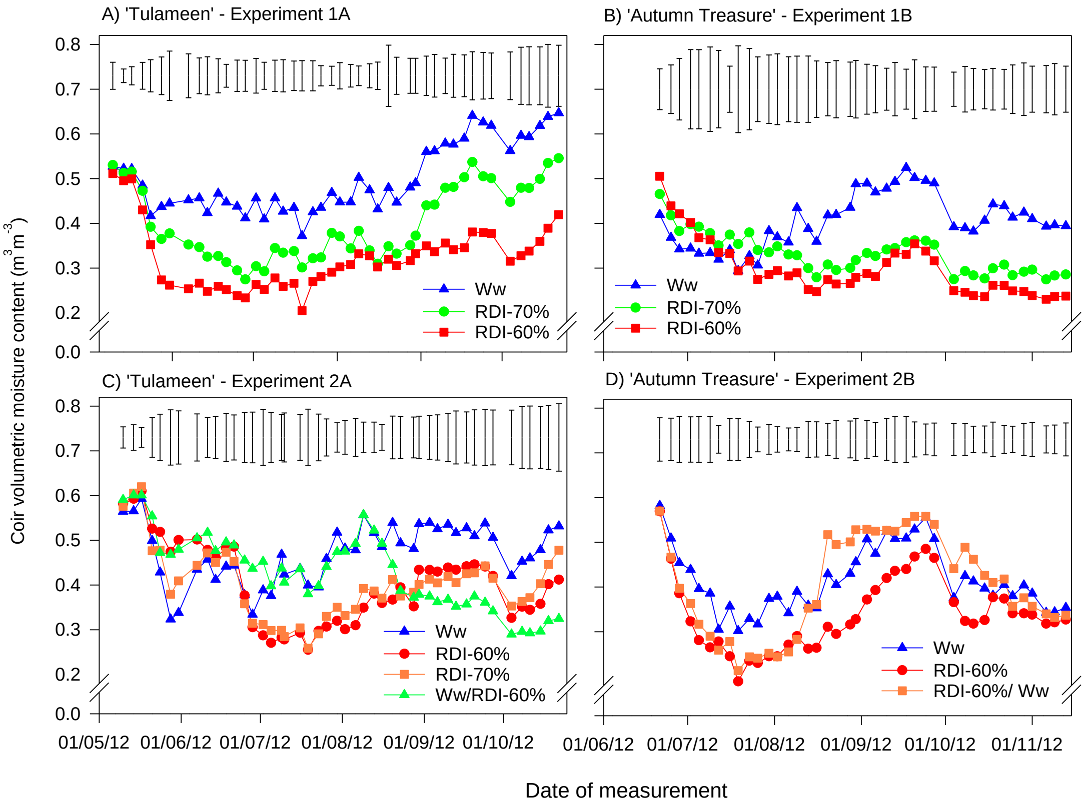

Figure 7. Changes in average pot CVMC for 'Tulameen' and 'Autumn Treasure' plants in Experiments 1A&B, and 2A&B, under different irrigation regimes (Ww, RDI-70% or RDI-60% of calculated ET_P). Results are means of six replicate plants per treatment; vertical bars are LSD values at $p<0.05$.

resulting in a rapid increase in CVMC from 0.3 m^3 m^{-3} to above 0.5 m^3 m^{-3} (Figure 7D).

Run-through of water and fertilisers

The volume of water running through the pots of Ww 'Tulameen' and 'Autumn Treasure' averaged across the season was 19% and 7% of the volumes applied for Experiment 1 A&B, respectively. Although the irrigation scheduling approach effectively matched demand with supply throughout the season and minimised losses of water and fertiliser in 'Autumn Treasure', this was not the case with 'Tulameen', especially from September onwards. This was due, in part, to the differences in water use between the guard plants used to measure ET_P and those within the experiment, the disparity increased further following the removal of fruiting cane. A further complication is that on days when evapotranspiration is low (low temperature, high humidity days), as frequently occurred in September and October 2012, evapotranspiration per degree hour is overestimated which leads to over-irrigation.

The volume of water running through the pots of Ww 'Tulameen' and 'Autumn Treasure' averaged across the season in Experiment 2A&B was 4.2 and 1.2% of the volumes applied, respectively, indicating that the demand and supply of water for the plants in the former were well matched throughout the season. Run through for the 'Autumn Treasure' plants that were initially irrigated at RDI-60% increased following the switch to the Ww regime, due probably to a combination of factors such as the initial poor water holding capacity of the dry coir and a residual but temporary suppressive effect of RDI on plant water loss.

Plant physiological responses to the RDI treatments

When the values of g_s for 'Tulameen' and 'Autumn Treasure' were averaged across the individual measurement dates, there were no significant treatment differences in Experiment 1A&B (Figure 8). In Experiment 2A, the 'Tulameen' average g_s value was significantly reduced in plants under each of the three RDI regimes, compared to Ww values (Figure 8).

The rate of photosynthesis, averaged across the three individual measurement dates, was significantly reduced by the RDI regimes imposed on 'Tulameen' in Experiment 2A, compared to Ww values (Figure 9). Rate of photosynthesis were unaffected by the irrigation treatments in the other experiments.

Midday leaf/stem water potential for 'Tulameen' plants under the RDI regimes in Experiments 1A and 2A were more negative than Ww values on two measurement dates (Figure 10A&B), indicating that transient mild shoot water deficits developed in RDI-treated plants. Leaf/stem water potential of RDI-treated 'Autumn Treasure' plants showed no signs of increased shoot water deficits compared to Ww values (data not shown).

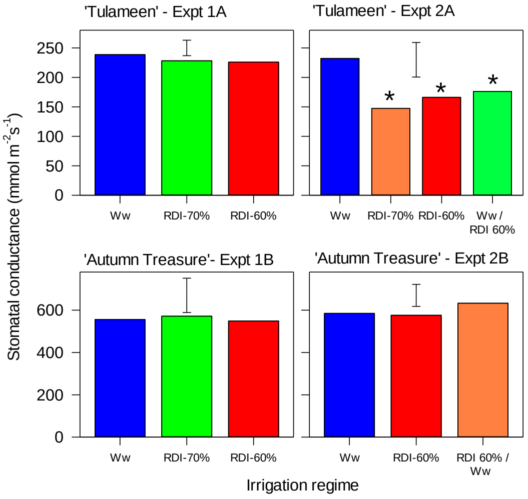

Figure 8. Average values of stom conductance for 'Tulameen' and 'Autu Treasure' plants in Experiments 1 and receiving various amounts of irrigation, W RDI-70% or RDI-60% of calculated E Results are averages across the season for plants for each treatment within each Measurements were carried out on occasions in Expt. 1A, 9 occasions for Expt. 4 occasions in Expt. 2A and 8 for in Expt. Vertical bars are LSD values at *p*<0. asterisks indicate statistically signific differences from the Ww (control) va (*p*<0.05).

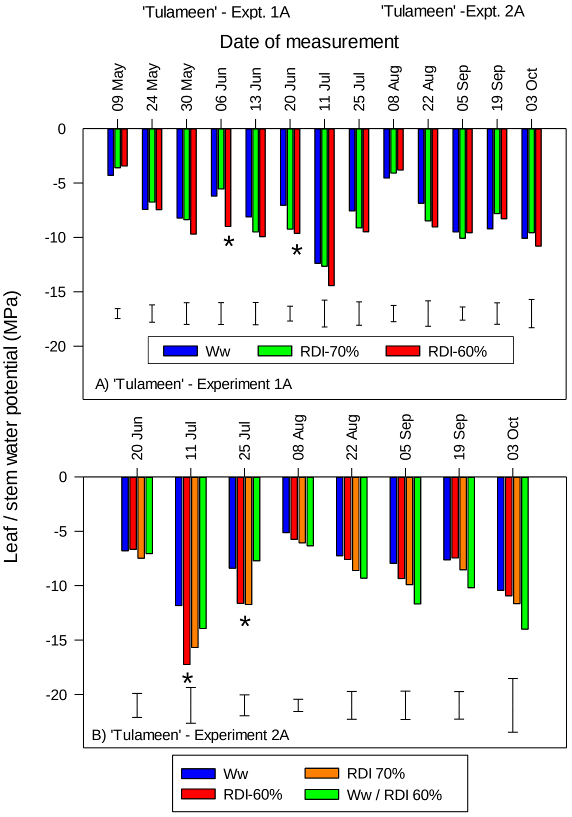

Figure 10. Midday leaf water potential for plants of 'Tulameen' in Experiments 1A and 2A. Results are means of six replicates. Vertical bars are LSD values at p<0.05; asterisks indicate statistically significantly differences from the Ww (control) value (*p*<0.05).

Effects of RDI during the second cropping year on cane vigour, marketable yields and quality

The growth of individual 'Tulameen' canes did not differ between the plants in the different irrigation regimes (Figure GS3A). Leaf elongation was reduced between 14 June and 21 July 2012 in plants in the RDI-60% treatment when compared to those in the Ww treatment (data not shown), which suggests that in 'Tulameen', leaf growth is more sensitive to limited substrate water availability than cane growth. Cane extension in 'Autumn Treasure' plants under RDI-70% and RDI-60% treatments was significantly limited during August 2012 compared to Ww plants (Figure GS3B). However, plants under both RDI regimes continued to grow throughout August and September whereas the rate of cane extension in Ww plants had slowed by the end of August, so values were similar in all treatments by the end of September 2012. Leaf elongation of 'Autumn Treasure' was not affected by the RDI regimes (data not shown).

Ripe fruit were first picked from 'Tulameen' plants on 14 June 2012, cropping peaked between 25 June to 16 July 2012 and continued until the middle of August 2012. The average yield of marketable fruits per plant in the Ww, RDI-70% and RDI-60% treatments were 1100 g, 808 g and 659 g, respectively (Table 2). Although these differences were not statistically significant due to high sample variability, a potential loss of yield of between 27 and 40% would be unacceptable to commercial growers. These lowered yields resulted from an effect of the RDI regimes on berry size since fruit number was unaffected by irrigation regime. Berry brightness, cohesion, flavour, outline, skin strength, texture, SSC and uniformity were unaffected by the different irrigation regimes. There were no treatment differences in rates of berry water loss during the shelf-life tests and aspects of fruit quality were unaffected at the end of the shelf-life period.

Table 2. Effects of RDI treatments on fruit number, marketable yields per plant and average fruit fresh weight for 'Tulameen' in Experiment 1A. Results presented are means of six plants for each treatment (significance levels, SED (d.f. 10) and LSD at 5% are shown).

	Total fruit number	Total Fruit yield (g)	Mean fruit weight (g)
RDI-60%	202	659	3.3
RDI-70%	225	808	3.5
Ww	256	1100	4.1
F.prob	n.s.	n.s.	0.002
SED	39.2	161.2	0.17
LSD	88.7	364.6	0.38

Fruit were first harvested from 'Autumn Treasure' on 13 August 2012 and cropping peaked between 10 September and 8 October 2012, with approximately 60% of the total yield being picked during this time. Fruit production declined during October and the final harvest was on 13 November 2012. The yield of fruit harvested on individual days was significantly greater for plants in the Ww treatment than for those receiving RDI and consequently, total marketable yields per plant were significantly lowered by the two RDI regimes (Table 3). This was due to reductions in fruit numbers rather than to smaller berries. There were no statistically significant effects of the RDI treatments on components of berry quality, rates of berry water loss or deterioration in berry quality at the end of the shelf-life period.

Table 3. Effects of RDI treatments on fruit number, marketable yields per plant and average fruit fresh weight for 'Autumn Treasure' in Experiment 1B. Results presented are means of six plants for each treatment (significance levels, SED (d.f. 10) and LSD at 5% are shown).

	Total fruit number	Total Fruit yield (g)	Mean fruit weight (g)
RDI-60%	129	462	3.8
RDI-70%	101	358	3.8
Ww	318	1280	4.2
F.prob	0.006	0.001	n.s
SED	53.7	179.9	0.40
LSD	121.6	407.0	0.84

Effects of RDI applied at different developmental stages on cane growth, yields and quality

*L*eaf elongation of 'Tulameen' was significantly reduced in those plants receiving RDI-60% when compared to plants in the other three treatments during the period 14 June and 21 July 2012, and whilst individual cane extension was also reduced by approximately 20% in those plants (Figure GS4A), this effect was not statistically significant due to high sample variability. Within one month of the application of RDI, cane length of 'Autumn Treasure' was significantly reduced compared to Ww values (Figure GS4B). However, when the early RDI treatment was returned to a Ww regime (RDI-60% / Ww) in early August, cane extension increased so that the final cane length was similar to that of Ww plants. Leaf elongation was only slowed by the continuous RDI-60% treatment, and then only during the period 19 July to 2 August 2013 (data not shown). Ripe fruit were first picked from 'Tulameen' plants on 14 June 2012, cropping peaked between 25 June and 16 July and continued until the middle of August 2012. Yields of marketable fruit from Ww plants averaged 1,632 g per plant and although not statistically significant, average yields were reduced by between 20 and 29% in RDI-treated plants (Table 4). Although fruit size was reduced by the RDI-60% and RDI-70% treatments compared to those in the Ww or Ww / RDI-60% treatments, this effect was just outside statistical significance. Berry brightness, cohesion, flavour, outline, skin strength and texture were unaffected by the different irrigation treatments but berry uniformity was significantly reduced in RDI-60% and RDI-70% treatments. Berry SSC was significantly improved by the RDI-60% when compared to the other three reatments. 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.

Table 4. Effects of RDI treatments on fruit number, marketable yields per plant and average fruit fresh weight for 'Tulameen' in Experiment 2A. Results presented are means of six plants for each treatment (significance levels, SED (d.f. 10) and LSD at 5% are shown).

	Total fruit number	Total Fruit yield (g)	Mean fruit weight (g)
RDI-60%	299	1252	4.3
RDI-70%	268	1160	4.4
Ww/RDI-60% 60%	266	1309	4.8
Ww	326	1632	4.9
F.prob	n.s.	n.s.	n.s.

SED	46.3	228.4	0.26
LSD	99.3	429.9	0.54

	Total fruit number	Total Fruit yield (g)	Mean fruit weight (g)
RDI-60%	299	1252	4.3
RDI-70%	268	1160	4.4
Ww/RDI-60% 60%	266	1309	4.8
Ww	326	1632	4.9
F.prob	n.s.	n.s.	n.s.
SED	46.3	228.4	0.26
LSD	99.3	429.9	0.54

Fruit were first harvested from ‘Autumn Treasure’ on 6 August 2012 and cropping patterns and duration were similar to those described for experiment 1B. The yield of fruit harvested was significantly greater for plants in the Ww treatment than for those receiving RDI and consequently, total marketable yields per plant were significantly lowered by the RDI regimes, due to the effect on fruit number (Table 5). Yields from the RDI-60% / Ww plants were significantly lower than those from Ww plants, even though over the fruiting period both sets of plants were effectively being well watered.

Table 5.. Effects of RDI treatments on fruit number, marketable yields per plant and average fruit fresh weight for ‘Autumn Treasure’ in Experiment 2B. Results presented are means of six plants for each treatment (significance levels, SED (d.f. 10) and LSD at 5% are shown).

	Total fruit number	Total Fruit yield (g)	Mean fruit weight (g)
RDI-60%	194	749	4.0
RDI-60%/Ww	168	664	4.0
Ww	330	1326	4.1
F.prob	<0.001	<0.001	n.s.
SED	21.9	84.5	0.17
LSD	48.8	188.2	0.37

Water productivity

Values of water productivity achieved under the well-watered irrigation regimes applied to ‘Tulameen’ and to ‘Autumn Treasure’ averaged 138 and 76 L water per kg of fruit produced, respectively, in Experiments 1A&B (Tables 6 and 7). In Experiments 2A&B, WP values for Ww treatments averaged 89 and 96 L water per kg of fruit produced by ‘Tulameen’ and ‘Autumn Treasure’, respectively (Tables 8 and 9). WP values obtained under RDI regimes can mislead if marketable yields are also reduced and so the WP values associated with the RDI regimes presented in Tables 6-9 must be interpreted with caution. Although a lower WP value indicates more efficient use of irrigation water, it may be at the expense of marketable yields.

Table 6. Water productivity values and volumes of water applied under the three irrigation regimes imposed on ‘Tulameen’ in Experiment 1A. Water productivity values are means of six replicate measurements for each treatment (significance levels, SED (d.f. 10) and LSD at 5% are shown).

Irrigation regime	Water productivity (L water per Kg fruit)	Water used (L)
RDI-60%	135	77
RDI-70%	113	89
Ww	138	138
F.prob	n.s	
SED	27.5	
LSD	62.2	

Table 7. Water productivity values and volumes of water applied under the three irrigation regimes imposed on ‘Autumn Treasure in Experiment 1B. Water productivity values are means of six replicate measurements for each treatment (significance levels, SED (d.f. 10) and LSD at 5% are shown).

Irrigation regime	Water productivity (L water per Kg fruit)	Water used (L)
RDI-60%	220	59
RDI-70%	381	63
Ww	76	126
F.prob	n.s	
SED	200.7	
LSD	454.1	

Table 8. Water productivity values and volumes of water applied under the three irrigation regimes imposed on ‘Tulameen’ in Experiment 2A. Water productivity values are means of six replicate measurements for each treatment (significance levels, SED (d.f. 10) and LSD at 5% are shown).

Irrigation regime	Water productivity (L water per Kg fruit)	Water used (L)
RDI-60%	84	93
RDI-70%	90	101
Ww / RDI-60%	131	124
Ww	89	138
F.prob	n.s.	
SED	30.6	
LSD	65.5	

Table 9. Water productivity values and volumes of water applied under the three irrigation regimes imposed on 'Autumn Treasure in Experiment 2B. Water productivity values are means of six replicate measurements for each treatment (significance levels, SED (d.f. 10) and LSD at 5% are shown).

Irrigation regime	Water productivity (L water per Kg fruit)	Water used (L)
RDI-60%	93	67
RDI-70%	171	107
Ww	96	125
F.prob	0.001.	
SED	16.7	
LSD	37.2	

Discussion

Over the course 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 eight 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 'Polka' at Belks' Farm in Year 2 using the appropriate regression equations developed in Year 1. 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 '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 carry out further experiments in 2012 before testing RDI under commercial conditions.

A comparison of irrigation scheduling methods

Much of the scientific work investigating the potential of using RDI or PRD regimes to improve plant water use efficiency and aspects of fruit quality that has been carried out at EMR over the last eight years has been based on using estimates of evaporative demand and crop co-efficients to calculate plant water use. We have shown that 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 and deficit irrigation very effectively[6,7,8,9], provided that values of ET °h^{-1} are calculated with sufficient accuracy and frequency. 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. Despite positive results with HNS crops, the data collected during this project show that values of ET °h^{-1} calculated using the best proxy measures of transpirational leaf area for each cv. (equations 1 & 2 in SF118 Annual Report 2011) 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 resulted in significant over-irrigation, increased cane vigour in 'Tulameen' and 'Autumn Treasure' and resulted in significant wastage of water and fertilisers. In our 2012 experiments, plant water use was underestimated for 'Autumn Treasure' in one experiment due to the differences in total transpirational area between the plants used to derive ET °h^{-1} values and the experimental plants. These difficulties arose because of the limited number of plants in our experiment and the need to avoid damage from repeated handling of the plants to measure gravimetric water loss. Nevertheless, given the difficulties in generating reliable and consistent irrigation guidelines based on crop co-efficients and estimates of evaporative demand, the approach is not currently recommended for use in commercial raspberry production.

Due to the uncertainty over the accuracy with which irrigation could be scheduled using equations developed in 2010 and 2011, it was thought prudent to develop an alternative irrigation scheduling tool for use in commercial raspberry production. An approach that has been used with success in other HDC-, Defra-, HortLINK- and industry-funded work is to maintain substrate volumetric moisture contents between pre-set upper and lower thresholds. This approach has also been used to apply deficit irrigation regimes that deliver further water savings but also help to reduce vegetative vigour, improve fruit quality and shelf-life potential. In this project, the range of CVMC in plants where irrigation was scheduled effectively to meet demand with supply was identified in experiments in 2011 under the 'Actual Regimes' (see SF 118 Annual Report 2011) where run-through averaged only 1% of the total volume of water applied and marketable yields were 1,237 and 1,108 g per plan for 'Tulameen' and 'Autumn Treasure', respectively. These irrigation set points could now be tested in experiments on commercial farms to assess the potential of this approach to reduce irrigation inputs and losses without reducing marketable yields.

A 'closed loop' irrigation scheduling tool that could trigger irrigation automatically in commercial substrate production, so that CVMC are maintained between upper and lower set points, irrespective of changing evaporative demand has recently been developed and tested in SF 136. The results suggest that significant water and fertiliser savings can be achieved in commercial substrate production without affecting berry size, marketable yields or fruit quality if irrigation is scheduled to match demand with supply. Water and fertiliser savings of 17% and 11% were achieved in our experiments at Manor Farm and New Farm respectively, and aspects of berry quality were improved. Although the automated irrigation scheduling tool effectively maintained CVMC between upper and lower set points at each site for much of the growing season, the reliance on a single value of CVMC taken from what was assumed to be a representative position in a coir bag meant that data had to be downloaded and analysed several times each day to ensure that any issues were identified and dealt with promptly. New developments in substrate moisture sensor and data logger technology are needed before the closed loop system can be implemented to manage irrigation reliably in large-scale commercial substrate production. The aim is to develop a system capable of controlling multiple zones of different crops or crops at different stages of growth. The new GP2 Advanced Logger and Controller from Delta-T Devices will facilitate the development of a closed-loop irrigation and fertigation control system, capable of averaging data from up to 12 sensors and disregarding data from malfunctioning soil moisture probes. Telemetry would enable data from the irrigation rig to be accessed remotely. This farm-scale automatic irrigation scheduling system would help to deliver the improvements in water and fertiliser use efficiency in substrate soft fruit production. Such a system is currently being developed and tested on substrate-grown strawberry in a commercial project at EMR.

Effects of RDI regimes on cane extension growth

Regulated Deficit Irrigation regimes were developed and imposed on two- and three-year-old cropping ‘Tulameen’ and Autumn Treasure’ plants. In experiments in 2011, 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 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.

In experiments in 2012, the continuous imposition of RDI-60% and RDI-70% regimes did not significantly affect cane growth in ‘Tulameen’ although cane length was reduced by 20% under the RDI-60% regime, compared to Ww values. The continuous RDI-60% and RDI-70% regimes also slowed cane extension growth of ‘Autumn Treasure’ but the period of cane growth was extended so that overall cane length was similar in all three irrigation treatments at the end of the growing season. Other shoot physiological responses to RDI were detected and this confirmed that the severity of the RDI regimes were sufficient to alter shoot growth and physiology. However, our results over two cropping seasons suggest that the effects of the two RDI regimes on cane vigour were inconsistent and a more severe RDI regime (e.g. RDI-50%) would be needed to control cane vigour reliably and consistently.

However, given the marked effects of the continuous RDI-60% and RDI-70% regimes on marketable yields (see below), there would seem to be little commercial value in testing this approach.

On some particularly vigorous varieties, current commercial practice is to withhold water at specific developmental stages to impose transient wilting. This can effectively reduce cane vigour without affecting marketable yields. This approach (termed Transient Deficit Irrigation) has also been used successfully at EMR to control growth, increase antioxidant capacity and extend shelf-life potential of strawberry[7] and other crops[6]. Although the 'wilting' regime is apparently very effective at controlling excessive cane vigour if applied at the correct developmental stage, the effects of this treatment on total marketable yields are not yet known.

Effects of RDI regimes on marketable yields

It is well known that if RDI regimes are too severe, yields and quality of marketable fruit can be reduced. Nevertheless, we have shown in substrate and soil-grown strawberry, and in a range of other crops, that if mild RDI regimes are imposed judiciously, both water use efficiency and product quality can be improved without reducing marketable yields. Previous work with RDI on raspberry[12] showed that water use efficiency could be improved without reducing marketable yields; in that study the effect of the RDI regimes on aspects of berry quality were not determined. In this project, the aim was to determine whether RDI could be used to control excessive cane vigour without reducing marketable yields or quality. In experiments at EMR in 2011, RDI regimes of differing severity were imposed throughout the growing season; yields of marketable fruit were generally reduced under the RDI regimes although the treatment differences were not always statistically significant. 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. In 2012, unacceptable losses in marketable yields were seen under both RDI regimes in 'Tulameen' and 'Autumn Treasure'; this was due to significant reductions in berry number and average berry fresh weight, respectively. Given the losses of marketable yields that occurred when RDI regimes of differing severity were imposed throughout the season, further developmental work was carried out in 2012 to test the potential of using short-term RDI at specific stages during plant and crop development to try to control cane vigour without reducing yields. Although yields of 'Tulameen' were not significantly affected by the RDI regimes imposed during different developmental stages, the loss of between 29% and 40% of marketable yield compared to the Ww value means that this approach would not be suitable to control cane length in commercial production systems. Losses of marketable yield in 'Autumn Treasure' under short-term RDI were also significant.

Overall, our results indicate that RDI cannot be used as a method to control cane vigour without reducing marketable yields. Although the severity of RDI could be increased to limit cane extension growth, the losses of marketable yield would be unacceptable.

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 SF Technical Manager, SF Communications 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 SF 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.

Conclusions

- A new irrigation scheduling regime has been developed using irrigation set point based on coir volumetric moisture contents. This approach has the potential to deliver significant water and fertiliser savings in commercial ‘Tulameen’ and ‘Autumn Treasure’ raspberry production without reducing marketable yields or quality
- Water productivities obtained using this approach were 89 and 96 L of water used to produce 1 kg of marketable fruit for Ww ‘Tulameen and ‘Autumn Treasure’, respectively
- The scheduling approach now needs to be tested in experiments on commercial growers’ sites with a high background EC in the irrigation water. This work would help to determine whether the reduced water inputs and associated loss of ‘flushing’ causes EC to rise in the substrates to the extent that plant growth and marketable yields are affected
- Although irrigation can be scheduled effectively using estimates of ET, gravimetric

water losses and crop co-efficients in scientific experiments, this approach is not practical for use in commercial raspberry production

- RDI-60% and RDI-70% regimes did not limit cane growth in ‘Tulameen’ and marketable yield was reduced by up to 40%
- RDI-60% applied to ‘Tulameen’ at the beginning of the fruiting phase did not limit extension growth of new canes but marketable yields were reduced by 20%
- The severity of RDI needed to limit cane extension growth in ‘Autumn Treasure’ also reduced marketable yields
- Applying an early RDI-60% regime to ‘Autumn Treasure’ and then switching to a Ww regime during fruiting did not limit cane extension growth but did reduce marketable yields
- The use of RDI is not recommended for the control of cane vigour in substrate-grown ‘Tulameen’ or ‘Autumn Treasure’
- The effects of very short-term ‘wilting’ treatments on cane extension, fruit yields and quality need to be determined and incorporated into the water-and fertiliser-saving irrigation strategy developed in SF 118

Knowledge exchange and technology transfer activities

- The project aims, objectives and results were presented to BIFGA during a visit to EMR, 25 April 2012
- Project aims, objectives and results were presented in a feature article for the HDC News in June 2012
- The project aims, objectives and results were presented at the Kent Water Summit: Water security for Farmers and Growers, 12 November 2012, EMR
- The project aims, objectives and results were presented at the HDC / EMRA Soft Fruit Day at EMR, 22 November 2012
- The project aims, objectives and results were presented during a visit to Angus Soft Fruit Ltd, 7 February 2013, Dundee

Overall Project results

- Several surrogate measures of plant water use were tested and regression analysis was used to determine correlation coefficients and the % variance in water use explained by the measured plant variables
- It was not possible to derive a single regression equation to enable irrigation to floricanes and to primocanes. Separate regression equations were derived for single or groups of cvs

- Total leaf area gave the highest correlation coefficient for both floricanes and primocanes and this measure is likely to be the most accurate plant variable (apart from direct gravimetric measures of plant water loss) on which to base irrigation scheduling. However, it would not be practical to carry out repeat estimates of total plant leaf area with the necessary accuracy on a commercial crop
- Scheduling irrigation using proxy measures of plant transpirational leaf area resulted in over-irrigation, increased cane vigour in ‘Tulameen’ and ‘Autumn Treasure’ and significant wastage of water and fertilisers
- In our experiments with ’Tulameen’ and ‘Autumn Treasure’, marketable yields were influenced by the total volumes of water and fertilisers applied. Higher yields were achieved with excessive water and fertiliser inputs than when irrigation was scheduled to match demand with supply
- Irrigation scheduling based on derived upper and lower coir volumetric moisture contents has the potential to deliver significant water and fertiliser savings in commercial ‘Tulameen’ and ‘Autumn Treasure’ raspberry production without reducing marketable yields and quality
- The severity of long-term RDI needed to limit cane extension growth will also reduce marketable yields

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