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Project leader:	Dr Mark A. Else
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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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31 March 2011

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Contents

Page

GROWER SUMMARY

Headline

- Irrigation of 'Tulameen' during vegetative growth could be scheduled effectively for much of the season using a simple equation relating total cane length to daily evapotranspiration.

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. 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. There is also increasing concern over the contribution of substrate soft fruit production to groundwater pollution. Recent research at EMR and elsewhere has provided major opportunities to use water and fertilsers more efficiently while continuing to meet consumer demand for sweet fruit with good flavour and shelf-life.

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

There are two aims to this project:

1. To improve water and nutrient use efficiencies in substrate-grown raspberry production.
2. To use RDI as a tool to control cane vigour and improve fruit quality.

Expected deliverables from this work will include:

- Reduced production costs per tonne of class 1 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

Two experiments were set up in a polytunnel at EMR to develop new irrigation scheduling tools for use in substrate-grown raspberry production (Figure GS1). Irrigation was scheduled to five floricane varieties ('Tulameen', 'Octavia', 'Glen Ample', 'Glen Doll', 'Cascade Delight') and 'and four primocane varieties ('Autumn Treasure', 'Erika', 'Polka' and 'Sugana') grown in pots of coir. Crop coefficients for each variety were calculated each week over the growing and cropping season by weighing plants and pots to determine water loss over 24 h. These coefficients were used in conjunction with daily estimates of potential

Figure GS1. Polytunnel experiments with potted primocane and floricane plants. Photo taken on 9 July 2010 evapotranspiration (*ETp*) to schedule irrigation to match demand with supply. Consequently, run-through was either reduced or eliminated and coir moisture content was maintained at optimal levels for each variety throughout the season (Figure GS2). Although substrate EC gradually increased over the season, periodic flushing with calcium nitrate solution removed accumulating 'ballast' ions and lowered substrate EC (Figure GS2).

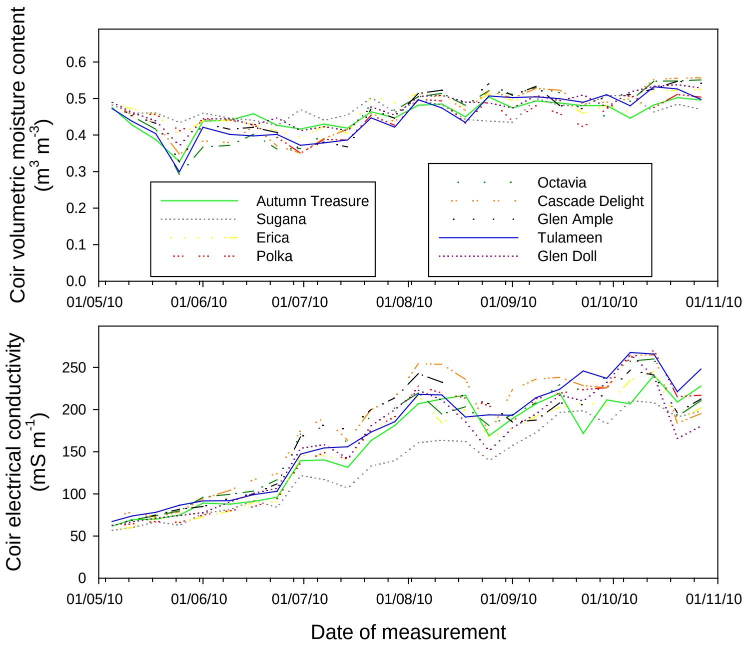

Figure GS2. Coir volumetric moisture content and EC measured at weekly intervals over the season in potted primocane and floricane plants

Several plant variables (total leaf area, plant height, total cane length) were measured over the season to try to identify surrogate measures of plant water use that could be used by growers to schedule irrigation to commercial crops. Regression analysis was then 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 flori-canes and to primocanes. Separate regression equations were derived for single or groups of varieties.

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.

Although the other measured variables (plant height and total cane length) explained between 59 and 80% of the variance in plant water use, they could only be used to schedule irrigation whilst extension growth continues. Once growth ceases, irrigation demands would tend to be overestimated in some primocane and floricane varieties using these crop coefficients. This is because the plant variables would remain constant while plant water use would decrease gradually due to leaf senescence and abscission. However, cane extension growth in 'Tulameen' continued until early October so the regression equation relating total cane length to plant water use could be used to effectively schedule irrigation throughout much of the season (but see below).

A caveat with using crop coefficients to schedule irrigation is that they may need to be determined in successive seasons if crop load differs during development. For example, the crop coefficients for the floricane varieties were derived in the year of establishment when plants were vegetative. Work with strawberry at East Malling Research has repeatedly shown a sudden and sustained demand for water during cropping that occurs despite a relatively constant leaf area. Therefore, any crop coefficient based on plant variables measured during the vegetative phase may underestimate plant water demand during the reproductive phase (Figure GS3). The derived regression equations will be used to schedule irrigation to cropping ‘Autumn Treasure’, ‘Polka’ and ‘Tulameen’ in polytunnel experiments at EMR in 2011 to to assess the effectiveness of this approach.

Figure GS3. The sudden and sustained increase in water demand that coincides with cropping must be accounted for in any irrigation scheduling tool

Due to the uncertainty over the accuracy with which irrigation could be scheduled using the regression, it would perhaps be prudent to develop an alternative irrigation scheduling tool for use in commercial raspberry production. An approach that has been used with great success in other HDC-, Defra-, HortLINK- and industry-funded work is to maintain volumetric substrate or soil 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. This approach will be used in conjunction with scheduling using the regression equations to develop RDI regimes for ‘Autumn Treasure’, ‘Polka’ and ‘Tulameen’ in trials at EMR in 2011.

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 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]. Legislation designed to safeguard these resources and limit damage to the environment (*e.g.* Water Framework Directive 2000, The Water Act 2003) will place restrictions on future water use and growers will have to demonstrate efficient use of available water before time-limited abstraction licences are renewed. The use of mains water to irrigate soft fruit will become increasingly expensive and environmentally undesirable as water companies strive to maintain supplies.

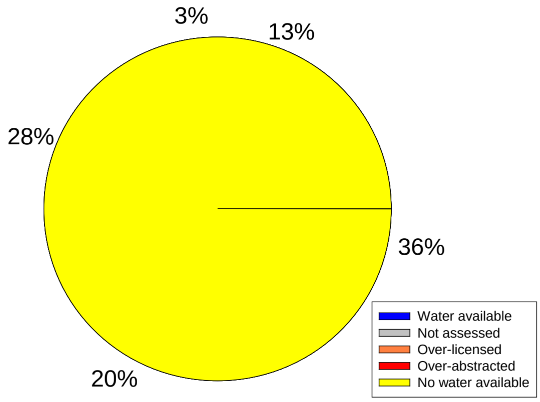

Figure 1. Assessment of water resource availability (for direct abstraction) for the soft fruit sector in 2008 (re-drawn from Knox *et al*., 2009).

Feeding continuously with every irrigation event is also recommended[2] but this approach is also unsustainable. The major soft fruit growing regions are, or will soon be, designated as Nitrate Vulnerable Zones (NVZ's) 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. In future, growers will have to limit their inputs to comply with legislation (The Nitrates Directive Action Programme). There is also a financial driver to reduce inputs; fertiliser prices have doubled in recent years and costs of production could be significantly reduced by using fertilisers more efficiently.

In addition to facilitating compliance with legislation, new irrigation guidelines that improve water and nutrient use efficiency could also be expected to improve the consistency of supply of high quality, healthy fruit with good shelf-life. 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.

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 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 thresholds 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 (ETp) 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 ETp 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, this approach is not feasible for commercial crops 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 *ETp* 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. 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 successfully established coefficients for a range of ornamental crops[10]. Therefore, one aim of this project 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 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. The appropriate percentage deficit must first be determined to avoid potentially deleterious effects such as lower yields or increasing substrate EC above acceptable levels. This work is scheduled to begin in Spring 2011.

Materials and Methods

Plant material and experimental location

Bare-rooted short canes of the cvs 'Glen Ample', 'Tulameen', 'Octavia, 'Cascade Delight' and 'Autumn Treasure' were obtained from RW Walpole Ltd and 'Glen Doll' was sourced from Welsh Fruit Stocks. Canes were delivered to EMR in mid-March 2010 and the roots were placed immediately into moist compost and stored at 2°C until needed. Rooted cuttings of ‘Erika’, ‘Sugana’ and ‘Polka’ were supplied in 9 cm pots from Hargreaves’ Plants Ltd on 1 April 2010 and placed in a polytunnel until needed; plants were hand-watered as necessary. Unfortunately, many plants of the cv. ‘Sugana’ established very poorly and these plants subsequently grew very slowly or died.

Figure 1. Polytunnel with experimental potted primocane and floricane plants laid out in the centre two rows. Photo taken on 9 July 2010.

Ten plants of each cultivar (cv.) were planted in to pots with washed coir supplied by Mr Tim Chambers, Belks Farm, on 21 April 2010. Floricane cvs were planted into 7.5 L pots whilst the primocane cvs were planted into 10 L pots. An additional 80 plants each of ‘Tulameen’ and ‘Autumn Treasure’ needed for experiments in 2011 were also potted in to 7.5 L and 10 L pots, respectively. 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 (Figure 1). The experimental plants were placed in the centre two rows with a pot centre spacing of 37 cm within rows and 140 cm between rows. There were 45 experimental plants in each row (five of each cv.) and the remaining four plants were used as guard plants. During the first two weeks of establishment, plants were hand-watered as necessary; irrigation was then applied to each pot *via* a 4 L h^{-1} pressure compensated emitter. Initially, drip irrigation was applied twice a day to maintain pot weights within upper and lower limits that ensured an optimum coir moisture content. From 3 June 2010, irrigation was scheduled using daily estimates of ETp and crop coefficients (see below).

On 15 June 2010, when new shoots were emerging, the old short cane on the floricanes was cut back to coir level, thereby removing all flowering laterals. Three weeks later, the number of canes per pot was reduced to four canes by removing the smallest and weakest canes.

Throughout the experiment, all plants received the standard EMR pest and disease spray programme. In addition, plants were sprayed with Masai at 75 g per 100 L on 28 July 2010 to control red spider mite, and with Roval / Copper / Cuprokylt on 4 October 2010 to control spur blight.

Experimental design

Two experiments were conducted simultaneously during 2010, one on the five floricane cvs and the other on the four primocane cvs. Each experiment was set up as a complete randomised block design, with one of each cv. in each block (Figure 2). There were ten blocks for each of the experiments, however only six blocks were used for routine measurements, Experimental plants were placed in rows 2 and 3 and the additional 'Tulameen' and 'Autumn Treasure' plants were placed 'pot thick' into rows 1 and 4 to act as guard rows for the 2010 season.

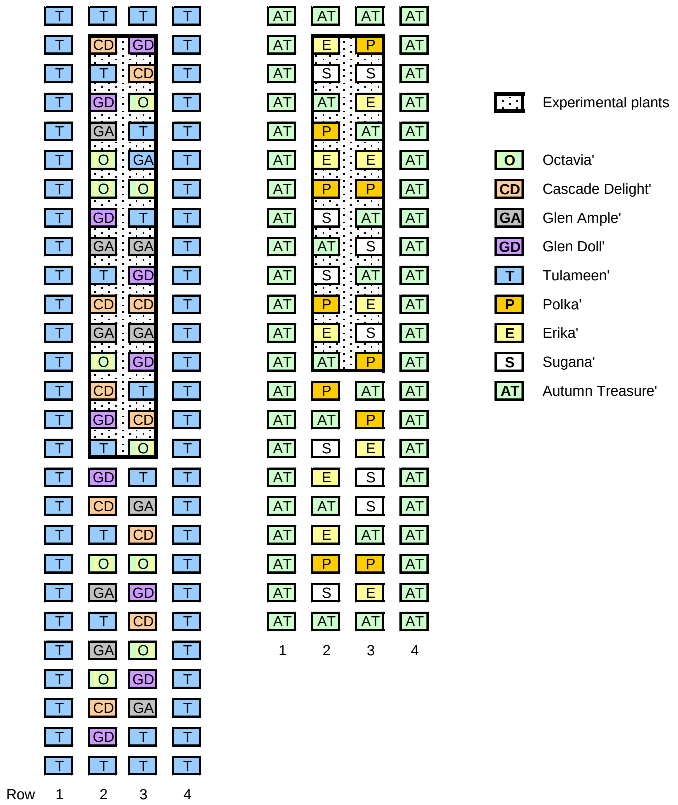

Figure 2. Plot plan showing the randomised block design for each experiment. All routine measurements were made on experimental plants in rows 2 and 3. Rows 1 and 4 were designated as guard rows.

Irrigation application and scheduling

The timing and duration of irrigation events was controlled using 3 Galcon DC-4S units (supplied by City Irrigation Ltd, Bromley, UK) connected to a manifold housing ten DC-4S ¾" valves (Figure 3). 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. The frequency and duration of daily irrigation events was adjusted throughout the season to ensure that run-through was minimised as plant water demand, and therefore irrigation volume, increased. The frequency of daily irrigation events was increased from two to three on 29 June 2011, and from three to four on 17 July 2011.

Figure 3. The Galcon timers used to control irrigation. Photo taken on 9 July 2010

Irrigation scheduling was first applied on 3 June 2010. 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 correlate *ETp* values with plant water demand is described below.

Figure 4. The Skye Evaposensor and Evapometer used to estimate daily potential evapotranspiration. Photo taken on 15 July 2010.

Determining crop coefficients

To calculate the appropriate amount of irrigation water to apply to each of the cvs, separate crop coefficients that related gravimetric estimates of plant water use to the accumulated *ETp* over 24 h were calculated each week. 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 daily irrigation events replaced the volume estimated to have been lost on the previous day. The weekly crop coefficients (g of water lost per degree hour) calculated for the five floricane and four primocane cvs are given in Appendix 2.

One aim of the project was to develop a suitable ‘proxy’ measure of plant water use that could be used as a crop coefficient in conjunction with estimates of ETp to schedule irrigation to commercial substrate-grown raspberry crops. The suitability of candidate ‘proxy’ measures such as total leaf area, plant height, total cane length and total cane plus lateral length were tested (see below).

Fertigation

The same concentration of nutrients were applied to all cvs and was 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, 14.5% NO_3-N, 1.0% NH_4-N) and a second for the Hortipray ‘Mars’ (6-11-37, 4 MgO, and trace elements) and magnesium sulphate (Hortipray, 9.6% Mg). 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. 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.

Initially, a diluted feed solution (1:200) was applied during establishment to avoid 'root scorch'; the feed concentration was then increased weekly until 17 June 2010 after which a dilution of 1:100 was applied. The EC and pH of the diluted feed solution were measured weekly at the drippers along with the volume of water emitted, the EC and volume of any run-off from the compost was measured twice weekly. Compost EC was also measured weekly with a Delta-T WET sensor (see below); when values reached 2.2 to 2.5 mS cm^{-1}, all pots were flushed through with calcium nitrate solution to flush out 'ballast' ions and lower substrate EC.

Table 1. Nutritional analysis of feed diluted 1:100 (including background water and nitric acid).

Nutrient	Concentration in diluted feed (mg L^{-1})
NO_3-N	125
NH_4-N	4
P	33
K	205
Ca	151
Mg	27
B	0.21
Cu	0.14
Fe	1.38
Mn	0.60
Mo	0.03
Zn	0.66
EC (mS cm^{-1})	1.74

Volumetric substrate moisture content and EC

Weekly measurements of volumetric substrate moisture content (VSMC) and substrate EC were made with 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 (Figure 5) 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 N and on the S side of each pot. This approach generated a detailed profile of changes in coir moisture content around the developing root system within each pot.

Figure 5. Insertion points for the WET sensor probe on the N side of the pot. Photo taken on 9 July 2010

Measurement of physiological parameters

All routine measurements were carried out on six experimental plants per cv. These measurements began on 24 June 2010 and continued until 29 October 2010. Whole-plant transpiration rates (*E*) were estimated gravimetrically every two weeks after correcting for evaporative losses from the coir surface. Stomatal conductance (g_s) of one young, fully-expanded, leaf per experimental plant was also measured fortnightly with a steady-state porometer (EGM-1, PP Systems, UK) 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 fortnightly using a Skye SKPM 1400 pressure bomb (Skye Instruments Ltd, UK); leaves were sealed inside the pressure chamber within 30 s of excision.

Non-destructive estimates of plant leaf area were made fortnightly for six experimental plants per cv. To increase precision and ensure reproducibility, a visual key was developed (Figure 6) in which raspberry leaves were graded according to size on a scale from 1 (smallest = 12 cm^2) to 9 (largest = 291 cm^2). This key was used to determine the number of leaves in each size category on each plant, and total leaf area of each plant was then estimated. 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. Plant height measurements were made twice weekly, with all canes in a pot measured. The length of any laterals that developed from the canes was also measured weekly but these measurements were only begun on 27 July 2010.

Figure 6. Leaf area key for grading leaves according to size. Photo taken on 11 November 2010

Fruit yields and quality

Although fruit yields and quality were not due to be assessed in the first year of the project, all ripe berries from fruiting plants were harvested twice a week. Fruit number and berry fresh weight from each plant was recorded. Juice was extracted from three ripe fruit from each fruiting plant and soluble solids content (SSC [%BRIX]) was measured with a digital refractometer (Palett 100, Atago & Co. Ltd, Tokyo, Japan).

Statistical analyses

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

To assess the extent of the correlation between water use and the measured parameters of total leaf area, total cane length and plant height, linear correlation coefficients were calculated for each cv. In total, ten sets of measurements were made at two-week intervals throughout the season. Log transformation of both plant water use (g per degree h) and the measured parameter (total leaf area, plant height or total cane length) was needed to generate the necessary linear relationships. To account correctly for the autocorrelations within plants (data points over time within the same plant are likely to be more highly correlated than points from different plants), a linear relationship (equation 1) was first fitted to each plant separately and the corresponding slope parameter (b) was then analysed with respect to cv. and block.

$$\log(\text{water use}) = a + b^{*}\log(\text{measured parameter}) \qquad (1)$$

Although total cane length plus lateral lengths were also measured at intervals during the season, there were too many missing values to carry out a statistically rigorous analysis and, in any case, the correlation coefficients for the data present were similar to those generated using total cane length.

The % variance in water use associated with each linear correlation coefficient was also calculated for each cv. - the higher the % variance value, the more accurate the estimate of plant water use would be using that measured parameter.

Results

Irrigation scheduling

For each cv., the frequency and duration of daily irrigation events were set to replace the volume of water estimated to have been lost over the previous 24 h. This was achieved by multiplying the daily degree hours by the crop coefficient based on gravimetric measurements of plant water loss. Crop co-efficients were re-calculated weekly to account for changes in total leaf area and so the rise and fall of the crop coefficient value over the season mirrored that of total leaf area. Crop coefficients for four of the floricanes were very similar but values for 'Glen Doll' were very much lower (Figure 7A). Crop coefficients for 'Sugana' were also much lower than those for the other three primocane cvs (Figure 7B).

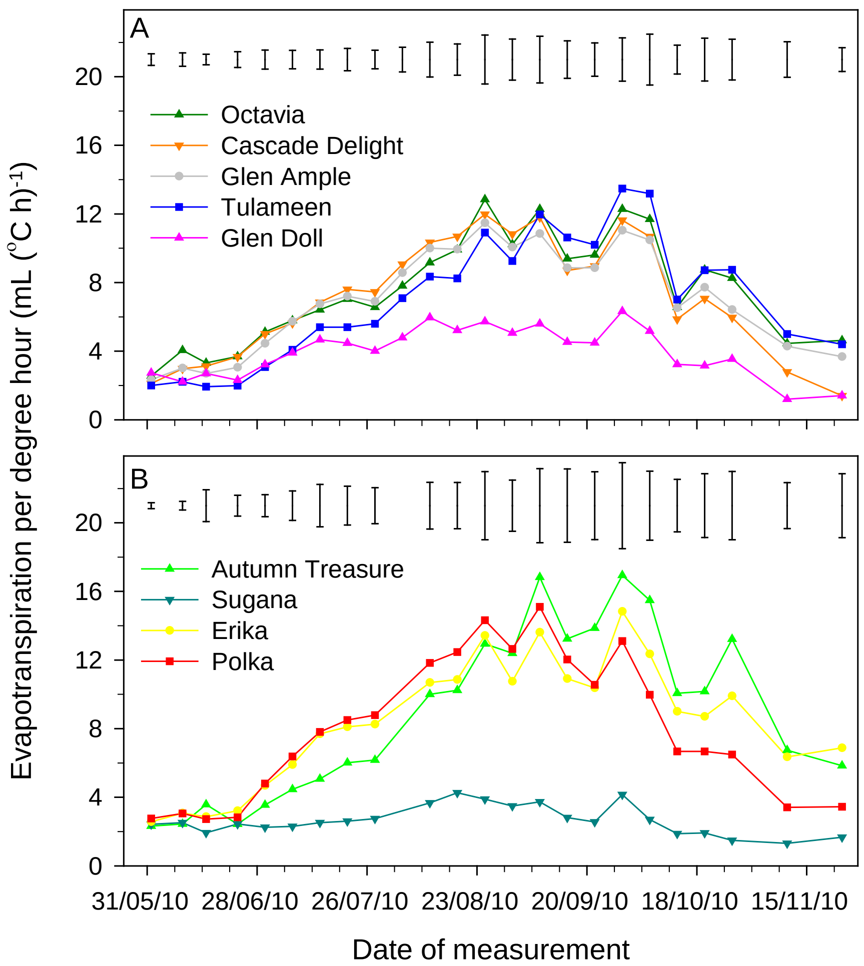

Figure 7. Changes in the crop coefficients for A) floricanes and B) primocanes over the season. Results are means of six replicate plants per cv.; vertical bars are LSD values for *p*<0.05.

Pot weights, VSMC and substrate EC

Matching water demand with irrigation supply using estimates of daily *ETp* and crop coefficients derived from gravimetric measurements of plant water loss effectively maintained plant-and-pot weights at optimum levels for each cv. throughout the experiment (Figure 8). This approach reduced run-through to between 1 and 7% over the season for most cvs and, consequently, substrate EC increased steadily (data not shown). However, flushing through with calcium nitrate to remove 'ballast' ions and lower substrate EC was only necessary on two occasions when EC rose above 2.5 mS cm^{-1}. Average VSMC increased gradually under the irrigation scheduling regime over the season for both floricanes and primocanes although the rate of increase was greatest in floricanes (Figure 9).

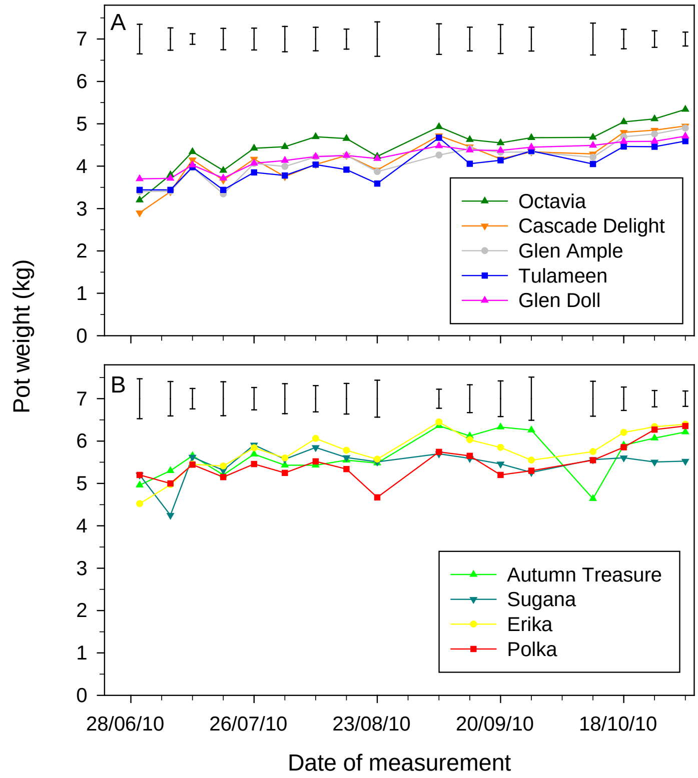

Figure 8. Changes in pot weight for A) floricanes and B) primocanes. Results are means of six replicate plants per cv.; vertical bars are LSD values *for* $p<0.05$.

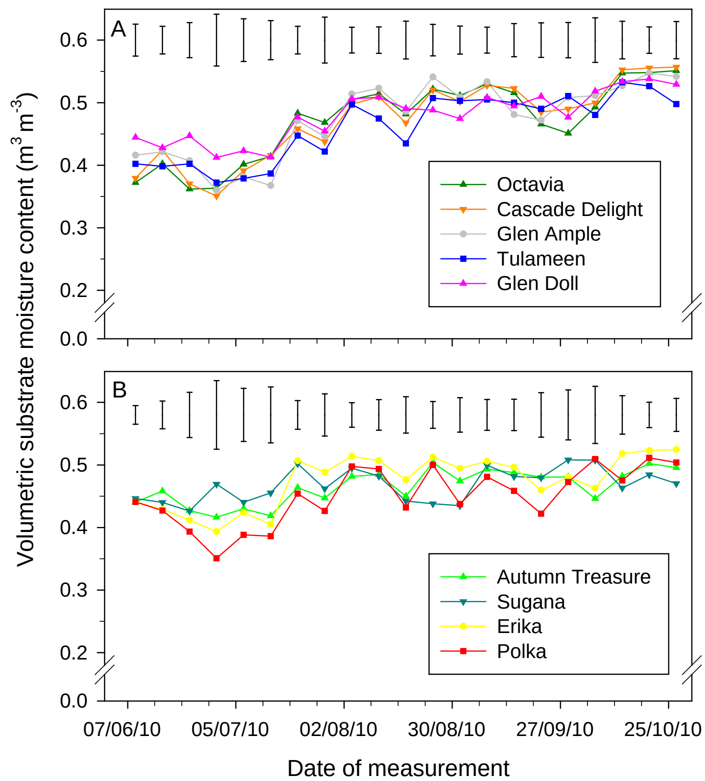

Figure 9. Changes in average pot VSMC for A) floricanes and B) primocanes. Results are means of six replicate plants per cv.; vertical bars are LSD values at $p<0.05$.

Plant physiological responses

Frequent measurements of *E*, g_s and ψ_L indicated that all plants received sufficient water under the irrigation scheduling regimes and did not experience any substrate moisture stress (data not shown). This was confirmed by the rates of leaf elongation measured in successive leaves sampled over three months from June until the end of August (Figure 10), although leaf growth slowed naturally as the season progressed. Total canopy areas increased steadily over the season in all cvs, although the extent of the increase and the time at which total canopy area peaked varied between cvs (Figure 11). Total canopy areas then decreased throughout September as leaves began to senesce and abscind. Plant heights increased steadily until the end of August after which time heights remained fairly constant (data not shown); the exception was cv. 'Tulameen' which continued to grow until mid September. Similar patterns of growth were evident for total cane length in the floricane and primocane cvs; total cane lengths remained relatively constant after mid-September (data not shown). The cessation of cane extension growth at a time when plant water use continued to change has important implications for the suitability of the plant height and total cane length variables as crop coefficients for use

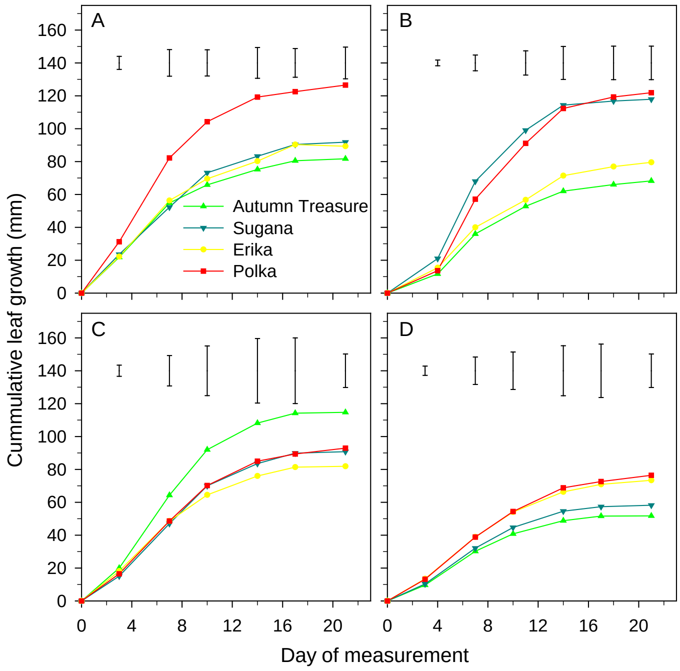

Figure 10. Accumulated leaf growth measured on expanding leaves, with day 0 being A) 6 June, B) 23 July, C) 10 August and D) 31 August, for each primocane cv. Results are means of six replicate plants per cv.; vertical bars are LSD values for $p<0.05$.

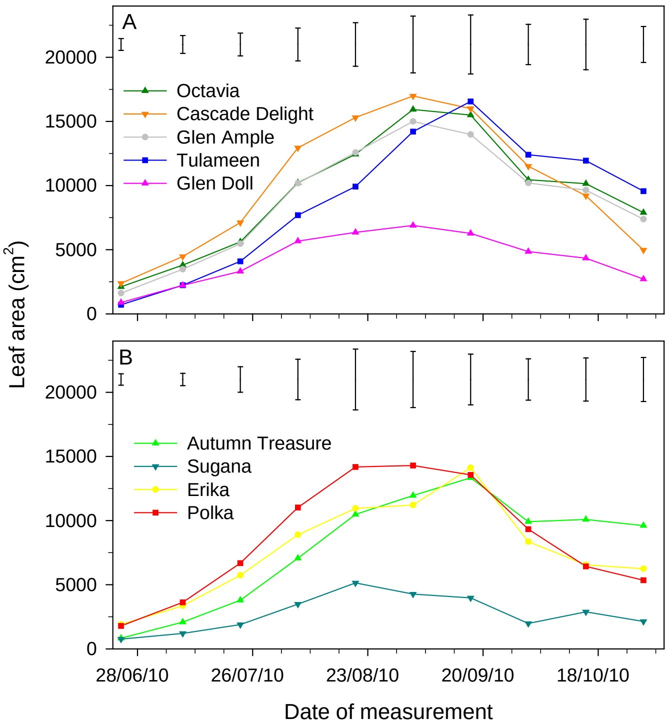

Figure 11. Changes in plant leaf area for A) floricanes and B) primocanes. Results are means of six replicate plants per cv.; vertical bars are LSD values at $p<0.05$.

in effective irrigation scheduling (see below). Leaf chlorophyll contents were similar in all cvs (data not shown).

Water and fertiliser use

Total irrigation volumes applied to each plant of each cv. over the 2010 season are given in Table 2. How these volumes compare to those applied to commercial crops is not yet known. However, current industry water use will be soon be established once completed water use questionnaires have been received and collated from a target group of substrate raspberry growers.

Table 2. Volumes of water (L) applied to each plant of each cv. over the season (3 June to 31 October 2010) using crop coefficients and daily estimates of *ETp* to schedule irrigation.

Cultivar	Average daily volume applied (ml)	Total volume of water applied (L)
'Autumn Treasure	548	82
'Erika'	670	101
'Polka'	582	87
'Sugana'	237	36
'Cascade Delight'	562	84
'Glen Ample'	543	81
'Glen Doll'	333	50
'Octavia'	543	81
'Tulameen'	453	68

In the 2011 season, values of water productivity (the volume of water used to produce 1 tonne of class 1 fruit) will be calculated from cropping 'Autumn Treasure', 'Tulameen' and 'Polka' crops to which irrigation has been applied using the scheduling tools developed in this project. Potential water savings delivered by effective irrigation sched-uling will then be compared to those achieved using current industry 'standard' and 'best' practice.

Fertiliser use was estimated by multiplying the concentrations in the diluted feed (Table 1) by the volume of water applied to each cv. over the season (Table 2). An estimated 106 g of N, 168 g of K and 27 g of P were applied to each plant of 'Autumn Treasure' over the season. Current industry nutrient use efficiencies will be determined from the completed grower questionnaires.

Calculation of linear correlation coefficients for measured plant variables - floricanes

The aim was to find a simple relationship between water use and other measured plant variables (total leaf area, plant height or total cane length) that, in principle, could be easily measured or estimated. Initially, linear correlation coefficients were calculated for each plant variable using nine of the ten data sets. For floricanes, the most highly correlated variable with water use was total leaf area (0.908), followed by total cane length (0.782) and then plant height (0.693). For primocanes, the linear correlation coefficients were 0.849 for total leaf area, 0.747 for plant height and 0.545 for total cane length. In each case, a relationship of the form *log*(WU) = a + b**log*(m) where m = the measured plant variable was then fitted. These relationships were investigated further in order of decreasing overall correlation for floricanes and primocanes.

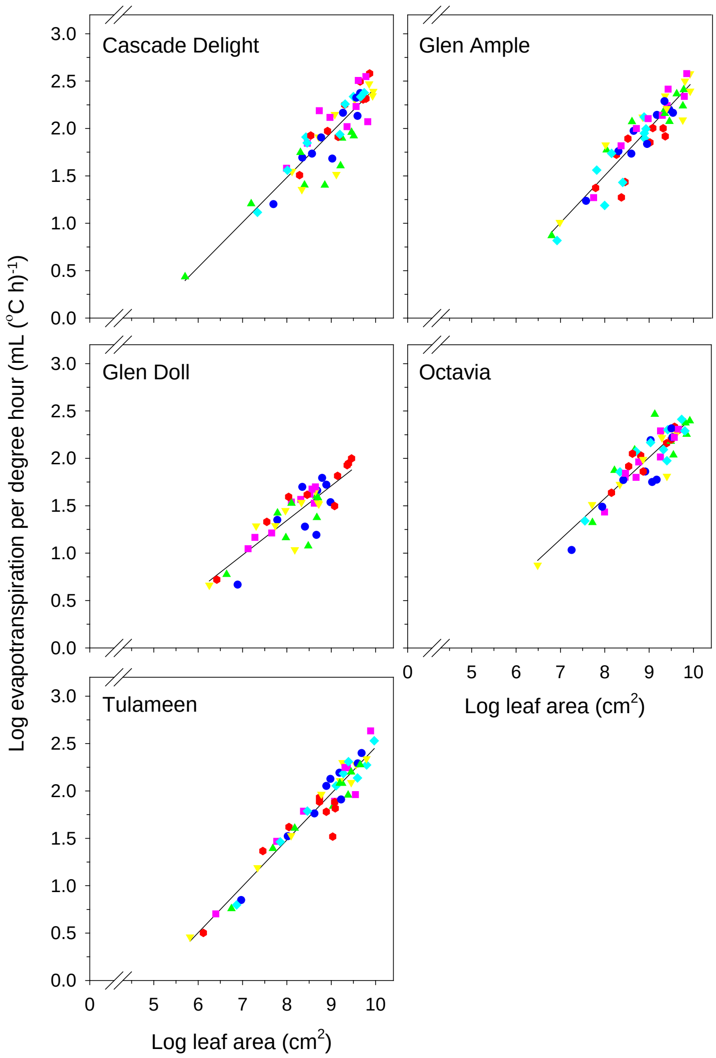

Figure 12. The relationship between evapotranspiration per degree hour and leaf area for each floricane cultivar. Each symbol and colour represents a single plant measured on nine different dates between 24 June and 29 October 2010.

<u>Total leaf area</u>: The 'best fit' of the linear relationship between water use and total leaf area was achieved using nine of the ten data sets (Figure 12); Values for the fitted parameter b are presented in Table 3 along with statistical analyses of the cultivar-specific b values.

There were significant differences in b values between cvs, with 'Glen Doll' being significantly lower than 'Cascade Delight', 'Glen Ample' and 'Tulameen'. The b parameter for 'Octavia was approximately midway between this group and 'Glen Doll' but the difference was not significant. These results suggest that three different b parameters, one for 'Glen Doll', one for 'Octavia' and one for the

Table 3. The value of the slope b, between water use and each of the measured plant variables for each floricane cv. The correlation coefficients and the % variance in water use that could be accounted for by each of the variables are also presented.

Variety	Value of b		
	Total leaf area	Plant height	Total cane length
'Cascade Delight'	0.4753	0.772	0.684
'Glen Ample'	0.4855	0.780	0.659
'Glen Doll'	0.3721	0.617	0.534
'Octavia'	0.4234	0.851	0.691
'Tulameen'	0.4883	0.847	0.698
F-prob	0.005	0.031	0.04
SED (df=19)	0.03093	0.0733	0.0548
LSD (p=0.05)	0.0648	0.1534	0.1147
Correlation coefficient	0.91	0.83	0.90
% variance	84	69	80

other cvs combined should be used to schedule irrigation. The correlation coefficient for total leaf area was 0.91 and the variance in water use accounted for was 84% (Table 3)

Plant height: Plant height remained relatively constant from September onwards but water use began to decrease as the season progressed. Therefore, these two variables were closely correlated only for the first ten weeks of the experiment and so the first five data sets were used to fit the linear relationships (Figure 13). The fitted b parameter was significantly lower in 'Glen Doll' compared to the other cvs (Table 3) while the mean b values for 'Cascade Delight' and 'Glen Ample' were very similar, as were values for 'Octavia' and 'Tulameen'. Differences between these four cvs were not statistically significant so an overall mean b value (0.813) could be used to schedule irrigation to these four cvs. The correlation coefficient for plant height over the ten week period was 0.833 and the variance in water use accounted for was 69% (Table 3).

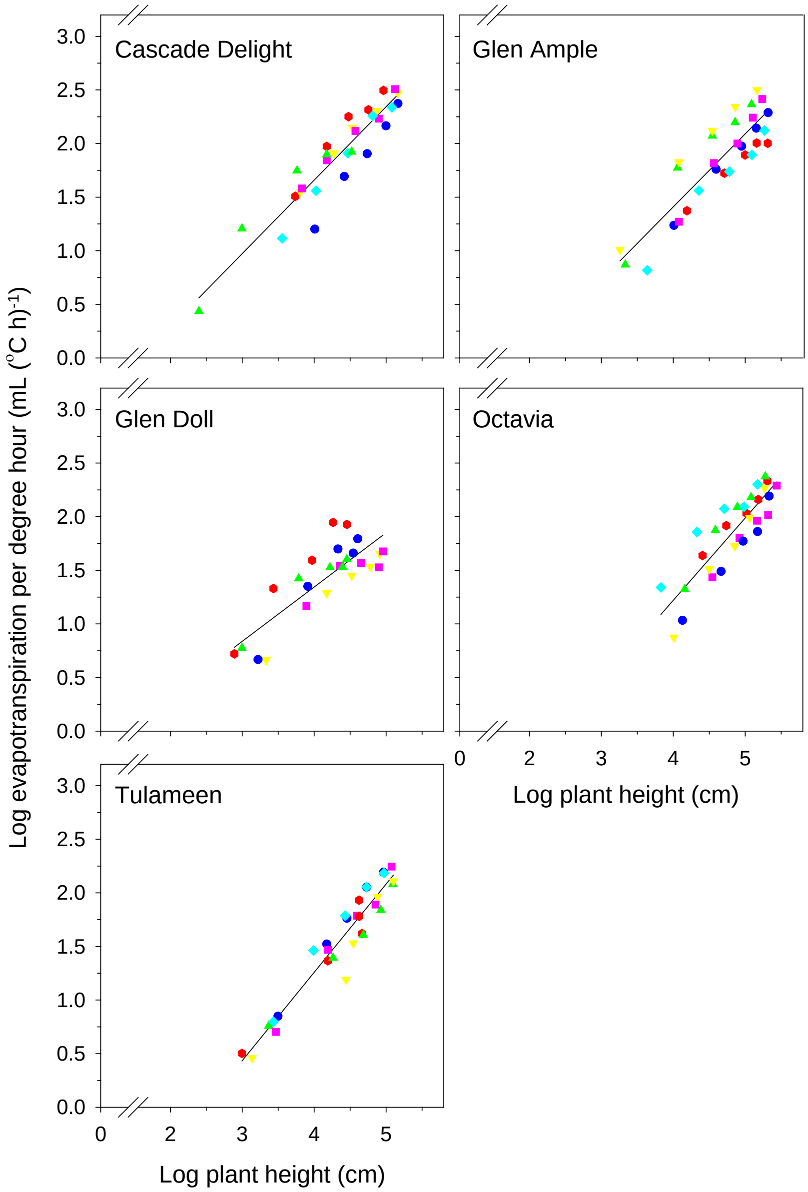

Figure 13. The relationship between evapotranspiration per degree hour and plant height for each floricane cv. Each symbol and colour represents a single plant measured on five different dates between 24 June and 20 August 2010.

Total cane length: Due to the increasingly poor correlation between total cane length and plant water use towards the end of the season, only the first six data sets were used to fit the linear relationships for each cv. (Figure 14). The fitted b value was lowest for 'Glen Doll' and was significantly different to the other four cvs (Table 3). There was no significant difference between b values for the other four cvs and an overall mean b value of 0.683 could be used to schedule irrigation to these four cvs. The correlation coefficient for total cane length over the 12 week period was 0.90 and the variance in water use accounted for was 80% (Table 3)

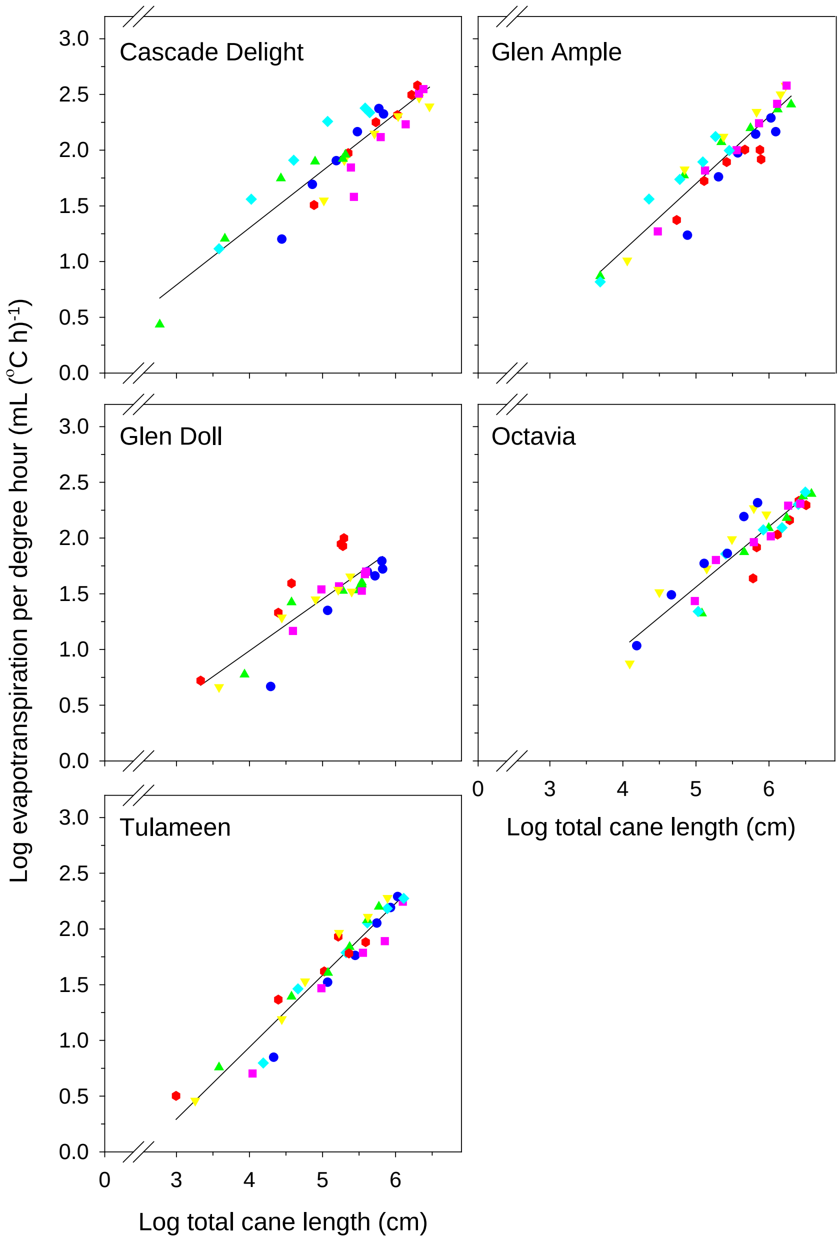

Figure 14. The relationship between evapotranspiration per degree hour and total cane length for each floricane cv. Each symbol and colour represents a single plant measured on six different dates between 24 June and 3 September 2010.

Calculation of linear correlation coefficients for measured plant variables – primocanes

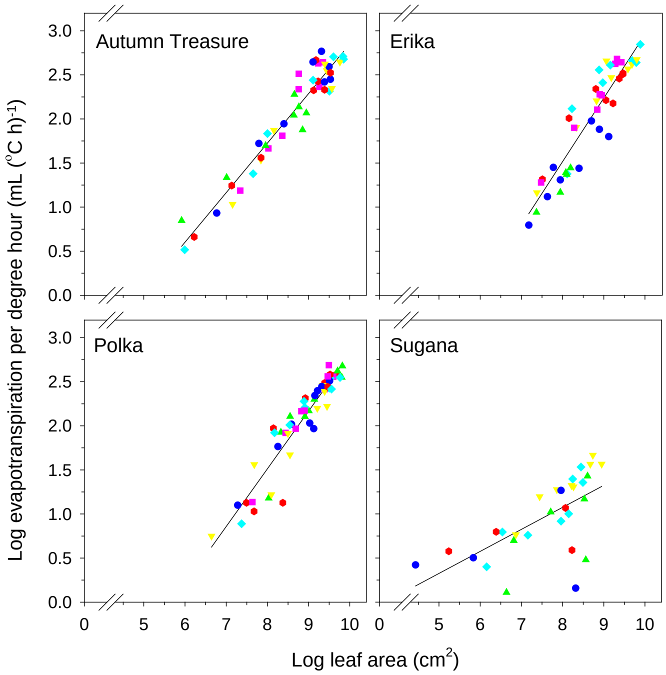

Figure 15. The relationship between evapotranspiration per degree hour and leaf area for each primocane cv. Each symbol and colour represents a single plant measured on nine different dates between 24 June and 29 October 2010.

Total leaf area: For primocanes, the 'best fit' of the linear relationship between water use and total leaf area was achieved using nine of the ten data sets (Figure 15). For primocanes, there were highly significant differences in b values for each cv. because the b value for 'Sugana' was so much lower than the rest. There were no differences in the b value between 'Autumn Treasure', 'Erika' and 'Polka' (Table 4) and an overall mean value of 0.612 could be used to schedule irrigation to these three cvs. The correlation coefficient for total leaf area was 0.85 and the variance in water use accounted for was 78% (Table 4).

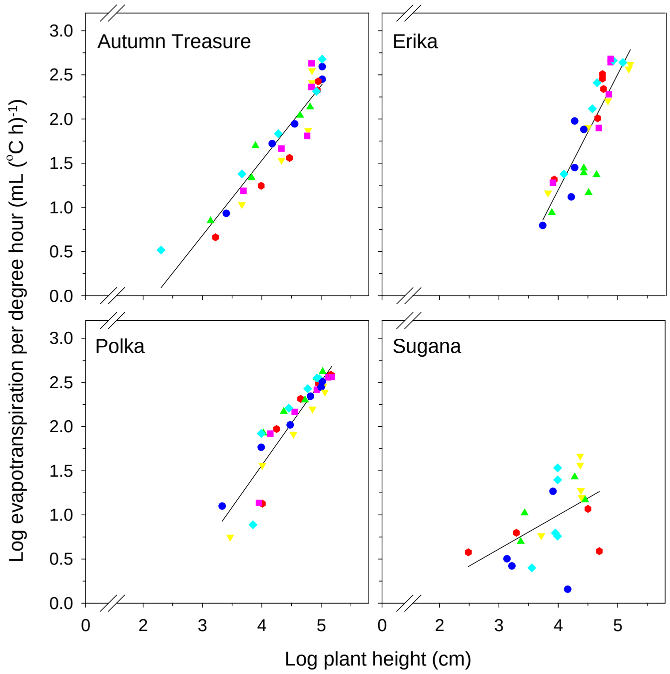

Figure 16. The relationship between evapotranspiration per degree hour and plant height for each primocane cv. Each symbol and colour represents a single plant measured on five different dates between 24 June and 3 September 2010.

Plant height: The first five data sets were used to fit the linear relationships (Figure 16). Differences in b values were not statistically different between cvs (Table 4) due to relatively high variability within each cv. Values of b of 0.971 could be used to schedule irrigation to all four primocane cvs. The correlation coefficient for plant height over the ten week period was 0.88 and the variance in water use accounted for was 77% (Table 4).

Table 4. The value of the slope b, between water use and each of the measured plant variables for each primocane cv. The correlation coefficients and the % variance in water use that could be accounted for by each of the variables are also presented.

Variety	Value of b		
	Total leaf area	Plant height	Total cane length
'Autumn Treasure'	0.581	0.860	0.849
'Erika'	0.601	1.184	0.752
'Polka'	0.654	0.972	0.701
'Sugana'	0.270	0.866	0.316
F-prob	<0.001	0.192	0.002
SED (df=14)	0.0562	0.1591	0.1162
LSD (p=0.05)	0.121	0.3411	0.249
Correlation coefficient	0.85	0.88	0.77
% variance	78	77	59

Total cane length: The first seven data sets were used to fit the linear relationships (Figure 17). Values of b in 'Autumn Treasure', 'Erica' and 'Polka' were similar but significantly different from the b value in 'Sugana' (Table 4). Values of b of 0.316 and 0.767 could be used to schedule irrigation to 'Sugana' and to 'Autumn Treasure, 'Erika' and 'Polka', respectively. The correlation coefficient for total cane length was 0.77 and the variance in water use accounted for was 59% (Table 4).

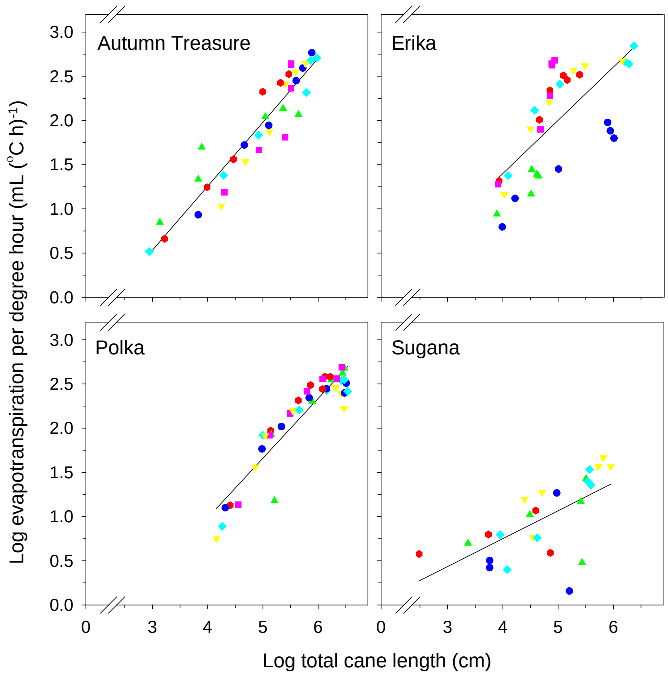

Figure 17. The relationship between evapotranspiration per degree hour and total cane length for each primocane cv. Each symbol and colour represents a single plant measured on seven different dates between 24 June and 17 September 2010.

Assessing the accuracy of the regression equations in estimating plant water demand

The measured plant variables were used in the appropriate regression coefficients to generate estimates of plant water demand for the floricane and primocane cvs. These predicted values were plotted against actual measures of plant water demand based on gravimetric measures of plant water loss (Figure 18). For 'Autumn Treasure' plant water use (g per degree h) would be underestimated from the end of July if total cane length were used and from mid-August onwards if plant height were used. Using this approach, shoot water deficits would soon develop and berry yields and quality would be reduced. For 'Polka', plant water demand would be greatly overestimated if total cane length were used to predict water loss (Figure 18). Using plant height to schedule irrigation would result in over-watering towards the end of the season when leaves were beginning to senesce.

For 'Tulameen', total cane length would appear to be an accurate way of estimating plant water demand for much of the growing season (Figure 18). Irrigation would be overestimated during the last few weeks of the season when leaves began to senesce and abscind.

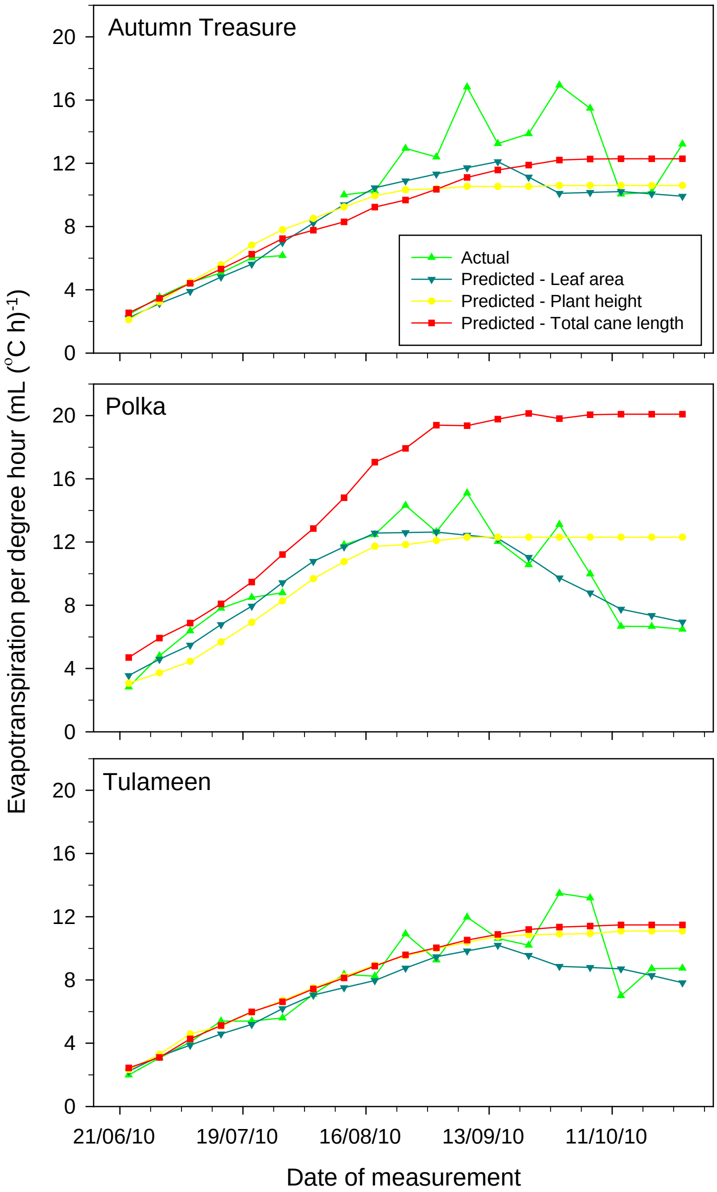

Figure 18. The actual evapotranspiration per degree hour compared with the predicted values obtained using the appropriate regression equations for leaf area, plant height or total cane length, for the cvs 'Autumn Treasure', 'Polka' and 'Tulameen'.

Discussion

Irrigation to the nine raspberry cvs was scheduled effectively to match demand with supply over the season and coir moisture contents were maintained at optimum levels. This approach has been developed over the last seven years at EMR for use with many different substrate-grown crops and consistently delivers significant water savings while maintaining product yields and improving quality. Compared to current industry practice for substrate-grown soft fruit where irrigation is often scheduled to achieve 10-20% run-through, the volume of water draining from the bottom of the pots in our experiments was either greatly reduced or eliminated. There is a general perception amongst agronomists and growers that, under these conditions, substrate EC will rise rapidly to a point where berry yields and quality are reduced. Although substrate EC did gradually increase, flushing with calcium nitrate solution effectively removed the accumulated ions and this was only necessary on two occasions during the season. Results from this project and other HDC-funded soft fruit work[8,9] suggest that scheduling to match demand with supply offers a good opportunity to save both water and fertilisers and to improve the economic and environmental sustain-ability of soft fruit production without jeopardising yields or quality. This approach will be tested further at EMR and at Belks Farm in 2011.

Although crop coefficients based on gravimetric measures of plant water loss can be used to schedule irrigation very effectively, this approach cannot be integrated into commercial substrate raspberry production. Crop coefficients based on plant variables that correlate well with plant water use and can be measured or estimated easily in commercial crops are needed if irrigation is to be scheduled using evaporative demand. The main objective of the first year's work was to develop a generic system that would enable crop coefficients to be determined easily and rapidly for a range of raspberry cvs. Previous work relating canopy density and plant height to water use successfully established coefficients for a range of ornamental crops[10] and so this approach was tested on raspberry.

Of the three plant variables measured, total leaf area showed the highest correlation with plant water use for both floricane and primocane cvs, this was not unexpected since leaf area is a major determinant of plant water loss. However, even with the very accurate approach used to estimate total leaf area developed in this project, this variable accounted for only between 78 and 84% of plant water use. Presumably, this was due to the inevitable inaccuracies inherent in estimating total leaf area and also to the influence of boundary layer resistances on evaporative losses from the leaf surfaces. On a commercial holding, total leaf area would have to be estimated at intervals over the season and this may lead to lower % variances than those achieved under scientific conditions at EMR.

The variance in plant water use that could be accounted for using plant height as the measured variable was 69% and 77% for floricanes and primocanes, respectively. However, because cane extension ceased after August whilst water use continued to change, using this variable to schedule irrigation is likely to lead to over-watering later in the season when leaves are beginning to senesce and water use declines.

Total cane length accounted for 80% and 59% of the variance in plant water use for floricanes and primocanes respectively. Total cane length would be the preferred variable with which to schedule irrigation to floricanes.

Overall, total cane length is the best variable to use to schedule irrigation to floricanes and plant height would be the best variable to use for primocanes. A single regression equation could be used for ‘Cascade Delight’, ‘Octavia’, ‘Tulameen’ and ‘Glen Ample’ (equation 2) and a separate equation used for ‘Glen Doll’ (equation 3)

$$log(\text{water use}) = -1.81 + 0.683*log(\text{total cane length [mm]} \qquad (2)$$

$$log(\text{water use}) = -1.20 + 0.534*log(\text{total cane length [mm]}) \qquad (3)$$

The lower coefficients for ‘Glen Doll’ imply that this cv. uses less water relative to increases in leaf area, plant height and total cane length, compared to the other floricane cvs tested. Further work is needed to determine whether the apparent high water use efficiency is a consistent trait of ‘Glen Doll’ over successive cropping seasons.

For primocanes, a single regression equation could be used for ‘Autumn Treasure’, ‘Erika’ and ‘Polka’ (equation 4) and a separate one would be needed for ‘Sugana’ (equation 5).

$$log(\text{water use}) = -\ 2.16 + 1.005*log(\text{plant height [mm]}) \qquad (4)$$

$$log(\text{water use}) = -\ 2.35 + 0.866*log(\text{plant height [mm]}) \qquad (5)$$

A caveat with using crop coefficients to schedule irrigation is that they may need to be determined each season if crop load differs during development. For example, the crop coefficients for the floricane cvs were derived in the year of establishment when plants were vegetative. Our work with strawberry has repeatedly shown a sudden and sustained demand for water during cropping that occurs despite a relatively constant leaf area.

Therefore, any crop coefficient based on plant variables measured during the vegetative phase may underestimate plant water demand during the reproductive phase. Clearly, this was not a complicating factor in previous work at EMR on developing crop coefficients for ornamental crops[10]. These regression equations will be used to schedule irrigation to cropping 'Autumn Treasure', 'Polka' and 'Tulameen' in polytunnel experiments at EMR in 2011 to assess the effectiveness of this approach.

Due to the uncertainty over the accuracy with which irrigation could be scheduled using equations 2-5, it would perhaps be prudent to develop an alternative irrigation scheduling tool for use in commercial raspberry production. An approach that has been used with great success in other HDC-, Defra-, HortLINK- and industry-funded work is to maintain volumetric substrate or soil 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. This approach will be used in conjunction with scheduling using the regression equations to develop RDI regimes for 'Autumn Treasure', 'Polka' and 'Tulameen' in trials at EMR in 2011.

Proposed amendments to the original work plan

The original intention was to schedule irrigation to a commercial crop of 'Polka' at Belks Farm using the appropriate regression equation (equation 4). However, we feel that it would be prudent to first test the accuracy of this approach in scientific trials at EMR. Scheduling irrigation to the commercial crop at Belk's Farm could, instead, be carried out using gravimetric measures of plant water use to derive crop coefficients that could be used with estimates of daily *ETp* as described above. Crop coefficients would be determined weekly by the EMR project team to ensure that irrigation demand was matched with supply. Water use efficiencies and water productivities obtained using this approach could then be compared to those achieved by the standard irrigation regime at Belks Farm. Volumetric substrate moisture contents in each irrigation regime could also be logged continuously to help inform future irrigation strategies on commercial holdings.

Imposing an RDI treatment on a commercial 'Polka' crop at Belks Farm was also proposed for Year 2 (2011-2012). However, we suggest that this trial should be re-scheduled and carried out in project year 3 so that the results of the RDI work at EMR in year 2 can be used to inform the RDI grower trial.

The grower water use questionnaire has been prepared and sent to a few key raspberry growers. Once feedback is received regarding layout and clarity, the questionnaire will be distributed to a target group of substrate raspberry growers and information on water use efficiencies will be collated and analysed. Site visits will be made in summer/autumn 2011 to discuss the results and the potential to reduce water (and fertiliser) inputs in commercial raspberry production.

The proposed amendments will be discussed with Mr Tim Chambers, the project co-ordinators and the HDC Technical Manager prior to the experiment. At this stage, no changes to the project milestones and objectives are needed and project costs will remain the same.

Conclusions

- Crop coefficients derived from gravimetric measures of plant water loss were used in conjunction with daily estimates of *ETp* to schedule irrigation to five floricane and four primocane raspberry cvs
- Using this strategy, coir volumetric moisture contents were maintained at optimum levels and average run-through was reduced to between 1 and 7% for most cvs
- Coir EC rose slowly due to the reduced run-through but flushing with calcium nitrate solution to remove 'ballast' ions and lower substrate EC was necessary on only two occasions over the season
- 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
- Although the other measured variables (plant height and total cane length) explained between 59 and 80% of the variance in plant water use, they could only be used to

schedule irrigation whilst extension growth continues. Once growth ceases, irrigation demands would tend to be overestimated using this approach

- Alternative irrigation scheduling tools for use on commercial raspberry crops are being developed

Technology transfer and knowledge exchange

- Presentation of work to School of Biological Sciences, University of Reading
- Poster at Fruit Focus 2010 (21 July 2010)
- Presentation of the work to Sainsbury's / BBSRC during visit to EMR
- Presentation of the work to Dr Jerry Know *et al*., Cranfield University
- Presentation of the work at Warwick-HRI Water Day II
- Presentation of the work to Dr Sue Popple, Defra
- Presentation of the work to Defra Food and Farming Group
- Presentation of the work at the HDC / EMRA Soft Fruit Day
- Presentation of the work to Board of Directors of EMR and of Stockbridge Technology Centre

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)

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