Project Title	Enhancing the quality of hardy nursery stock and sustainability of the industry through novel water-saving techniques
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Project leader:	Prof. Bill Davies, Lancaster University
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The results and conclusions in this report are based on a series of experiments conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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Grower Summary

- Variation in water use by different sized plants can mask the effect of variable water delivery
- Scheduling using either an Evaposensor or a GP1 is suitable for application of deficit irrigation; thermal imaging also distinguishes clearly between fully irrigated and deficit irrigated crops
- Measured water use per degree hour was found to be similar to that predicted based on plant height and crop cover. Combined with a newly automated system for adjusting irrigation times according to daily Evaposensor readings, this result is encouraging for the less labour-intensive use of the Evaposensor on nurseries
- A software tool for cost-benefit analysis will soon be available to growers to evaluate.
- Alkaline buffers have been tested on nursery to assess their effects and the possibility of integration of their use into a standard propagation protocol.
- Further insights have been gained into the mechanisms behind the chemical changes that occur to sap as it ascends to the leaves.
- Preliminary trials with plant growth promoting rhizobacteria suggest that application of particular strains to rooting substrates can enhance plant quality
- Trialling of the irrigation boom has continued with positive results
- Further progress has been made with sensor development and trialling with the aim of increasing the precision of the assessment of water requirements of plants
- Plant/no plant sensors have been trialled
- The wireless transmission distance of the sensing technology was tested in a greenhouse environment and has been shown to be greater than 50 meters at low power

Headline

Good progress in 2007/8 with optimising existing irrigation systems and improving scheduling using both existing and novel systems.

Effective collaboration between science and industry partners has led to development of new technology which is currently being trialled on a range of nurseries

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Novel science has led to publication in international journals and industry publications

Background and expected deliverables

Legislative pressures and the increasing cost of mains water make it vital for the Hardy Nursery Stock (HNS) industry to increase the efficiency of water use. Furthermore, poor irrigation directly affects profitability by inducing variability within batches of plants which adds to labour costs, particularly for order picking and crop wastage due to small/poor quality plants. Labour costs may increase by up to five times as a result of this variability and manual labour is a diminishing resource within the industry. In addition, reductions of wastage by only one third can increase profitability by up to 300% (source: Hillier Nurseries).

Non-uniformity of water application from the overhead irrigation systems used on most nurseries represents a barrier to reducing wastage. It also hinders the use of Regulated Deficit Irrigation (RDI) and nutrient treatments to control growth and plant development. Identifying cost- efficient ways to substantially improve uniformity of irrigation, combined with optimal systems to monitor and control it, will make a major contribution to maintaining the competitiveness of the UK HNS industry.

The project aims to develop novel ways to effectively apply appropriate quantities of water and nutrients to the crop. This will serve to: (a) Conserve diminishing water supplies; (b) Manipulate plant growth in order to increase the profitability and sustainability of the HNS industry.

The project aims to address problems of poor uniformity of application of irrigation to container-grown nursery stock and the practical application of deficit irrigation and novel chemical (fertiliser) treatments to control growth and water use.

The project is evaluating thermal imaging as a means of sensing plant water status and comparing this with other means of monitoring and controlling irrigation on HNS nurseries and assessing the scope for high precision delivery of water to HNS in containers. To achieve this, the project is building a test rig to evaluate the feasibility of regulating water application to individual plants by using automated sensing of plant water status and automated irrigation delivery.

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A previous ‘Water LINK’ project (HL0132LHN) clearly demonstrated that RDI has considerable potential as a non-chemical growth control agent if the application and regulation of irrigation is sufficiently precise. This project aims to provide more research and development to achieve substantial and reliable water saving while minimising the risk of potentially catastrophic plant water deficits and crop losses. The project is also investigating novel fertiliser treatments, designed to mimic the effect of drought on the plants’ internal signalling systems to reduce growth and water use of well watered plants.

The project is guided by 9 objectives:

1. Assess the potential to increase the precision of water delivery by refinement of existing irrigation systems in comparison with more capital intensive systems (e.g. flood-and-drain, drip or gantry).

2. Optimise methods by which evaposensor and soil water sensing equipment may be used to regulate irrigation/fertigation systems on the nursery.

3. Determine the theoretical and actual performance of thermography and infrared thermometry in direct comparison with other techniques for monitoring HNS irrigation.

4. Develop methods for relatively risk-free application on the nursery of deficit irrigation and novel fertiliser treatments to modify plant morphology, growth and quality.

5. Identify physiological mechanisms underlying plant responses to deficit irrigation and novel fertiliser treatments in order to optimise practical exploitation of such techniques.

6. Identify the relationship between stomatal closure and plant performance for representative HNS species and relate these to their thermal behaviour.

7. Devise, construct and operate test rigs for automated precision irrigation based on thermal stress monitoring to test the feasibility of sensing and

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ameliorating plant stress at a single plant or local level.

8. Develop user-friendly guidelines for application of different methods of stress sensing and plant manipulation in nursery practice and produce 'User Manuals'.

9. Perform cost/benefit analysis of different methods of irrigation, stress sensing and plant growth control to inform investment decisions on nurseries. Report on conclusions of the study.

Summary of the main conclusions

In the third year of this project, the researchers have focused on the following five major areas of investigation and made substantial progress as detailed:

Irrigation scheduling using existing delivery systems

Trials showed that the rate at which pot mass decreased when irrigated at 50% ET_p was more variable under overhead irrigation than under drip. However, the pattern of variation changed rapidly. This suggests that variation in water use by the plants largely masked the effect of variation in water delivery on drying down of the growing medium.

The pattern of differences between soil moisture probes tended to be consistent over many days, but soil moisture content at fixed locations within pots did not appear to provide a reliable estimate of water delivery to the whole pot. As the substrate dries out, differences in the amplitude of wetting and drying cycles (i.e. water delivery) at different points within a pot are to be expected. It was impossible to distinguish such consistent within-pot effects from consistent differences in water delivery to the pot as a whole.

On single days, water delivery to individual plants on the same bed differed by up to 3-fold. Differences were well correlated over time. Placing pots on a disc of MyPex in large saucers, to define the "catchment area" for surface uptake, greatly reduced variability. The effect of raising pots off the floor, thereby preventing surface uptake, was very similar. It appears that the foliage can 'collect' irrigation by intercepting water droplets that are moving with a horizontal component, so that plants with more foliage tend to have greater water delivery. This is supported by a strong correlation between plant height and water delivery.

Although similar water use was metered from the two irrigation systems in use at Palmstead Nurseries, substantially more time was spent hand-watering the crop under the older system than under the new "improved" system. This apparently relates almost entirely to the ability of the new system to get water right up to the edge of the tunnel, as in fact coefficients of uniformity for water deposition, water delivery, and water uptake were very similar in the two systems.

We conclude that the coefficient of uniformity alone is not necessarily a sufficient description of the distribution of irrigation when determining whether a particular irrigation system's output is suitable. Variation in water use by different sized plants can mask the effect of variable water delivery.

Optimising use of the evaposensor and soil water sensing equipment

Water use per degree hour (i.e. crop coefficients for use with the Evaposensor) was found to correlate with plant height and canopy cover for most of the 12 species studied in 2007. An equation describing the relationship was used to predict the water use per degree hour of three species in 2008. Measured water use per degree hour was found to be similar to the prediction. Combined with a newly automated system for adjusting irrigation times according to daily Evaposensor readings, this result is encouraging for the less labour-intensive use of the Evaposensor on nurseries

Both the Evaposensor and GP1s were successfully used to schedule deficit irrigation and thus control plant growth. Based on three years of collecting substrate moisture content data in deficit irrigated crops, it appears difficult to define exact set points for use with the GP1: however, fairly rapid assessment of the average condition of plants across a bed e.g. by weighing pots should allow growers to adjust the GP1 set points to optimise control of deficit irrigation.

GP1s were successfully used with commercial crops to schedule both full and deficit irrigation.

A relatively low-cost thermal camera highlighted the variation in temperature caused by differences in stomatal conductance in crops receiving deficit or control (full) irrigation.

Use of chemicals/soil additives to improve water use efficiency

Cortaderia, *Fatsia*, and *Lonicera* were grouped together in a typical horticultural polytunnel and supplied with both overhead irrigation and hand watering 50 mM phosphate buffer was applied as a foliar spray to half the plants with water sprayed on the remainder as controls for comparison. Stomatal conductance, leaf temperature and plant height measured weekly. Initial results were encouraging with alkaline buffers reducing transpiration when the plants were kept well-watered but no final assessment could be made due to Russell Sharp's road accident.

We investigated at the use of comparatively poorer quality (ionic) water from boreholes, to see whether it could be used to formulate alkaline buffers (or does the natural acidity or impurities block buffer effects or form precipitates when formulated). Although some precipitation formed in buffers formulated with borehole water, this should not represent a barrier to application or mark plants. The ability of buffers to reduce transpiration were unaffected, with water loss per plant lower when buffers were formulated using tap, bore or deionised water. A saving in water use of 14% with the tap water treatment is consistent with the improvement in water use efficiency reported in previous years. Root drenches were not as effective as the foliar spray in this experiment.

Applications of 50mM Phosphate buffers (pH7.5) and water controls were made on *Buddleja davidii* plants in 1L. Effects were long-lasting, with pH and ABA concentration being raised above control levels for three weeks. The effects were seen both in plants where buffers were supplied as a foliar spray and as a root drench.

The prevention of leaf chlorosis in HONS using Rhizobacteria

A problem with *Aquilegia* production is unwanted leaf senescence and abscission. This is particularly apparent at the end of the growing season. In Cytisus, leaf drop is a problem if water deficits are accidentally applied. It is known that senescence and abscission are often associated with a build up of the plant hormone ethylene.

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We hypothesise that the leaf drop response in both species is signalled by a build up of ethylene under water deficits.

Ethylene build up might be preventable if PGPRs that possess the enzyme ACC-deaminase (which degrades the ethylene precursor ACC) are applied to the growing media.
Plants were treated with rhizobacteria or with water (as a control). These plants were then left to dry down in the greenhouses. Irrigation was supplied intermittently. This treatment was imposed in order to simulate the uneven irrigation delivery plants might receive on a nursery and hopefully result in a build up of ethylene in the control plants. For comparison other plants were kept irrigated to container capacity. Rhizobacteria decreased the proportion of senescing plants, suggesting that this treatment may increase stress resistance in response to variation in water supply on the nursery.

Infra-red imaging to sense plant water deficit and automate irrigation

Studies have confirmed that the proposed control system should include the following sensors:

(a) An array of downward-facing sensors on boom to estimate **plant** temperature

(1) Infrared temperature (long wave thermal sensor)

(2) Visible light (e.g. around 650 nm)

(3) Near Infra-Red (e.g. 800 nm)

(b) A set of additional sensors to allow the determination of the Crop Water Stress Index (see previous reports) for irrigation control. These could be located anywhere in the glasshouse, though there may be benefits in having some of these mounted on the boom to obtain local data. These would include essentially

(1) Air temperature

(2) Air humidity (or possibly a wet reference surface), but the former is easier to automate

(3) Dry reference surface temperature

(4) A measure of incident radiation

There is a need for downward facing visible red light (650 nm) and near infrared (800 nm) sensor pairs to enable the boom to detect the presence/absence of plants and to correct the temperature for the canopy density; it will also provide a measure of reflected visible light as a proxy for incident radiation to correct for the local effects of sunshine and shade. A key to the success of the system will be the need to minimise errors in leaf temperature estimation as variation due to differing water status may only be a degree or so in extreme shade conditions though larger differences will be common in summer.

Further testing or calibration is required
(a) to determine the most robust conversion between NDVI/SAVI and leaf fraction in the focal area using R/NearIR sensors, optimised to the new cheaper sensors being developed by PERA
(b) to investigate the impact of differing time lags in thermal responses of background, canopy and air temperature in a real production environment.
(c) to finalise the control algorithm to be based on calculated plant temperature and the ancillary variables mentioned above.

The testing conducted on the thermopile scanning system has now progressed to trialling an 8 metre sensor boom, containing 32 sensors and capable of scanning the complete green house bay. A number of test runs have been made and improvements carried out to the software in order to handle the large amount of data now being transmitted

The wireless transmission distance was tested in a greenhouse environment and has been shown to be greater than 50 meters at low power. When the gantry travel was increased to 200 metres, and possibly even greater distances in the future, the wireless link has been one of the areas which required further development in order to maintain communications.

The large sensor boom has been on site for 6 months now and has functioned appropriately each time tested, the watering gantry to which the boom is attached has been used to water the plants on a daily basis.

Financial benefits

The early and rapid detection of stressed plants and prompt watering is believed to be expected to save approximately £1000/ha/ann for mains water. The financial benefit of more uniform and even plant growth (reduced labour costs for pruning and order picking and reduced wastage) is likely to be an important driver.

Action points for growers

For growers considering installing a watering gantry the sensor system should also be given consideration as levels of watering can be more tightly controlled and plant condition monitored.

The gantry mounted system needs more testing in greenhouse environments, with a variety of plants and in a variety of conditions.

The consortium need to determine whether they need to include data from the soil / pot based sensors in the system.

Science Section

Introduction

This current project aims to achieve, through research and development, substantial and reliable water saving while minimising the risk of potentially catastrophic plant water deficits and crop losses. A variety of novel sensing technologies will be used to assess water requirement, including infra-red thermometers or thermal imaging systems (thermography) which monitor stomatal closure from the resultant rise in leaf temperature (e.g. Jones et al. 1997; Jones 1999). More recently, novel fertiliser treatments, designed to mimic the effect of drought on the plants' internal signalling systems, have been shown to reduce growth and water use of well watered plants (Davies et al. 2002; Wilkinson and Davies, 2002). Treatments are currently being developed within the project to be delivered via a range of modern water delivery systems that have the potential to deliver precise quantities of water where and when required.

An assessment of the potential to achieve uniform delivery of water using a range of alternative irrigation equipment provided the starting point for the project to develop robust protocols for more efficient irrigation, including effective implementation of Regulated Deficit Irrigation (RDI), where relevant. Theoretical and practical evaluation of thermal, soil moisture and evaporation sensors has started and will inform the development of optimal control systems. Detailed mechanistic studies, particularly of plant signals involved in responses to drought and nutrient treatments, are underway and will guide the development of protocols, while the novel fertiliser treatments emerging from recent studies are currently being evaluated at the practical level.

OBJECTIVE 1

Assess the potential to increase the precision of water delivery by refinement of existing irrigation systems in comparison with more capital intensive systems.

Introduction

Careful attention to the layout of overhead sprinklers can achieve very uniform water *deposition* but work reported in the 2nd Annual Report showed that, on an impervious surface such as Mypex over polythene, variation in the amount of water taken up from the surface through the base of the pots results in very variable water *delivery*. That work used 'standard absorbency pots' to simulate uptake by container plants at a standard water deficit. Using *Forsythia* plants growing in 3 L pots in standard growing media we aimed to (i) to confirm the validity of the results with 'standard absorbency pots' and (ii) to determine whether the pattern of variation changes over time, lessening the impact on crop uniformity.

In addition, on nurseries monitoring of water use in conjunction with water deposition and delivery tests under different overhead irrigation systems is being used to determine the extent to which relatively small improvements to irrigation systems can improve water delivery to HNS crops.

Materials and Methods

Using *Forsythia* 'Lynwood' plants irrigated with deficit irrigation (DI: 50% or 70% ET_p), three approaches were used to study variation in water delivery between individual plants:

1. Pots were weighed at 2-4 day intervals for the first two weeks after DI was imposed
2. Soil moisture sensors were installed at two depths in 8 pots and used to estimate daily water delivery
3. Pots were weighed before irrigation and 20 minutes after the end of irrigation

At Palmstead Nurseries, water use was metered in two different irrigation systems and time spent hand-watering recorded. Water deposition into saucers was measured to determine the uniformity of application of irrigation, and actual water delivery to pots determined by weighing them before and after irrigation.

Results and Discussion

Water delivery to *Forsythia*:

Approach 1. The rate at which pot mass decreased when irrigated at 50% ET_p was more variable under overhead irrigation than under drip (Coefficient of variation, *CV* = 49% and 36% respectively). However, the pattern of variation changed rapidly (correlation coefficient, *r*, between successive intervals was only 0.28 for drip and 0.33 for overhead respectively). This suggests that variation in water use by the plants largely masked the effect of variation in water delivery on drying down of the growing medium.

Approach 2. The pattern of differences between soil moisture probes tended to be consistent over many days, but soil moisture content at fixed locations within pots did not appear to provide a reliable estimate of water delivery to the whole pot. As the substrate dries out, differences in the amplitude of wetting and drying cycles (i.e. water delivery) at different points within a pot are to be expected (as a function of e.g. root density and proximity to drainage holes). It was impossible to distinguish such consistent within-pot effects from consistent differences in water delivery to the pot as a whole.

Approach 3. On single days, water delivery to individual plants on the same bed differed by up to 3-fold and the *CV* ranged from 22% to 50%, compared to an average of just 5% for water deposition (Table 1.1). Differences were well correlated over time. Placing pots on a disc of MyPex in large saucers, to define the "catchment area" for surface uptake, greatly reduced variability, but this effect was much less under 70% ET_p than 50% ET_p. The effect of raising pots off the floor, thereby preventing surface uptake, was very similar. There is evidence that the difference between the two DI treatments was due to the much larger and more variable shoot growth at 70% ET_p than at 50% ET_p. It appears that the foliage can 'collect' irrigation by intercepting water droplets that are moving with a horizontal component, so that plants with more foliage tend to have greater water delivery. This is supported by a strong correlation between plant height and water delivery (*r* = 0.79).

Table 1.1. Effects of modifying the interface between pots and floor on water delivery to 3 L containers under Eindor 861 (50 L h^{-1}) mini-sprinklers at 1 m above the floor. Delivery is expressed as the equivalent area of floor at the mean rate of water application (9 mm h^{-1}). For comparison, the top of the pots = 254 cm^2, the saucers = 490 cm^2, and the area of bed per plant = 625 cm^2

Modification	**Effective catchment area (cm^2)**			
	Mean		***CV* (%)**	
	50% ET_p	**70% ET_p**	**50% ET_p**	**70% ET_p**
Pots on ground	400	553	25	45
Pots in 25 cm saucers	440	517	8	31
Pots raised off the floor	305	406	8	28

Although similar water use was metered from the two irrigation systems in use at Palmstead Nurseries, substantially more time was spent hand-watering the crop under the older system than under the new “improved” system. This apparently relates almost entirely to the ability of the new system to get water right up to the edge of the tunnel (Figure 1.1), as in fact coefficients of uniformity for water deposition, water delivery, and water uptake were very similar in the two systems.

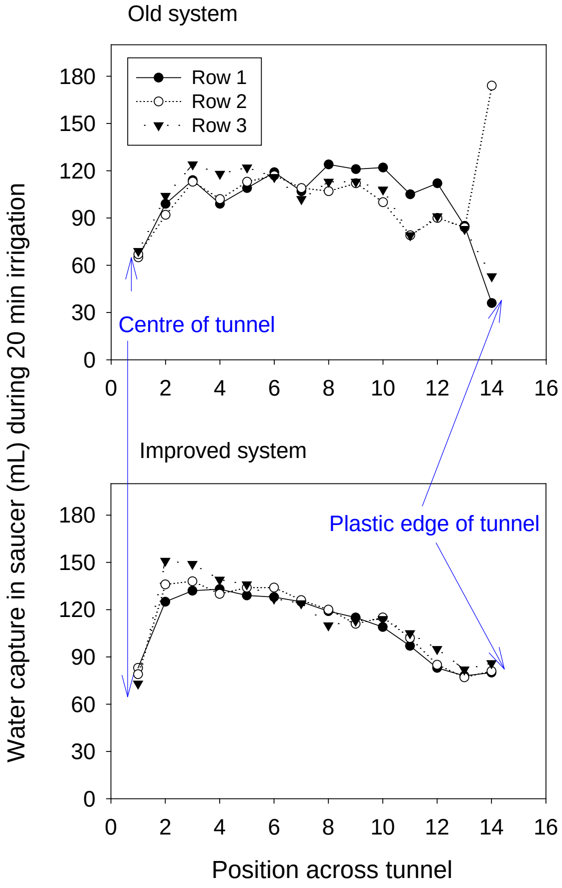

Figure 1.1. Irrigation water captured into saucers spaced from the centre to the plastic edge of two tunnels at Palmstead Nurseries during 10 (top graph) or 20 (lower graph) minutes of irrigation.

Conclusions

The coefficient of uniformity alone is not necessarily a sufficient description of the distribution of irrigation when determining whether a particular irrigation system's output is suitable. Variation in water use by different sized plants can mask the effect of variable water delivery.

OBJECTIVE 2

Optimise methods by which evaposensor and soil water sensing equipment may be used to regulate irrigation/fertigation systems on the nursery.

Introduction

Experiments were undertaken during 2007 to establish a generic system for the use of Evaposensors on nurseries, without the need for growers to perform timeconsuming calibrations. Relationships between plant height and crop cover as estimated by eye (‘eye cover’) and water use as measured in 2007 experiments were used to predict coefficients for use with the Evaposensor for three crops. The predictions were validated over the summer of 2008.

A separate experiment during 2007 had shown that deficit irrigation imposed with overhead systems can be used to control growth in *Forsythia* ‘Lynwood’. The effect of deficit irrigation on flowering was determined in the spring of 2008. In a separate experiment, GP1s were used to schedule both full and deficit irrigation, and the resulting growth and physiology of the GP1-scheduled crops was compared with that of Evaposensor-scheduled crops.

GP-1 scheduled irrigation was also used to impose deficit irrigation or control full irrigation on crops grown at Hillier Nursery.

Materials and Methods

Digital images were taken of each group of plants and the percentage leaf cover was estimated using Adobe Photoshop (Adobe Systems Incorporated, USA). Multiple regressions were performed on all the data collected during 2007 for each experiment separately, to analyse the influence of different factors (leaf cover, leaf area, interception of photosynthetically active radiation (PAR), plant height, and stomatal conductance) on water use.

Coefficients for use with Evaposensor readings were validated for species which had previously been found to be high, medium and low water users (*Cornus*, *Buddleia*, and *Griselinia* respectively). Plant height and cover were measured every two weeks. For three weeks out of every four, water was applied using the predicted coefficients. For the remaining weeks, water use was measured by weighing pots daily.

At John Woods Nursery, evaposensor-based scheduling was compared with timer-based watering on a crop of young *Hydrangea* in 1 L pots under glass during the summer of 2008 (Figure 2.1). This was based on weighing the pots to determine calibrations (rather than the generic coefficients being developed above). The trial was run from mid May to end August 2008, with a calibration performed in May and repeated in August.

Figure 2.1. *Hydrangea* in 1 L pots at John Woods Nursery. A bay in which irrigation was scheduled following Evaposensor readings was compared to one in which irrigation was scheduled without any sensors.

Based on work developed in HNS 159, an interface has been connected between an Evaposensor and a Heron timer to allow automated adjustment either of the timing of irrigation or the length of an irrigation run (Figure 2.2).

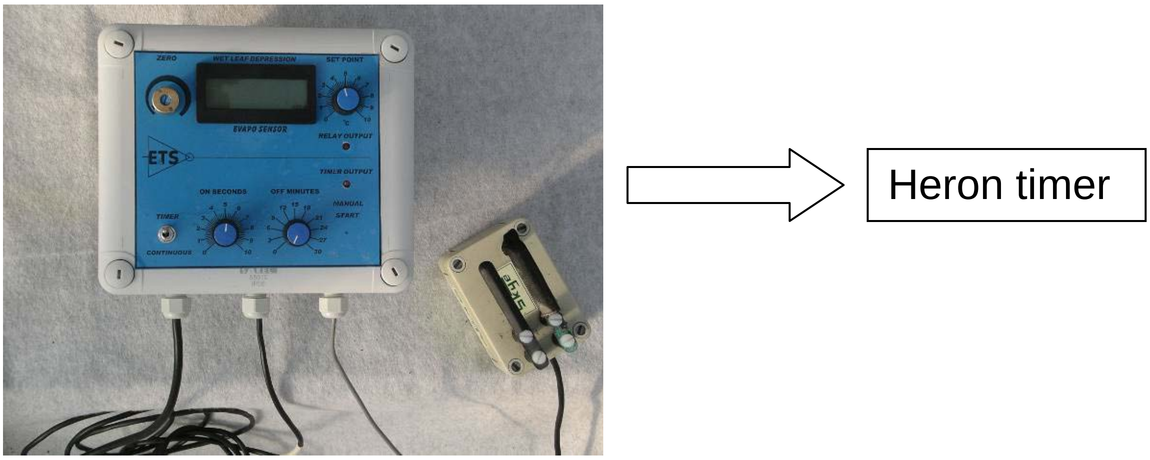

Figure 2.2. ETS interface and Evaposensor, which together allow automatic daily adjustment of the length of irrigation runs triggered by a Heron irrigation timer.

An experiment to determine the effects of overhead *vs.* drip irrigation, substrate, and deficit irrigation *vs.* control 'full' irrigation on growth of *Forsythia* x *intermedia* 'Lynwood' was described in the last annual report. In the deficit irrigation treatments either 70% or 50% of evapotranspiration (ET_p) was replaced by irrigation. During flowering February/March 2008, when approximately 80% of flower buds on a given plant were open, the extent of flowering was estimated.

From May 2008, in a new experiment, two scheduling methods were used to apply each of three levels of irrigation to crops of *Forsythia* x *intermedia* 'Weekend'. Irrigation treatments applied were: 150% ET_p, 70% ET_p, and 150% ET_p until pruning (late June) and 50% ET_p thereafter. Scheduling treatments applied were: Evaposensor-based *vs*. GP1-based. GP1 set points were initially chosen to track soil moisture contents from previous experiments and were then fine-tuned in various ways. Plant height, transpiration (measured by weighing pots), stomatal conductance (measured with a porometer (PP Systems)), water potential (measured with a pressure chamber (Skye)), and canopy temperature (measured with a thermal camera (IRI 4010, IRISYS)), were measured to determine the effects of deficit irrigation.

To determine whether deficit irrigation could be applied to a commercial crop using gantry irrigation, an experiment was set up at Hillier Nurseries in September 2007. *Solanum crispum* 'Glasnevin' and *S. jasminoides* 'Album' were grown in 3 L tall pots. Irrigation was triggered by a GP1 and SM200 probes connected to a gantry controller. The GP1 program utilised two probes in the central part of separate pots. The program was initially set for Probe 1 and Probe 2 <25% moisture triggered irrigation to turn on; Probe 1 or Probe 2 >27% moisture triggered irrigation to turn off. This was to ensure that if one probe was accidentally dislodged, the irrigation would not flood the trial. The gantry speed was set at its fastest so that the smallest irrigation dose was applied. The deficit irrigated treatment received irrigation during the forward pass of the gantry only, whereas a control treatment received irrigation during both the forward and reverse passes of the gantry, thus receiving twice as much. The irrigation run would automatically repeat if the off point had not been reached. From November to the end of the experiment in April 2008, a more severe deficit was imposed using set points of 19-21% for on with an off point 1% above to minimise the irrigation dose per application.

Experiments to test whether deficit irrigation could be applied to commercial crops using gantry irrigation were set up at Hillier Nurseries. *Solanum crispum* 'Glasnevin' and *S. jaminoides* 'Album' were grown in 3 L tall pots from end September 2007 to April 2008. Treatments started on *Tradescantia* 'Sweet Kate' in 1.5 L pots in July 2008 and will continue until spring 2009. In each case gantry irrigation was triggered by a GP1 and two SM200 probes in separate pots. One arm of the boom delivered water on just the forward pass of the gantry with the other arm irrigating on the forward and reverse passes, thus giving a 'Dry' or deficit treatment which received half the irrigation of the 'Wet' treatment. The irrigation run would automatically repeat until the moisture value in the pots with the probes exceeded the ‘Off’ set point. For the *Solanum* trial, probes were placed in the Dry treatment. The initial ‘On’ set point of <25% was found to be too high to give sufficient deficit stress to the Dry treatment, so this was reduced to between 19% and 21% from November 2007 for the remainder of the trial with an ‘Off’ point 1% higher, to minimise irrigation doses per application.

For *Tradescantia*, the probes were placed in the Wet treatment as it was thought this could be more easily set to provide irrigation to replace 100% ET_p so the Dry side would receive a 50% ET_p dose. This approach was also considered useful to overcome some of the erratic control difficulties that could occur when rewetting relatively dry peat. Initially a 31% On set point was used but this was increased to 36% on 20 August as growth reduction in the Dry treatment was excessive, but then dropped back to 33% on 9 Sept. The Off set point was 2% higher in each case. Irrigation doses were logged automatically with a pulse output water meter connected to a GP1 logger. Pots were weighed on 20 Aug, 9 Sept and 16 Oct to establish the uniformity of pot moisture status across treatments.

To determine whether water savings or other advantages are associated with use of GP1s rather than irrigation timers alone, automatic GP1 vs. timer-based scheduling was set up on a large area outdoor crop of 3 L *Ligustrum* at Wyevale Nurseries via a single SM200 probe in a representative pot. Other pots were monitored with probes on both the GP1 and timer-controlled beds. Initial set points of <28% On / 30% Off was used from 23 May to 18 September, followed by <23% On / 25% Off to the end of the season to limit irrigations during a hardening off phase once extension growth had slowed down. Daily rainfall and water consumption were recorded and and potential evapotranspiration estimated by recording daily degree hour totals using an Evaposensor.

Results and Discussion

Combining data over several months, a linear relationship was seen for several species/varieties between water use per degree hour and an estimate of cover from digital photos (Figure 2.3). Estimates of percentage cover from digital photos, which we expect to be more accurate than estimates by eye, did not generally result in stronger correlations with water use, possibly because with assessments by eye the viewer is unconsciously influenced by other factors such as plant height that also play a role in water use.

Multiple regression of water use per degree hour for all the measured variables over all species and months showed that the different variables combined explained 64% of the variation in water use in the outside experiment, and 77% of the variation in water use in the polytunnel experiment. In the polytunnel, a combination of plant height and percentage cover estimated by eye accounted for 66% of the variation. These are both straightforward and rapid variables to measure, so this is very encouraging for calculation of correlation coefficients on nurseries. For individual species, combining all variables gave very strong regressions (R^2>0.9) for 5 of the species studied. Stomatal conductance had only limited influence on the water use. The combination of plant height and percentage cover (estimated by eye) accounted for a high percentage (>79%) of the variation in water use for several of the varieties tested, indicating that for many crops information about these two variables should be sufficient to estimate crop coefficients. The percentage of variation in water use that could be explained was far lower in October than in the other months (May – September), presumably due to the reduced growth rate in the autumn. Plants were pruned prior to the October measurements, and as growth was very limited for some species at that time the relationship between water use and canopy measurements may have been disturbed. The relative importance of different variables changed over the course of the season, with plant height playing a greater role early on, and leaf area being more important later.

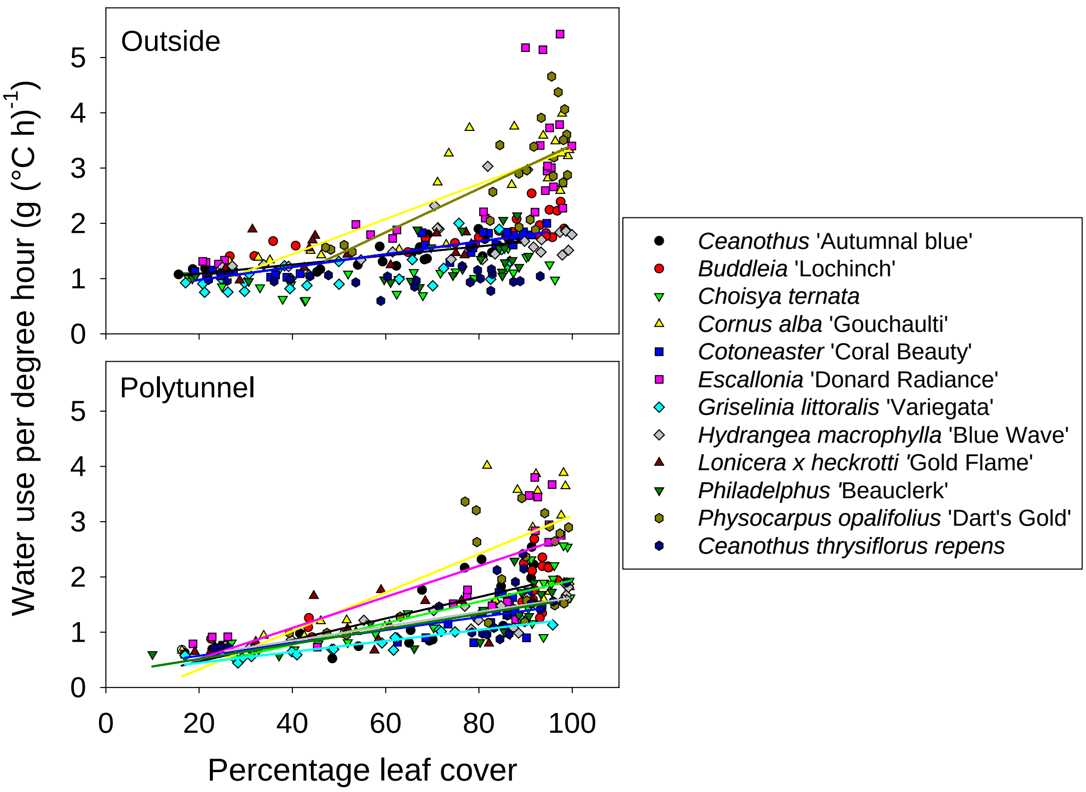

Figure 2.3. The relationship between water use per degree hour and cover as estimated from digital photos of groups of plants of each species/variety.

Outside, a combination of plant height and percentage cover estimated by eye accounted for 60% of the variation in water use. In general, it is more difficult to find universally strong correlations with water use across species for plants grown outside than plants grown in the polytunnel, partly because plants outside grew far less than in the polytunnel, and therefore the range of water use was far smaller.

Regression analysis produced the following predictions of water use for the three selected species used for validation this year:

Buddleia: g water use/degree hour = 0.036 x plant height (cm)

Cornus: g water use/degree hour = 0.037 x plant height (cm)

Griselinia: g water use/degree hour = 0.22 x logit (eye cover) + 0.92

Despite some deviations from the model, overall the correlation between predicted and actual water use was strong (Figure 2.4, upper graph), although tending to overestimate water use.

Multiple regressions using data for all twelve species studied in 2007 yielded the following equation for the two most easily measured variables:

Water use per degree hour = 0.016 x height + 0.015 x eye cover – 0.007

Overall, data obtained in 2008 showed a better fit to this model than to the species-specific models (Figure 2.4, lower graph). This is encouraging for the application of one model across most HNS crops.

The Evapometer scheduling at John Woods nursery was applied more successfully to the *Hydrangea* this year than with the tunnel grown *Ilex* in 2007. Nevertheless, the predicted irrigation doses for the Evapometer were overridden on several occasions when the crop was getting a bit dry, or when higher doses were needed in order to apply sufficient liquid feed, and estimated settings were used at weekends when Evapometer readings were not taken. It was also difficult for the grower to apply the manual scheduling treatment independently. The Evaposensor treatment averaged 2.1 mm/day compared to the manual treatment at 1.7 mm/day over the May to August period. In general, the nursery has not found Evapometer scheduling easy to use, either because of difficulties in getting reliable calibrations or a reluctance to trust the sensor and consistently apply the predicted doses. A combination of an easier calibration to perform on the nursery and automated daily adjustments might overcome these problems. In the case of this particular grower trial, not undertaking any calibrations between May and August would seem a serious flaw, as plants would be expected to grow substantially over that duration and hence the calibration coefficients increase substantially.

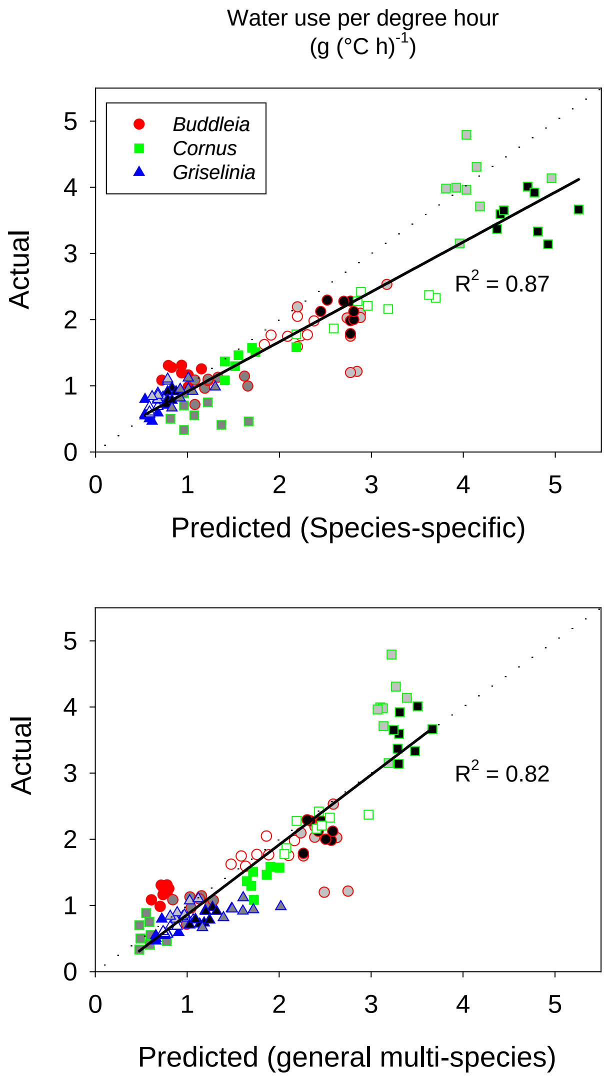

Figure 2.4. Actual *vs.* predicted water use per degree hour for 3 species measured every 4 weeks from early June to late August 2008, at which point *Buddleia* and *Cornus* were pruned, and then measured once in October 2008. Solid colours represent the earliest set of measurements, followed by open symbols, followed by light grey fill, followed by black fill, followed by dark grey fill. The upper graph relates to specific predictions for each of the three species, while the lower graph uses a single general regression that was derived from data obtained from 12 species in 2007. Linear regressions are through all data points; the dotted lines represent 1:1.

In the 2007 *Forsythia* experiment, deficit irrigation did not significantly affect the percentage of the plant on which there were flowers the following spring (percentage flower cover, Figure 2.5a). On average pruned plants had 83% flowers cover and pruned plants had 96% flower cover. The number of flowers per decimeter (dm) (i.e. per 10 cm) of stem for plants pruned was significantly affected by the % ET_p applied (Figure 2.5b). The plants receiving 150% ET_p had approximately half the number of flowers per dm compared to plants receiving 50% ET_p. The higher density of flowers in the deficit irrigation treatments can be seen in Figure 2.4d. The increased number of flowers over a given length of stem in the deficit treatment is a combination of two factors. Firstly, the number of flowers per node increased in plants receiving the deficit treatments when compared to those receiving 150% ET_p (Fig 2.5c). Plants in the deficit treatments reduced their vegetative growth and possibly a greater proportion of their resources were applied to flower initiation. Secondly, the internode lengths were significantly shorter in deficit irrigated plants (2.9 cm for 50% ET_p vs. 3.7 cm for 150% ET_p). As *Forsythia* flowers at the nodes, an increase in internode length means that over a given section of stem fewer nodes results in fewer flowers. In conclusion, flowering of *Forsythia* was not deleteriously affected by the application of deficit irrigation. Indeed, the density of flowering was increased under deficit as opposed to control irrigation.

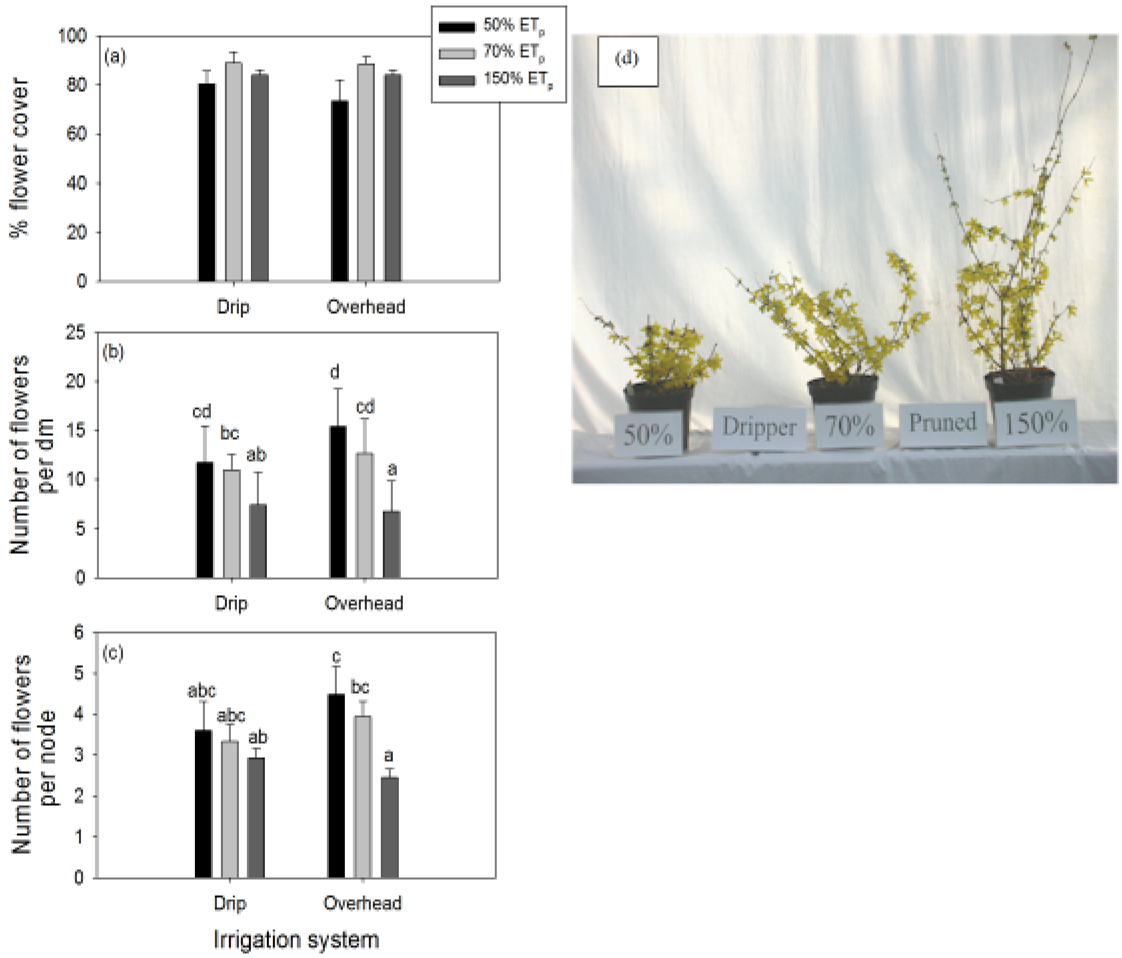

Figure 2.5. Percentage of *Forsythia* x *intermedia* 'Lynwood' covered in flowers (a), numbers of flowers per dm (b), and number of flower nodes per dm (c) during flowering in the spring following different % ET_p treatments, and with irrigation

applied either overhead or by drippers, and examples of flowering on plants irrigated to match 50%, 75%, or 150% ET_p (d). Data in (a) – (c) are means of 10 replicates. Plants had been pruned in June.

Early in the 2008 *Forsythia* experiment, it was found that the substrate moisture content in the pot selected for control of the irrigation could vary widely from that of the average pot in a bay. Therefore, settings that were higher or lower than the desired substrate moisture content were used to obtain the desired average across the bay. It was also found to be necessary to reduce the window between on and off settings to 1% (Figure 2.6) in order to obtain good control over the substrate moisture in the control pot. This was due to the gradual increase in substrate moisture content in the area around the SM200 probe during and after irrigation, largely as a result of wetting up of the substrate from the MyPex below, which meant that after irrigation substrate moisture content could reach considerably higher values than the off setting.

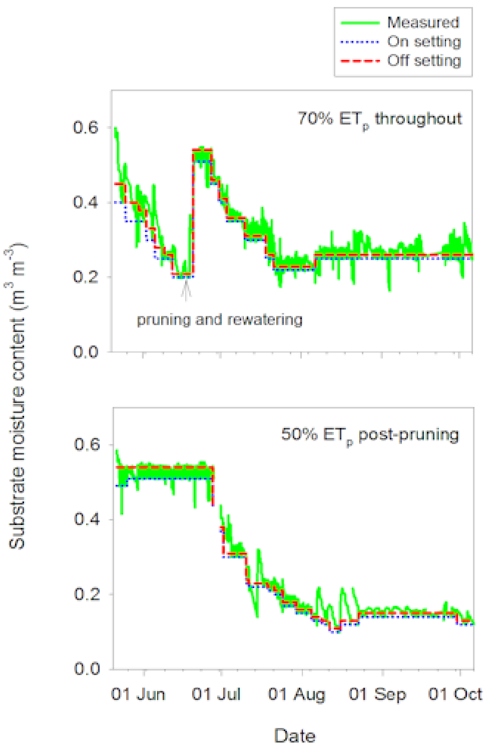

Figure 2.6. Measured substrate moisture content, and on and off settings used to apply approximately 70% ET_p to a *Forsythia* crop from the start of treatments (upper graph), and approximately 50% ET_p after pruning (lower graph). When the substrate moisture content falls below the on setting, the relay closes and irrigation is triggered.

Up to pruning, the substrate moisture content was on average significantly lower in the 70% treatment than in the fully irrigated pots (repeated measures analysis of variance, P < 0.001) (Figure 2.7a). However it was also significantly higher (analysis as before, also P < 0.001) in the Evaposensor-scheduled bays than in the GP1-scheduled bays. After pruning, there was a significant interaction of irrigation and the type of sensor used (P < 0.001): the 50% Evaposensor-scheduled pots had the lowest substrate moisture, followed by the 50% and 70% GP1-scheduled pots, then the 70% Evaposensor-scheduled pots, and with the fully irrigated pots showing the highest substrate moisture content. Pot weights (Figure 2.7b) showed the same pattern as substrate moisture content. Plant growth (increase in height) was not significantly affected by the irrigation treatment or the type of sensor used for scheduling up until pruning, but after pruning there was a significant interaction of irrigation treatment and sensor (P < 0.001). At this stage, where the Evaposensor was used for scheduling both 50% and 70% treatments resulted in less growth than in the control fully irrigated plants (but there was no significant difference between 50% and 70%, whereas where the GP1 was used for irrigation scheduling, growth in the control was rather limited, and therefore no greater than that in the 70% treatment – but the 70% treatment showed greater growth than the 50% treatment (Figure 2.7c). This “growth” however refers to increase in “natural” height i.e. without extending the drooping branches to their full length. When the plants were measured at the end of the experiment with their longest branches fully extended, the benefit of deficit irrigation, and the greater effect of the 50% compared to 70% treatment was clear: plants irrigated to 50% ET_p were smaller than those irrigated to 70% ET_p, which in turn were shorter than those given full irrigation (Figure 2.8a). The examples in Figure 2.8b indicate the difference in size in different treatments. Total leaf area and leaf fresh mass, and leaf plus stem fresh mass at this time showed clear patterns of increasing with increasing irrigation ($P \leq 0.002$, n = 8), whereas numbers of leaves, the average leaf size, and leaf dry weight were only reduced in the 50% ET_p treatment (P < 0.001, n = 8). Bud break after pruning was similar across treatments, but the growth of axillary branches was reduced under 50% irrigation compared to the control, and was also greater where scheduling was applied using GP1s compared to using the Evaposensor (P = 0.005, n = 16). With respect to plant quality in autumn, similar numbers of plants in each treatment had three or more strong shoots and evenness of branching was also similar across treatments (n = 32).

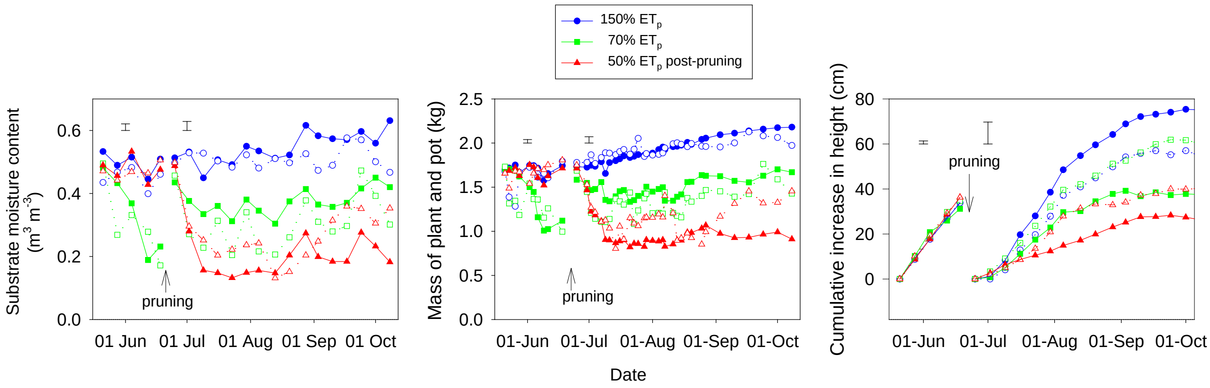

Figure 2.7. Substrate moisture content (a), pot mass (b), and cumulative increase in *Forsythia* plant height (c) under different % ET$_p$ treatments, and with irrigation scheduled either with an Evaposensor (closed symbols) or with GP1s (open symbols). Error bars indicate overall standard errors of the difference of the means before pruning and after pruning, *n* = 16.

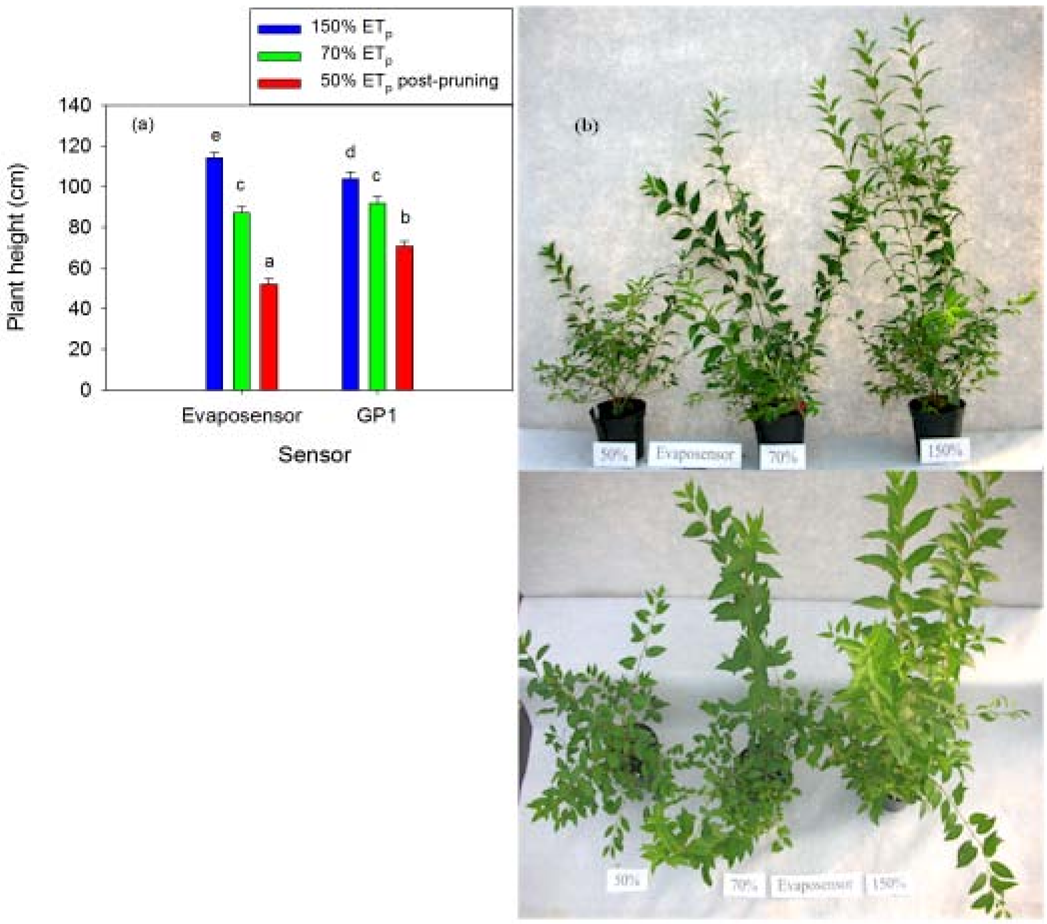

Figure 2.8. Height of plants in three irrigation treatments scheduled using two different types of sensor at the end of the experiment (*n* = 32; a) and examples of the different sizes of plants irrigated to match 50%, 70% and 150% ETp (left to right) (b).

Evapotranspiration, measured gravimetrically, was lowest after pruning in the 50% treatment and highest in the 150% Evaposensor-scheduled treatment (Figure 2.9a). Since irrigation scheduled by the GP1s was sometimes triggered in the morning and sometimes in the afternoon or evening, midday stomatal conductance and photosynthesis of the different treatments where GP1s were used did not always show clear treatment effects, but stomatal conductance of the Evaposensor-scheduled plants was generally greater where more irrigation was applied (Figure 2.9b). Midday stomatal conductance measured in August and September correlated strongly with water potential of the same leaves ($r \geq 0.65$, $P < 0.001$). Early in the season reductions in stomatal conductance led to increased photosynthetic water use efficiency (the ratio of carbon gained to water lost) for the 70% ET_p plants, but in the 50% ET_p after pruning treatment a more substantial reduction in photosynthetic rate meant that there was no increase in photosynthetic water use efficiency in this treatment compared to the control (Figure 2.9c); later in the season however the pattern was not so clear. Thermal images reflected differences in stomatal conductance between treatments (Figure 2.10).

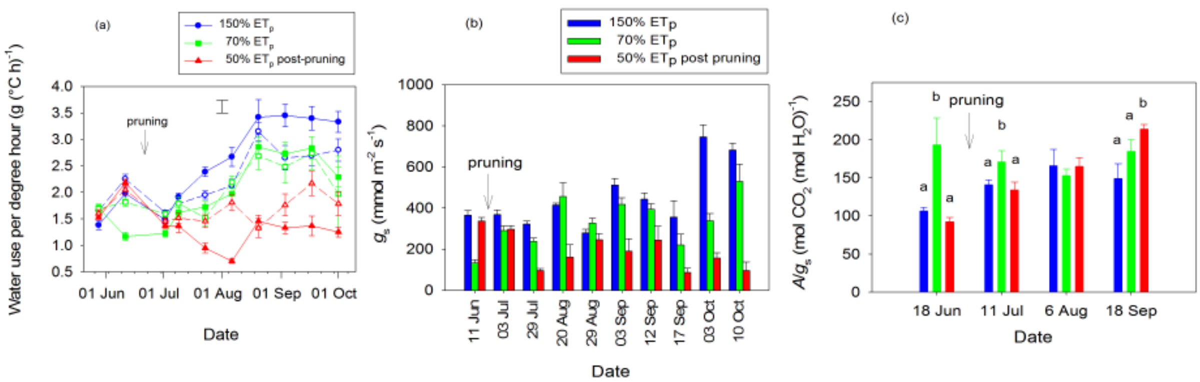

Figure 2.9. Evapotranspiration (water use per degree hour) (a), stomatal conductance (b), and photosynthetic water use efficiency (the ratio of assimilation to stomatal conductance) (c) of *Forsythia* plants under three different irrigation treatments. Results for irrigation scheduled either using an Evaposensor (closed symbols) or GP1s (open symbols) are shown in (a), n = 16; results for the Evaposensor-scheduled treatments only are shown in (b), n = 8-18; and pooled data from Evaposensor and GP1-scheduled treatments are shown in (c), n = 24, except on 18 June when n = 14.

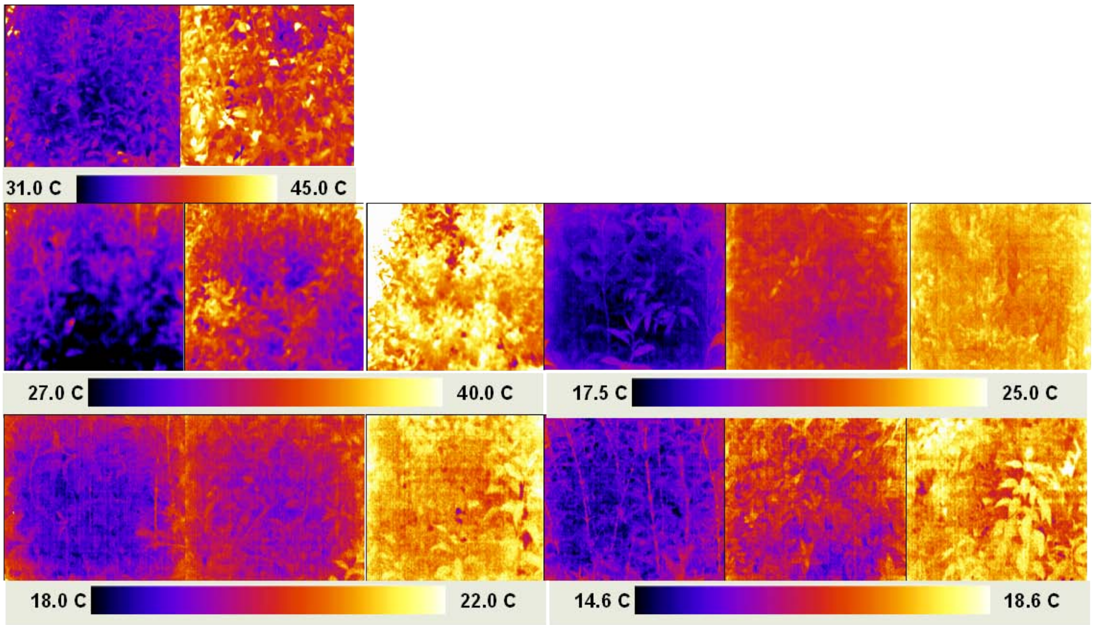

Figure 2.10. Examples of thermal images of Evaposensor-scheduled *Forsythia.* Sharing the same thermal scale, from left to right: 150%, 70%, and 50% ET_p treatments (except in the case of 8 June when the 50% treatment had not yet been imposed), captured on (top to bottom and left to right) 8 June, 21 July, and 4, 10, and 17 September. Air temperature and relative humidity for each date at the time of taking the images were respectively: 30.5°C and 45.1%, 32.6°C and 27.5%, 19.5°C and 70.8%, 21.8°C and 67%, and 19.7°C and 60.5%.

In the *Solanum* experiment run at Hillier Nurseries in the autumn/winter of 2007, the rate of water use and drying down was slow over autumn and winter, and irrigation events infrequent (e.g. only two irrigations in the first 2.5 months of the trial). The dry state of the peat medium in the deficit treatment may have affected how evenly it rewetted during irrigation events, and therefore how quickly the zone near the probe became moist enough to switch off the irrigation: there were clearly defined moist top and basal layers with very dry peat in between. A clear growth reduction occurred in the deficit treatment (Figure 2.11a, b), but it was rather excessive in the less vigorous variety 'Glasnevin'. Plants require at least one shoot to be more than ¾ cane height before sale, meaning that sale of some of the 'Glasnevin' was delayed by the deficit treatment (Figure 2.11c, d), but all were eventually marketable. The nursery commented that the Wet treatment was also dryer than in previous years, and did not show the yellowing and lower leaf loss due to shading from excessive top growth that this caused.

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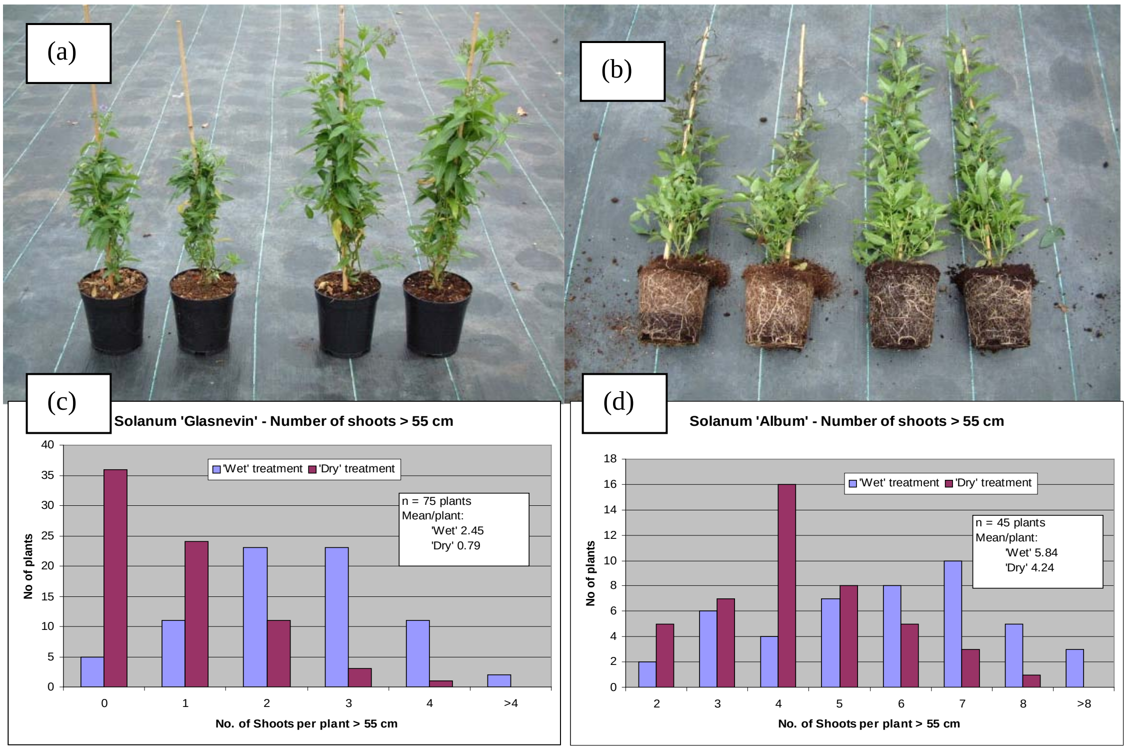

Figure 2.11. *Solanum* 'Album' (a) and 'Glasnevin' (b) plants that received deficit (left) and control (right) irrigation, and numbers of shoots per plant over ¾ cane height.

In the 2008 experiment at Hillier Nurseries, GP1 control with a 2% difference between the on and off settings has resulted in full irrigation treatment doses of normally 2-4 mm but up to 10-15 mm on some occasions (Figure 2.11). Disturbance of moisture probes during pruning operations were responsible for some of the excessive irrigations. Initial growth reduction by the Dry treatment was excessive (Figure 2.12) requiring adjustment of set points (Figure 2.11). Uniformity of irrigation within treatments was good. Results from these two nursery trials of imposing deficit irrigation with the GP1 have been encouraging, but it is clear that moisture probes are sensitive to being disturbed in containers, and that some careful monitoring and adjustment of set points is required to ensure reliable growth controlling irrigation regimes to be applied in commercial nurseries in this way.

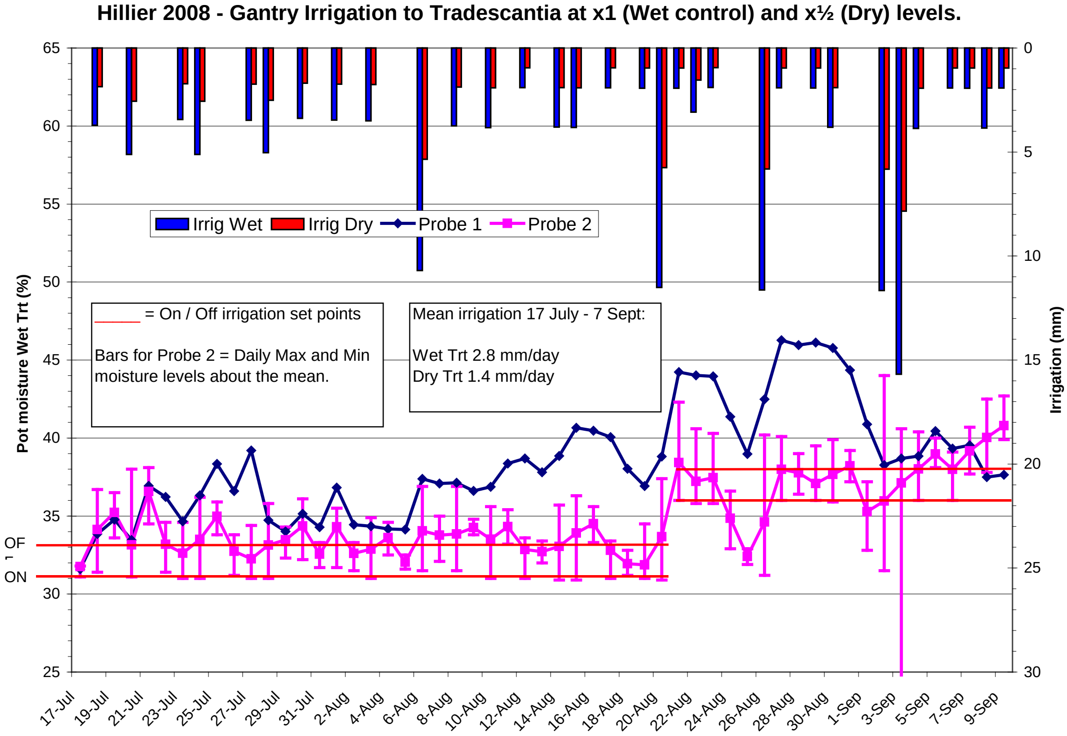

Figure 2.11. Mean daily moisture traces for GP1 controlled 'Wet' (full irrigation) treatment, and irrigation applications 17 July – 7 September.

Figure 2.12. *Tradescantia* 'Sweet Kate' by 20 August showing significant growth reduction in the Dry treatment (right)

Despite the wet summer, the GP1 controlled bed at Wyevale (mean 1.1 mm/day) applied less than half the irrigation used on the manually adjusted timer-controlled bed (Figure 2.13a). It is clear that a number of surplus and unnecessarily heavy irrigations were applied to the timer-controlled bed (Figure 2.13b). Growth of *Ligustrum* was similar with both treatments. No unplanned adjustments of GP1 set points were required after early June, and the trial has ratified earlier findings that irrigation control from monitoring a single representative pot can work well on large scale commercial production beds with overhead systems.

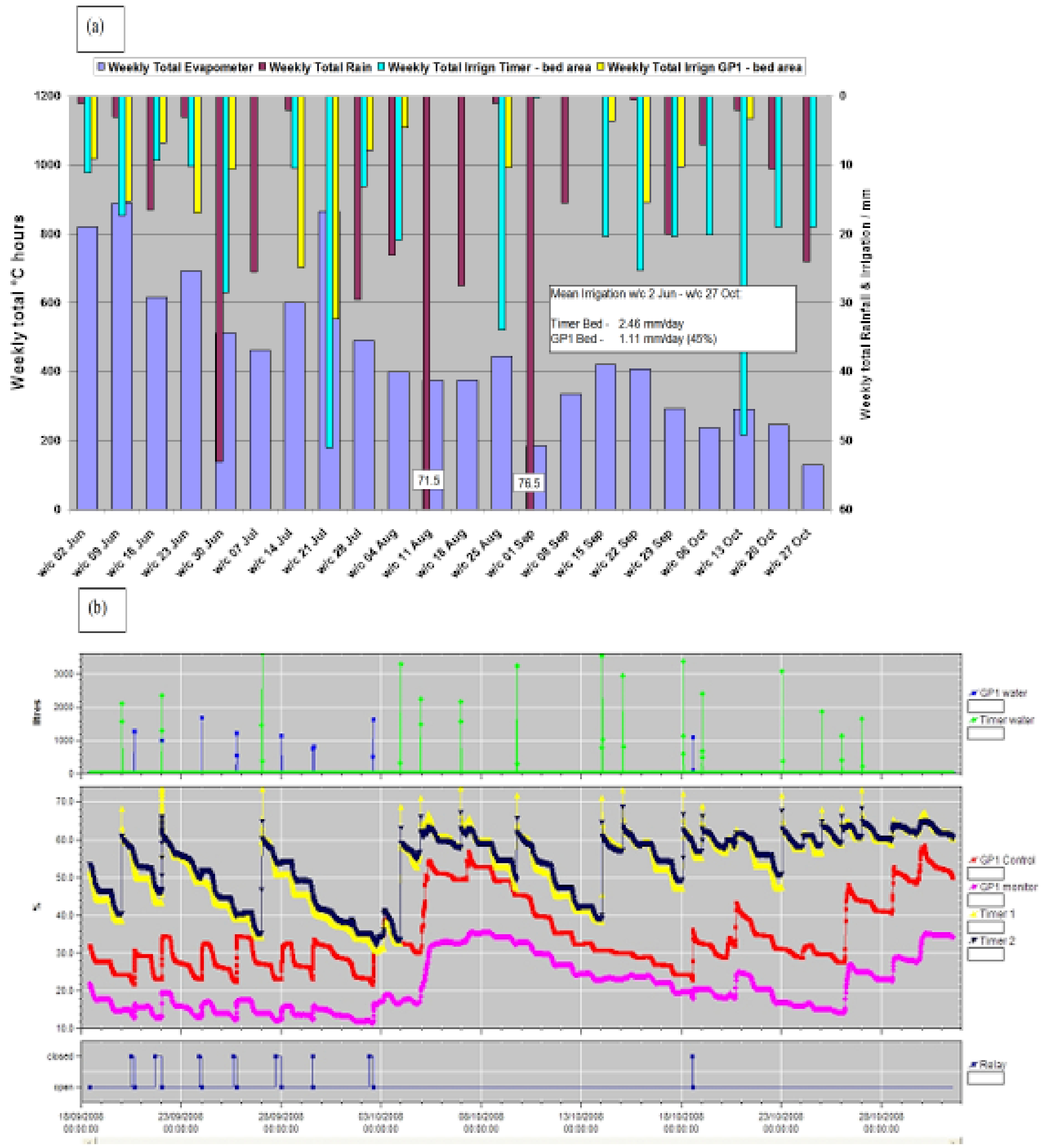

Figure 2.13. Weekly evaposensor, rainfall and irrigation on GP1 vs timer-scheduled crops of *Ligustrum* at Wyevale Nurseries (a) and excessive irrigations to the timer-scheduled bed during October (green bars and black / yellow moisture traces). GP1 irrigation (blue bars) was controlled by the soil moisture probe represented in red.

Conclusions

- Water use per degree hour i.e. crop coefficients for use with the Evaposensor was found to correlate with plant height and canopy cover for most of the 12 species studied in 2007. An equation describing the relationship was used to predict the water use per degree hour of three species in 2008. Measured water use per degree hour was found to be similar to the prediction. Combined with a newly automated system for adjusting irrigation times according to daily Evaposensor readings, this result is encouraging for the less labour-intensive use of the Evaposensor on nurseries

- Both the Evaposensor and GP1s were successfully used to schedule deficit irrigation and thus control plant growth. Based on three years of collecting substrate moisture content data in deficit irrigated crops, it appears difficult to define exact set points for use with the GP1: however, fairly rapid assessment of the average condition of plants across a bed e.g. by weighing pots should allow growers to adjust the GP1 set points to optimise control of deficit irrigation
- GP1s were successfully used with commercial crops to schedule both full and deficit irrigation
- A relatively low-cost thermal camera highlighted the variation in temperature caused by differences in stomatal conductance in crops receiving deficit or control (full) irrigation

OBJECTIVE 3

Determine the theoretical and actual performance of thermography and infrared thermometry in direct comparison with other techniques for monitoring HNS irrigation

The secondary milestone (S3.3) ‘Complete trials of thermography as a hand-held monitoring system not requiring calibration for identifying poorly watered plants to direct remedial action’ was successfully completed early and reported in the previous annual report. There it was clearly demonstrated that hand-held thermal imager operation could provide a useful monitoring tool for assessing irrigation performance. There has been substantial interest from growers in using and evaluating this system.

OBJECTIVE 4

Develop methods for relatively risk-free application on the nursery of deficit irrigation and novel fertiliser treatments to modify plant morphology, growth and quality.

Alkaline buffers: Garden Centre Plants Trial

In summer 2008, we attempted to transfer the knowledge gained from using buffer treatments in the LEC greenhouses, to a more industry-relevant setting. Alkaline buffers were applied to large plants (in ~5L containers) on a horticultural nursery and the responses monitored throughout the growing season. By doing so we hoped to answer the following questions

- Can buffers regulate growth and water use in the in the more variable growing conditions of a nursery?
- Are alkaline buffers able to act on larger/older plants?

Cortaderia, *Fatsia*, and *Lonicera* were chosen for the study, due to their differing growth patterns (grass, large leaves, and climber respectively). They were grouped together in a typical horticultural polytunnel, with flag pathing and supplied with both overhead irrigation and hand watering (Figure 4.1). 50 mM phosphate buffer was applied as a foliar spray to half the plants with water sprayed on the remainder as controls for comparison. Stomatal conductance, leaf temperature and plant height were measured weekly.

Initial results are encouraging with alkaline buffers reducing transpiration when the plants were kept well-watered (Figure 4.2) but no final assessment could be made due to Russell Sharp's road accident. Potassium phosphate powder was posted to John Woods Nursery for trials of alkaline buffer treatment on a second nursery location.

Figure 4.1. The Lonicera, Fatsia and Cortaderia plant used for ‘on-nursery’ alkaline buffer experiments.

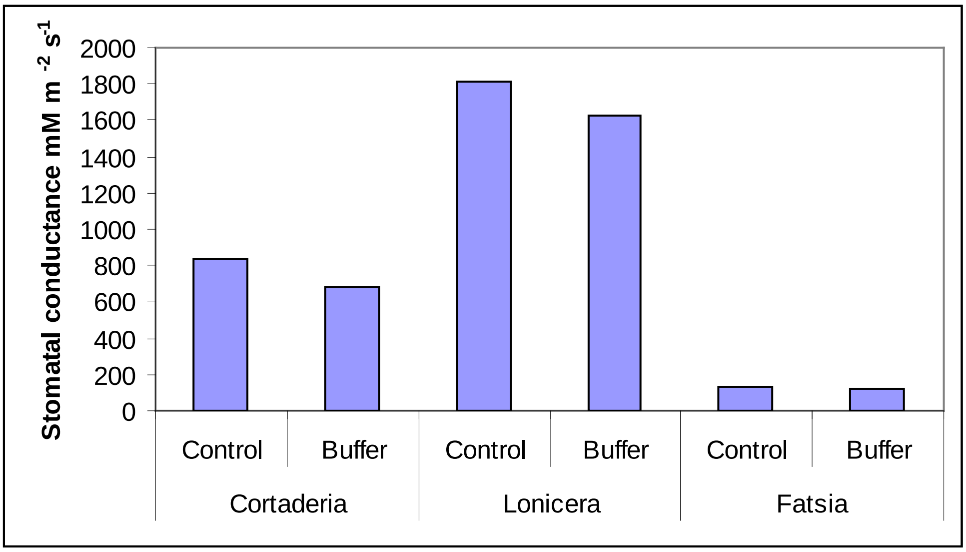

Figure 4.2. The stomatal conductance of Cortaderia, Lonicera and Fatsia plants one week after the application of a 50mM pH7.5 potassium phosphate buffer. Plants were grown at the Garden Centre Plants Nursery, Barton, Lancs.

Alkaline buffers: water quality

In late 2007/early 2008, we investigated at the use of comparatively poorer quality (ionic) water from boreholes, to see if they could be used to formulate alkaline buffers. One possibility is that the natural acidity or impurities block buffer effects or form precipitates when formulated. Comparisons were made of the effects on water use from foliar sprays made using deionised, tap (Lancaster) and borehole water (from GCP nursery).

Although some precipitation formed in buffers formulated with borehole water, this should not represent a barrier to application or mark plants. The ability of buffers to reduce transpiration was unaffected, with water loss per plant lower when buffers were formulated using tap, bore or deionised water (Figure 4.3). A saving in water use of 14% with the tap water treatment is consistent with the improvement in water use efficiency reported in previous years (Figure 4.4). Root drenches were not as effective as the foliar spray in this experiment. This could be due to the measurements being taken soon after application. Foliar sprays will act quicker, as it easier for the pH signal to get into the xylem sap across the leaf cuticle, than for effects in the root-zone to take effect.

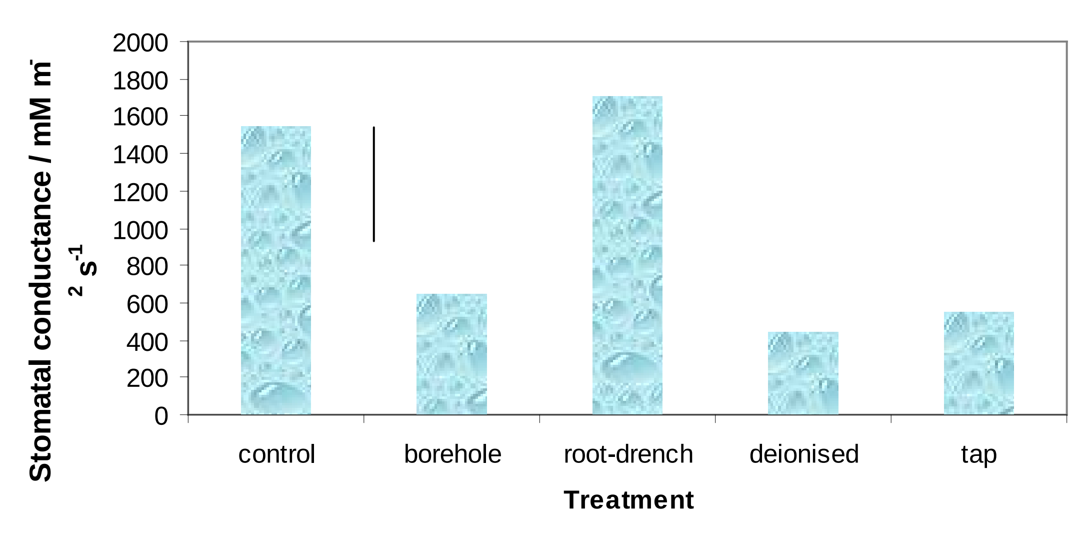

Figure 4.3. The mean stomatal conductance of *Buddleja davidii* plants treated with 50 mM (pH 7.5) potassium phosphate alkaline buffers with water sourced from different locations.

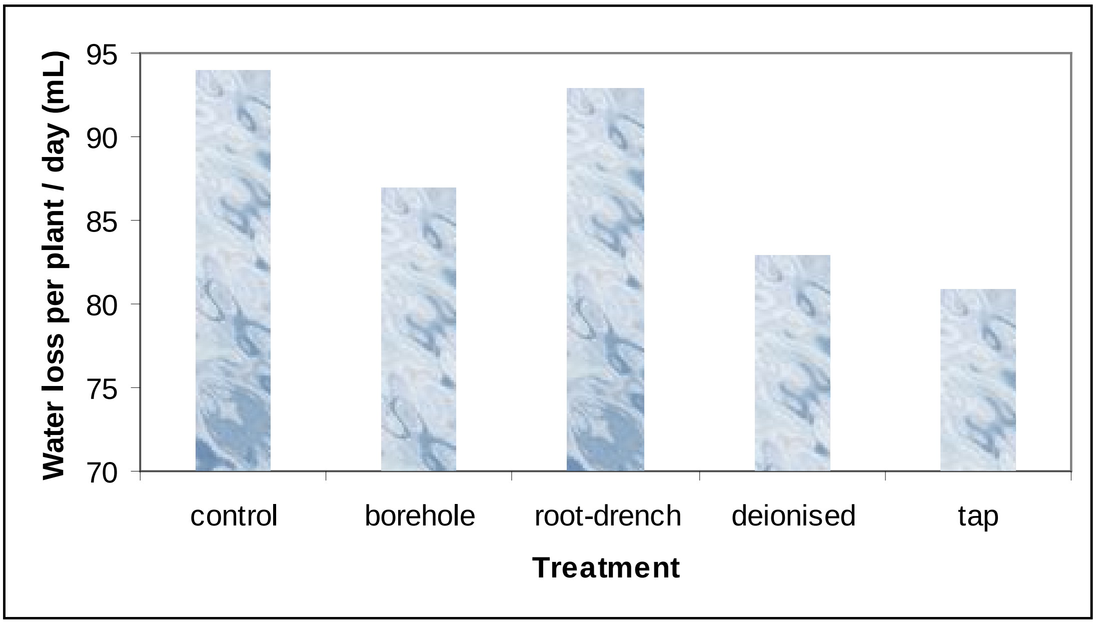

Figure 4.4. The mean daily water loss per plant (evapo-transpiration) from *Buddleja davidii* plants treated with 50 mM (pH 7.5) potassium phosphate alkaline buffers with water sourced from different locations.

Alkaline buffers: persistence and resetting

2008 saw progressive refinement of the buffer treatment regimes. We needed to see how many days the pH signal is maintained for in the xylem sap after alkaline buffer application, thus giving us data on how frequently buffers should be applied and how long you can expect them to persist for. We also investigated whether buffer effects can be cancelled by the application of a reversing acid buffer if a grower wished to cut short the effects of a previously applied alkaline spray.

Persistence of Buffers

Applications of 50mM Phosphate buffers (pH7.5) and water controls were made on *Buddleja davidii* plants in 1L containers growing in the LEC greenhouses. Measurements were made of the effects on xylem sap pH and ABA concentration after 0, 7, 14, 21, 28 days. The results show that the effects are long lasting, with pH and ABA concentration being raised above control levels for three weeks (Figure 4.5&4.6). The effects were seen both in plants where buffers were supplied as a foliar spray and as a root drench. This combined with data reported in previous years clearly shows that the method of application does not matter. After four weeks xylem sap chemistry returned to the control values.

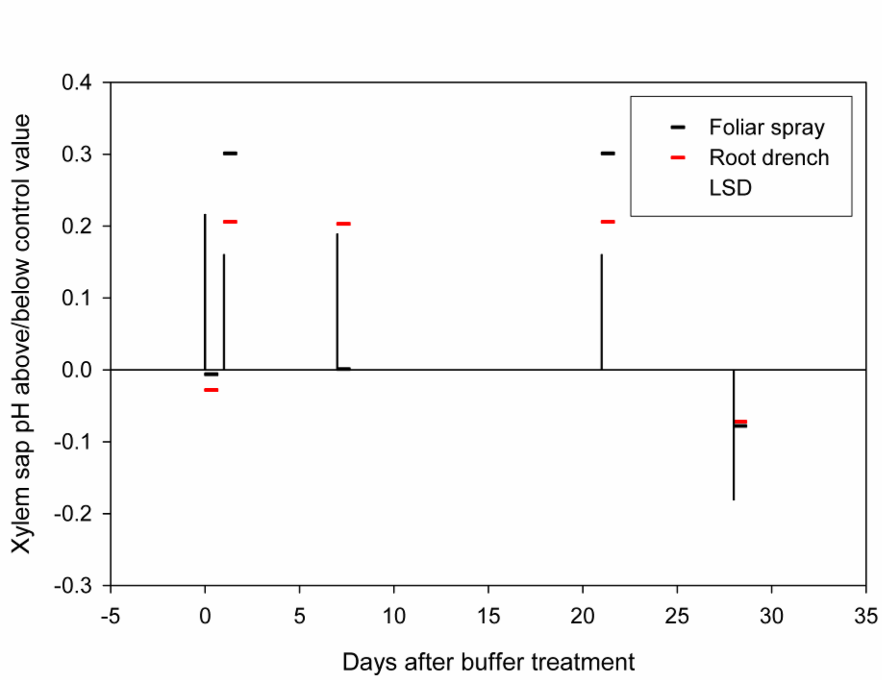

Figure 4.5. The response of xylem sap pH to a single application of phosphate buffer, either as a root drench or foliar spray. Data is presented as means of eight stems and is represented as pH value as compared to control values.

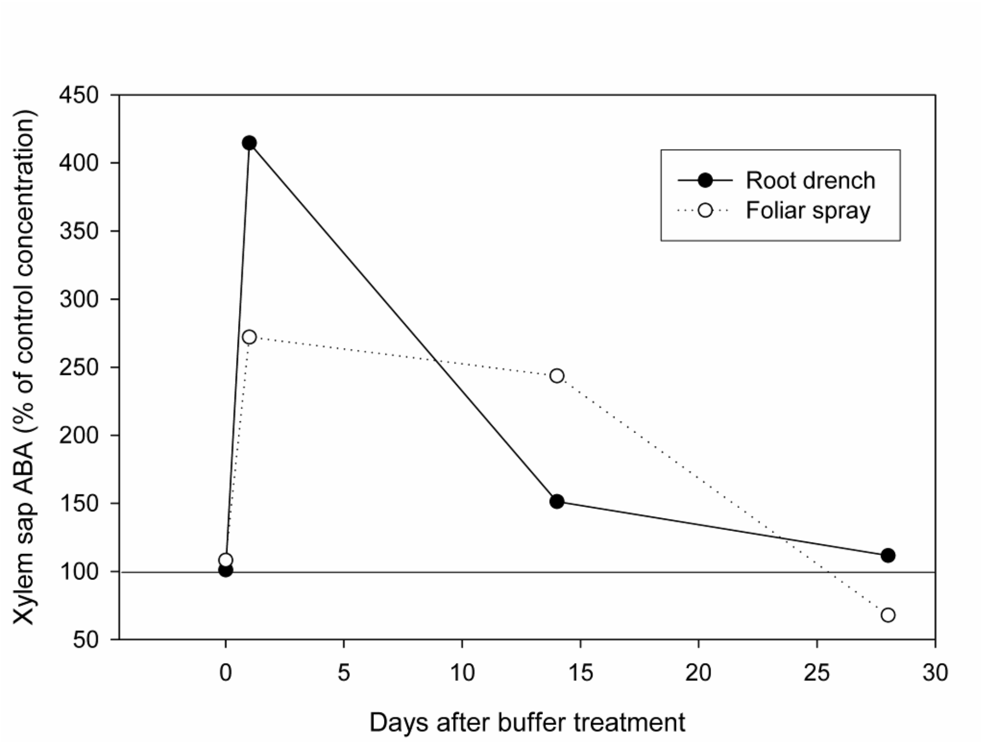

Figure 4.6. The xylem sap ABA content after a single application of phosphate buffer. Data are means of eight stems and are represented as comparisons to the mean ABA level in control plants.

Restoration of xylem sap pH

Alkaline buffers were applied to 18 Buddleja plants from the same population as the above experiment. Another nine plants had water sprayed onto them as control. After three days nine of the alkaline buffer treated plants had a 50mM pH5.0 buffers applied in order to chemically rebalance the pH on the leaf surface and internally in the sap and tissues. Stomatal conductance was then measured after 24 h to determine the effects of treatment on transpiration.

Unfortunately the results of this experiment were inconclusive with no significant differences between treatments observable (data not shown). It is hoped that in 2009 we will attempt to add an acid restorative treatment when alkaline buffers are applied.

The prevention of leaf chlorosis in HONS using beneficial bacteria Rhizobacteria

Aquilegia and cytisus

A current challenge in the production of aquilegia is unwanted leaf senescence and abscission. This is particularly apparent at the end of the growing season. While in Cytisus a current problem associated with production is leaf drop if water deficits are accidentally applied (Figure 4.7). This is thought to result from this species evolving a 'summer deciduous' strategy in its native Mediterranean habitat. It is known that senescence and abscission are often associated with a build up of the plant hormone ethylene. We hypothesise that the leaf drop response in both species is signalled by a build up of ethylene under water deficits. This ethylene build up might be preventable if PGPRs that possess the enzyme ACC-deaminase which degrades the ethylene precursor ACC are applied. Such PGPR can be applied to the growing media.

Currently on-going: Grower-relevant measurements being taken – chlorophyll content, the number of plants having senesced, and visual plant health assessment (scored out of 10).

The Plant Growth Promoting Rhizobacteria (PGPR) *Variovorax* 'CM4' and '5C2' from stock accessions were grown in liquid culture for 24 h, washed, centrifuged, and applied as a root drench to plants. Groups of nine plants were treated with either CM4, 5C2, or water controls. These plants were then left to dry down in the greenhouses in LEC. Irrigation was supplied intermittently so that it switched from excess to deficit. This treatment was imposed in order to simulate the uneven irrigation delivery plants might receive on a nursery and hopefully result in a build up of ethylene in the control plants. For comparison another nine plants were kept irrigated to container capacity.

Figure 4.7 Top: Dormant and leafless Cytisus plants before acclimatisation in LEC greenhouse. Bottom: A control Aquilegia suffering chlorosis and one treated with plant growth promoting rhizobacteria.

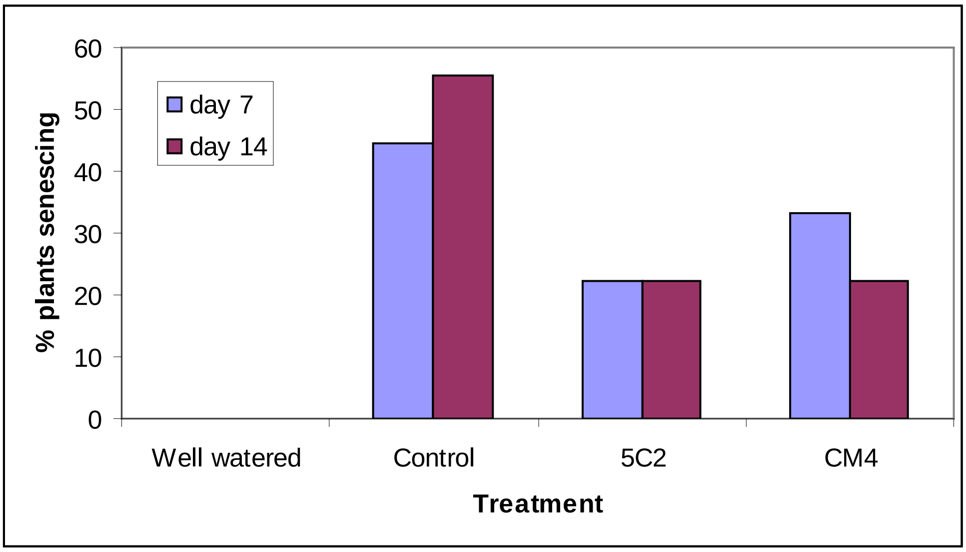

Figure 4.8. The senescence of Aquilegia plants is prevented by keeping plants well watered. However, if drought is applied, the effects can be mitigated against by the application of bacteria containing ACC-deaminase.

This future Cytisus experiment will also determine if MCP-1, a commercially available ethylene perception blocker can be used to prevent drought/flooding related leaf drop/senescence in problematic HONS species.
The first experiment to begin was on Aquilegia. This showed that both CM2 and 5C2 decreased the proportion of senescing plants (figure 4.8). However, it is seen that all plants can be prevented from senescing if they are kept well-watered; thus reinforcing the need for controlled irrigation on the nursery. Results for chlorophyll content and the effects of PGPR on Cytisus will be obtained in early 2009.

OBJECTIVES 5

Identify physiological mechanisms underlying plant responses to deficit irrigation and novel fertiliser treatments in order to optimise practical exploitation of such techniques

The *Forsythia* and *Solanum* and *Tradescentia* experiments described under Objective 2 also relate to objective 4, showing the applicability of deficit irrigation to control plant growth and quality.

Apoplastic pH signalling

Drought signalling in ericaceous species

As was reported in the 2007 report. Rhododendron are acid-loving plants, and intolerant of high pH soils and irrigation and thus alkaline buffers cannot be used on or near areas on a nursery where they are growing. However, we wanted to know if they still are able to generate and respond to elevations in xylem sap pH. Plants show elevated sap pH when they are actively controlling the response to soil drying and it leads to a concurrent increase in the ABA reaching the leaves where it acts to control growth and transpiration. However, increases to levels seen in other species would be toxic in Rhododendron, so may not occur. 30 Azalea plants in 1L containers were placed in the LEC greenhouses and pruned to stimulate a flush of growth. Then a mild and a severe water deficit were imposed in the same manner as described in the 2006 report. Once leaf temperature had increased in the severe deficit treatment stomatal conductance was measured on two leaves per plant and then two stems were excised for measurement of stem water potential. An over-pressure was excerpted on the cut stems when they were in the pressure bomb so that sap could be exuded and collected. The pH of this sap was then immediately measured using a micro-pH probe.

It was found that *Rhododendron* raise their xylem sap pH under water deficits, and although it is a significant increase, it is not to the levels seen in other species and it never reaches the level were it would be toxic to the tissues. The mean pH level is 5.9 in well-watered Azaleas and reached 6.2 under water deficits.

Transpiration Bioassays

Transpiration bioassays were performed to test if plants with differing growing requirements respond differently to changes to xylem sap pH (do they have specific zones of sap pH which transpiration can occur in). Acid-loving, generalist, and alkali-loving plants represented by Azalea, Buddleja, and Dianthus respectively were chosen for study (However, only Azalea and Buddleja were so far tested). It was expected that the optimal soil pH required by each species would determine the optimal sap pH, while a generalist like Buddleja would maintain transpiration over a wider pH ranger. However, no correlation was found between the xylem sap pH and transpiration (Figure 5.1). Transpiration rates remained stable in Azalea, while it was highly variable in Buddleja leaves; the reasons for which we currently are unsure on. These bioassays will be repeated in early 2009 with an artificial sap recipe with greater buffering capacity.

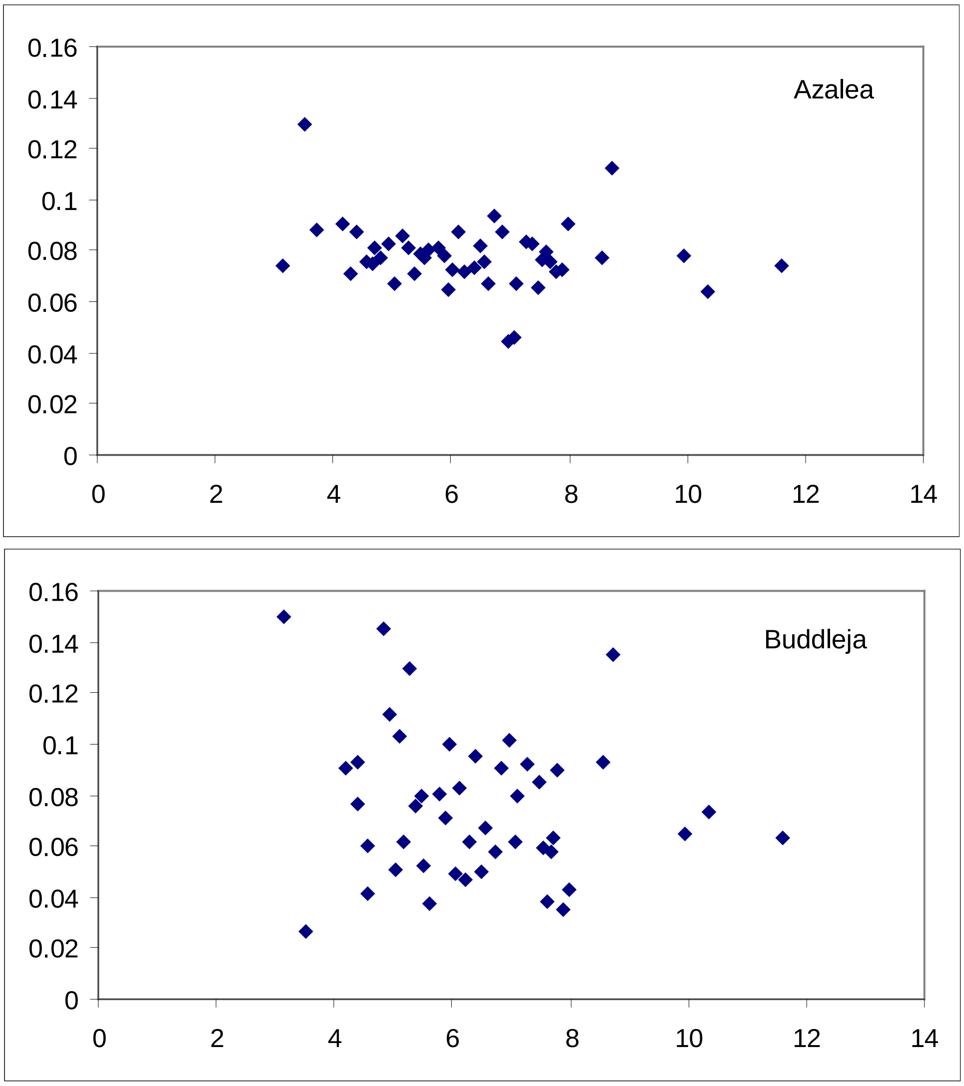

Figure 5.1. Transpiration of shoots of Azalea and Buddleja in artificial xylem sap adjusted to a range of pH values. Points equal measurements of single stems.

Internal pH gradients

In 2008 Lancaster University tried to gain further insights into the underlying reasons for differences in the responses of sap chemistry to drought stress. We studied how sap chemistry is adjusted as it is delivered from roots to shoots among HONS species. If sap naturally alkalises as it ascends under well-watered conditions, then as transpiration slows under drought stress then the alkalising action of the components in the xylem vessels will have longer to act on a single unit of sap; thus compounding early alkalisation responses. However, if sap doesn't alkalise as it ascends, then the plant may lack the ability to do so under drought stress. In addition, those species that show acidification should have a gradient of acidification as the sap travels from root to shoots.

Buddleja, Hydrangea and Euonymus were studied due to the sap in each alkalises, acidifies and doesn't response to drought stress respectively. Stems of well-watered plants were excised in placed in a pressure bomb, where a balancing pressure was applied. Sap was extracted in increments, each progressively further into the tissue by applying an over pressure in 1 bar increments up to 10 bars. The volume of sap collected was recorded, the pH determined and the sap frozen and later its ABA content was determined by radio-immunoassay. To obtain xylem sap from lower stems and roots the root-ball was pressurized in a specialised pressure chamber for this specific task and sap was once the plant had been sealed in, the stem cut and an over-pressure applied.

It can be seen in Figure 5.2 that in Buddleja, as sap is extracted from further into the stem it becomes progressively more alkaline. In Hydrangea the pH first reduces for the first three extractions and then after four bars of over-pressure is excerpted the alkalisation seen in Buddleja begins. In Euonymus there was no significant change in pH as it is withdrawn from the shoots and leaves. In the roots, there appears to be some alkalisation of the sap as it travels into the shoots in Euonymus, while in Hydrangea and Buddleja there is no significant change in pH as sap travels to the stems.

In Hydrangea and Buddleja the ABA concentration increases as it travels out of the roots and into the stems (Figure 5.4). While in Euonymus it remains at very low concentrations throughout the transpiration stream. Euonymus was previously found to be highly anisohydric (poor control over its water status under drought conditions). The findings that it doesn't alkalise sap under stress, there is no natural alkalisation a sap ascends the plant, combined with a very low ABA concentration may be the underlying reasons for the anisohydricity.

The findings that Buddleja shows alkalisation in ascending sap, and Hydrangea exhibits acidification mirrors these species response to water deficits. It therefore might be possible to predict (assay) a plant species response type to drought stress without stressing them. However, to confirm this several other species will need to be tested to confirm the link between the pH changes as sap ascends and the plants response to soil drying.

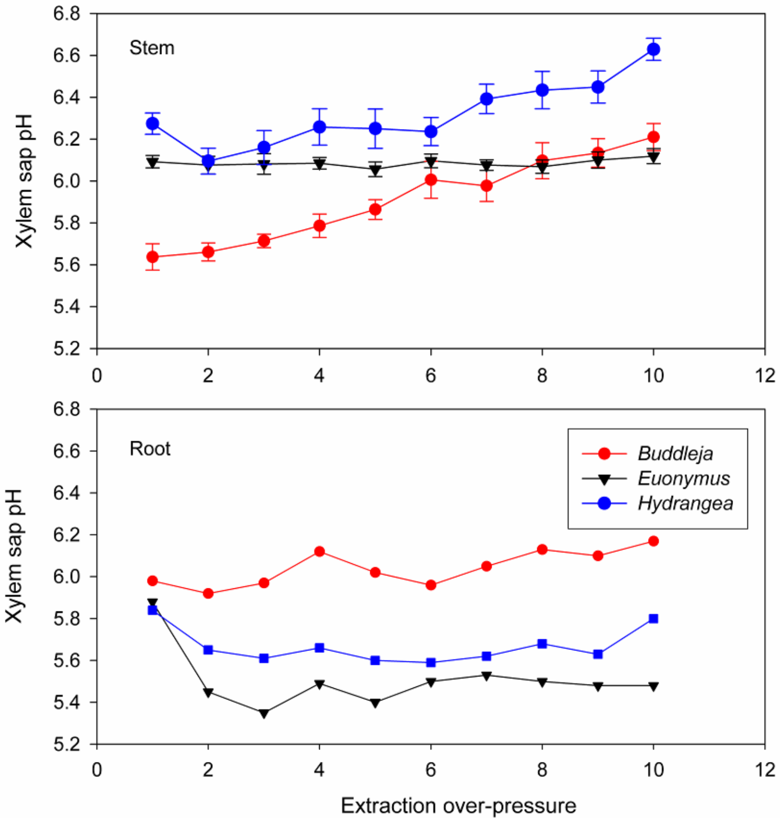

Figure 5.2. The pH profile of xylem sap as it is extracted from further into the shoots (above) or further into the roots (below) in three ornamental species.

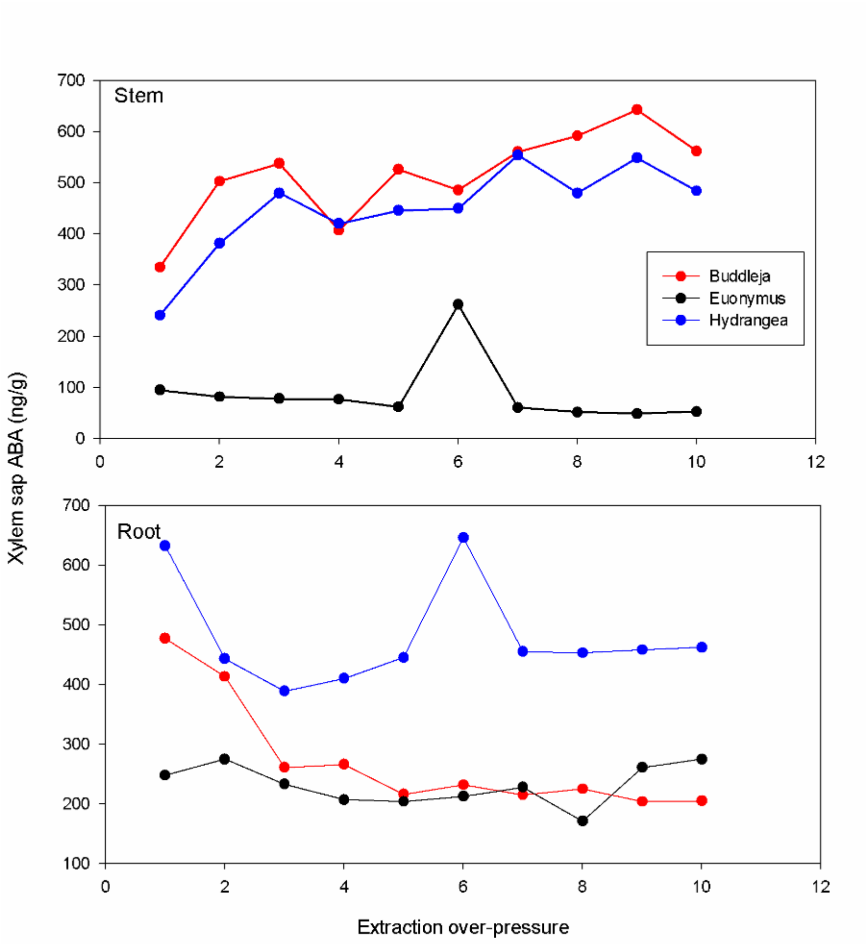

Figure 5.3. The ABA concentration in xylem sap as it is extracted from further into the shoots (above) or further into the roots (below) in three ornamental species.

Attempts were made to study the pH response to soil drying in xylem and phloem sap concurrently. Castor plants (Figure 5.4) were chosen for study because of their ability to exude phloem sap if excisions are made into the stem and there closeness to ornamental nursery stock. However, it was not possible to collect sufficient phloem sap under soil water deficits to obtain data on delivery and re-circulation of pH and ABA signals.

Figure 5.4. Castor plants used for the extraction of xylem and phloem sap samples.

Conclusions

- The applicability of both conventional and gantry overhead irrigation for scheduling deficit irrigation has been verified this year
- Deficit irrigation was shown not to have any detrimental effect on flowering of *Forsythia* ‘Weekend’. Deficit irrigation, even as severe as 50% ET_p, did not have any detrimental effect on quality of *Forsythia* ‘Lynwood’ after 3-4 months of application
- Scheduling using either an Evaposensor or a GP1 is suitable for application of deficit irrigation; thermal imaging also distinguishes clearly between fully irrigated and deficit irrigated crops

OBJECTIVE 7

Devise, construct and operate test rigs for automated precision irrigation based on thermal stress monitoring to test the feasibility of sensing and ameliorating plant stress at a single plant level.

Introduction

A key component of a successful test-rig will be systems for identifying plant/no-plant in the area to be controlled so that it is possible to measure the plant temperature unbiased by background. Dundee has therefore concentrated on the development

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and comparison of approaches for the extraction of vegetation temperature from images or scans with infrared sensors combined with sensors for the quantification of canopy cover. The first system (see earlier reports) developed by Dundee to test the concept of identifying thermal pixels that were plant and distinguishing them from non-plant pixels was a fixed system that incorporated two cameras, one visible and one thermal, and moving mirrors and an IR filter to obtain three images (thermal, visible and near infrared). The visible and near infrared images allow calculation of a Normalised Difference Vegetation Index (NDVI) which can be used to estimate the proportion of plant in the image. Although this system successfully achieved the objective, it proved rather too large and awkward, with sensitive moving parts, to use for handheld monitoring or for mounting on a gantry; this meant the plants had to be moved to the camera rather than the camera to the plants. Therefore we have investigated alternative approaches both to the development a mobile scanner and to the development of a possible component of an integrated system for incorporation on the test-rig for a gantry. The incorporation of an NDVI sensor will permit the gantry system to determine both (a) the true plant temperature from any temperature measured, and (b) will detect empty areas in the bed automatically and switch off irrigation over these areas.

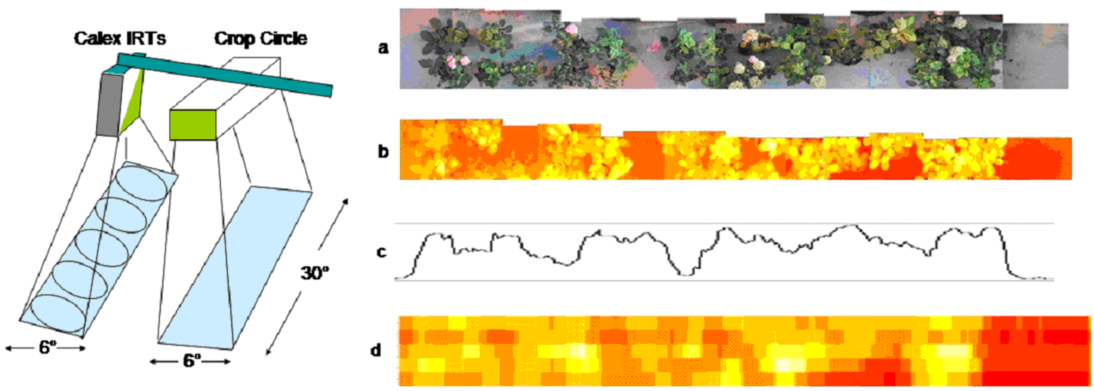


Figure 7.1 hand held sensor configuration.(left) a) Visible radiation stitched images from camera, b) thermal radiation stitched images from thermal camera c) Crop Circle™ scan percent leaf area reading d) Calex IRT thermal scan

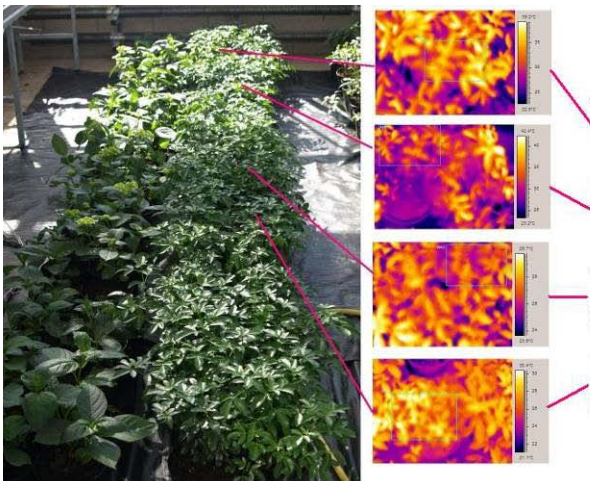
Initial trials of an analogue of the PERA sensor system were undertaken with an array of five Calex Convir EL infra-red temperature probes and a Crop Circle™ sensor. The Crop Circle™ is an "active" green leaf area sensor based on modulated LED illumination and R/NIR sensor that a single NDVI reading for an area of 6° by

30° corresponding to the area covered by the 5 calex sensors (see Figure 7.1). This system therefore gives 1 common NDVI value for all the temperature readings. Despite this relatively low resolution it can be seen from the scans in Figure 7.1a-d that the main features of the plant canopy are captured well by the low resolution mobile scanner. The breaks in the canopy are apparent as drops in the percent leaf area and the hot spots in the plant canopy are captured in the Calex scan data. It was not possible, however, to assess the individual temperature readings based on whether they were recording plant or background temperatures but only to obtain and correct an average temperature reading across the whole field of view.

The scan shown in Fig. 7.1 was made in a greenhouse where the concrete floor was much cooler than the leaf temperature. In this case the warm areas correspond with plant cover. The system copes equally well with the more usual summer conditions where the background is warmer than the plants. Quick calibration of the system by recording a representative background temperature is required for the system to determine the correct plant temperatures from combined thermal and NDVI data.

The next step has been to investigate methods for providing higher resolution canopy density data than the Crop Circle™ to correspond to the thermal data. Two alternatives are being developed in parallel to fit in with the shift in the approach being adopted by PERA from a thermal camera to a mobile linear array of point thermal sensors: (a) an approach based on the use of cheap red/infrared cameras to identify areas of plant scanned by the line sensor, and (b) an approach based on simple 650nm (red), 800nm (NearIR) sensor pairs collimated to the same field of view as the thermal sensors (6°). The former is designed to allow us to collect accurate data for calibration of the red/NearIR sensor pairs, while the latter is more a prototype of the real system for the gantry.

Recent work has highlighted key environmental challenges that a practical gantry system will face. Although the approach is based on the effect of water status on the canopy, the observed temperature is also affected by the ambient air temperature and also by the incident radiation (sunlight). In Figure 7.1 it can be seen that the temperature of the wet plants in full sun can be as much as 4° C greater than the dry plants in shade. Therefore for effective irrigation decisions it will be necessary to compensate for incident sunlight. We propose that this can be done either by using local reference surfaces that are experiencing the same incident sunlight, or else it should be possible to use the intensity of reflected radiation as indicated by the web-cams/NDVI sensors as a measure of incident radiation, and then use this directly with a single reference temperature in the correction.



	Min	Max	Mean	Std
Wet Sun	25.0	40.5	31.6	2.7
Dry Sun	23.3	41.5	33.7	3.0
Wet Shade	24.1	31.1	26.6	1.3
Dry Shade	24.6	29.9	27.2	1.0

Figure 7.1 Bed of Hydrangea and Choisya plants in dappled sunlight, table rows (right) correspond to adjacent thermal images and give temperature reading in °C for highlighted areas

System details and development

<u>(a) Two Camera NVDI sensor.</u>

The system uses the same principle as the earlier moving IR filter system except the moving mirror is replaced by a fixed half-silvered acrylic mirror. One camera was fitted with a lens and an IR blocking filter (>700 nm) the other camera with a filter that blocked visible light. (<700 nm). This provides an NDVI pixel map over the viewing area of the Calex sensors which can be used to provide reference data for calibration of other systems on leaf area. The system was lighter and more portable as a handheld scanner than the relatively heavy Crop Circle™ sensor. The new system uses two Unibrain Fire-I™ webcams, as these were to hand and Dundee already had expertise in programming video frame capture with these, although much smaller cheaper webcams are available that could provide the same 640x480 pixel resolution at around a fifth of the cost of the Unibrain cameras.

Figure 7.2 shows the construction of the NDVI sensor (left) and the combined handheld temperature/leaf area sensor in use (right). Currently the processing speed of the combined sensor is only 2 frames a second. This is not a problem when used as a spot-check or calibration system, but the speed may need to be increased as the system is used to scan a bed of plants. The rate of data capture depends both on capture of the raw data and the subsequent image processing steps, in particular the erosion step to remove noise pixels.

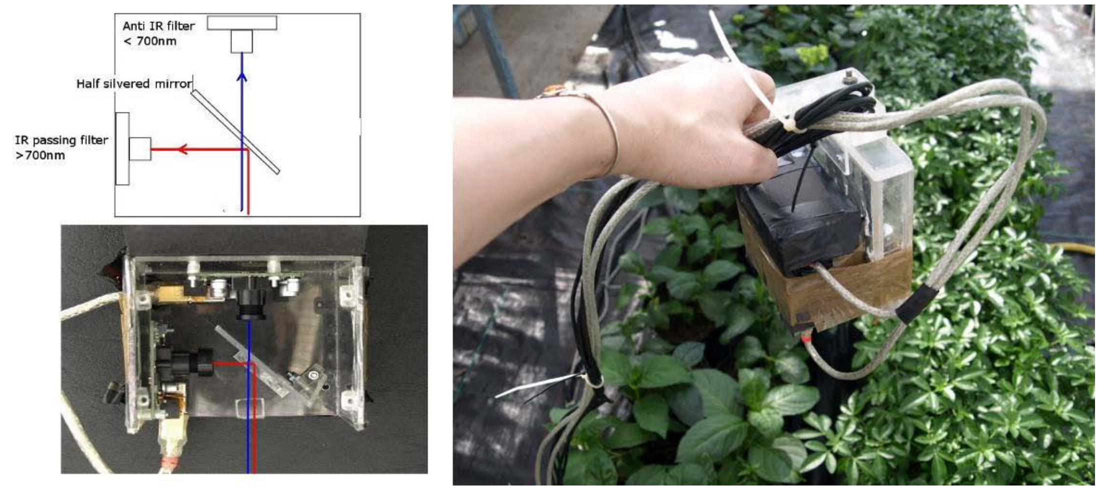


Figure 7.2 left: Twin webcam NDVI sensor construction. right: Hand held scanner NDVI sensor combined with Calex temperature sensor

The non-co-linearity of the temperature and NDVI sensors creates a potential parallax shift which varies with crop height, as illustrated in Figure 7.3, though the displacement is only a few cm which is unlikely to be a problem in most crop situations.

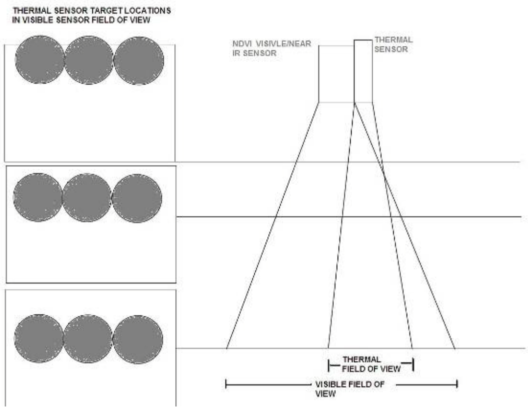


Figure 7.3 Parallax of non-collinear sensors causes shift in thermal sensor target areas in NDVI image, showing the shift of the thermal detector spots in relation to the camera image as the height of crop changes

<u>(b) Two Channel NDVI Sensor</u>

We propose that the production system for the gantry should be based on a system that provides NDVI data at the same resolution as the thermal data by grouping Red and NearIR sensors with each thermal sensor (Fig. 7.5) at each point on the gantry boom. We have been investigating the sensitivity of this method using a single set of three sensors (a Calex Convir IRT and two single channel light sensors supplied by Skye Instruments, one 650nm (red) sensor and one 800nm (near IR) sensor). As with the camera system there will be a similar issue with parallax, but the sensors are even closer together so errors are small. We expect that much cheaper red and NearIR sensors will be able to replace the Skye sensors in a production system.

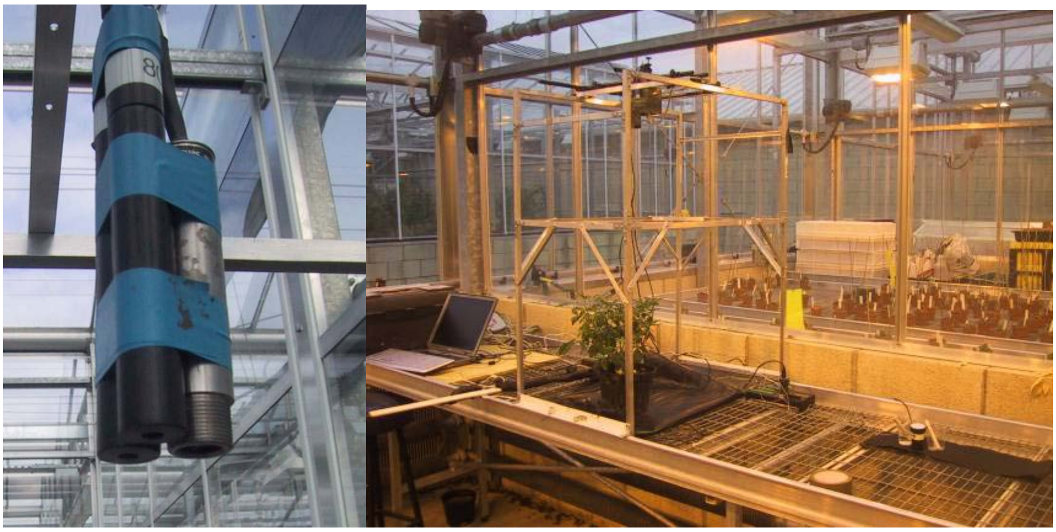


Figure 7.4 (left) Three sensor cluster with thermal sensor (8-14μm), red (650 nm) and near IR (800 nm) sensors, (right) Experimental setup with combined sensors and environmental references

<u>NDVI Temperature Correction</u>

If the canopy density is not 1 (i.e. leaves do not cover the entire area covered by the temperature sensor) the temperature measured by the thermal sensor will be a combination of plant temperature and background temperature. This is illustrated in Figure 7.5

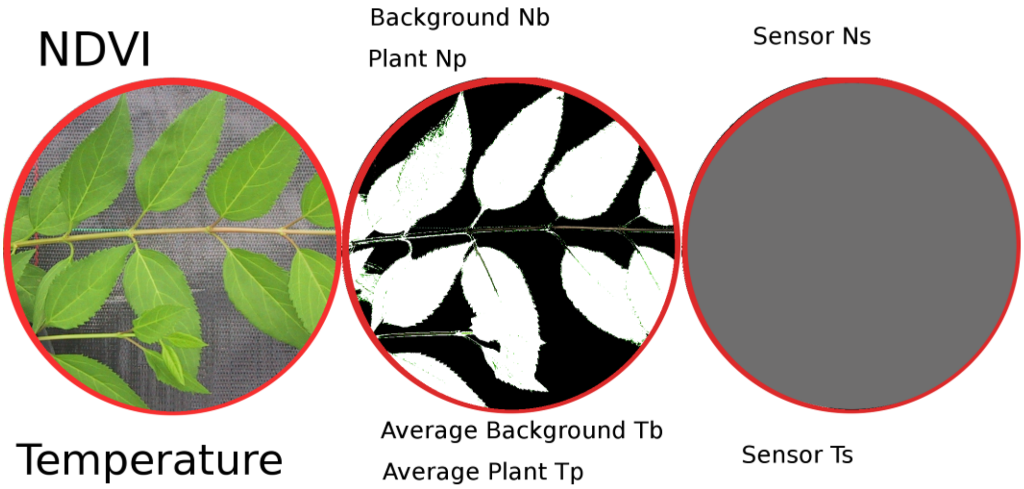


Figure 7.5 The area seen by the thermal sensor (red circle) corresponds to a mixture of leaf and background (left). The high resolution camera system identifies plant pixels (middle), while the two-sensor system provides an average NDVI proportional to the amount of leaf cover (right).

While the high resolution camera system can threshold the individual pixels in the focal area to give an accurate measure of fraction of view area that is plant, the single sensors can only give a single reading for the focal area. This means the sensor temperature T_s is an average of both plant temperature T_p and background temperature T_b.

$$T_s = T_p * N_p + T_b * (1 - N_p)$$

where N_p is the proportion of plant pixels in the focal area. If the background temperature is known but the plant temperature is not known the plant temperature can be derived by rearranging to give:

$$T_p = \frac{T_s - T_b * (1 - N_p)}{N_p}$$

The value of N_p for use in this equation is estimated from the relationship between NDVI and N_p, which needs to be derived separately for different sensor systems.

Incident Light Correction and Reference Temperatures

In order to determine whether the derived plant temperature represents a droughted or well watered plant it is important to correct for ambient and local environmental conditions so that the plant temperature can be compared with the expected temperature of a well watered plant in those conditions. As mentioned in earlier reports this was previously done by the use of reference surface temperatures. In the previous reports these references surfaces were local to the plant and experienced the same ambient air temperature, humidity and incident radiation. The use of local reference surfaces with the gantry irrigation boom is unlikely to be practical so we have investigated alternative strategies. One possibility proposed is that a single pair of reference surfaces (or even a single dry reference) could be used and the incident radiation on these be measured. For trial purposes we successfully tested a simple pair of references based on wetted and dry filter papers, and the incident radiation was measured using a Skye SKR1800 Two Channel Light Sensor (see Figure 7.6). Further evaluation suggests that a favoured option might be to use the reflected visible (650nm) sensor reading as a proxy for local incident light, and to have one dry reference which could be mounted on the boom or be fixed in one part of the glasshouse.

Figure 7.6 Wet and dry filter paper reference surfaces and Skye SKR1800

Vegetative Index sensitivity to environment

Although the camera system for proportion of plant was very precise, it was noticed that it was somewhat sensitive to the incident radiation. This is demonstrated in Figure 7.7. With the same NDVI threshold for each pixel of 0.4 in the image of a plant in the shade (top row) all the concrete background is thresholded out where as in the bright sunlit image large areas of concrete and compost are included. Therefore some operator input is required for highest precision.

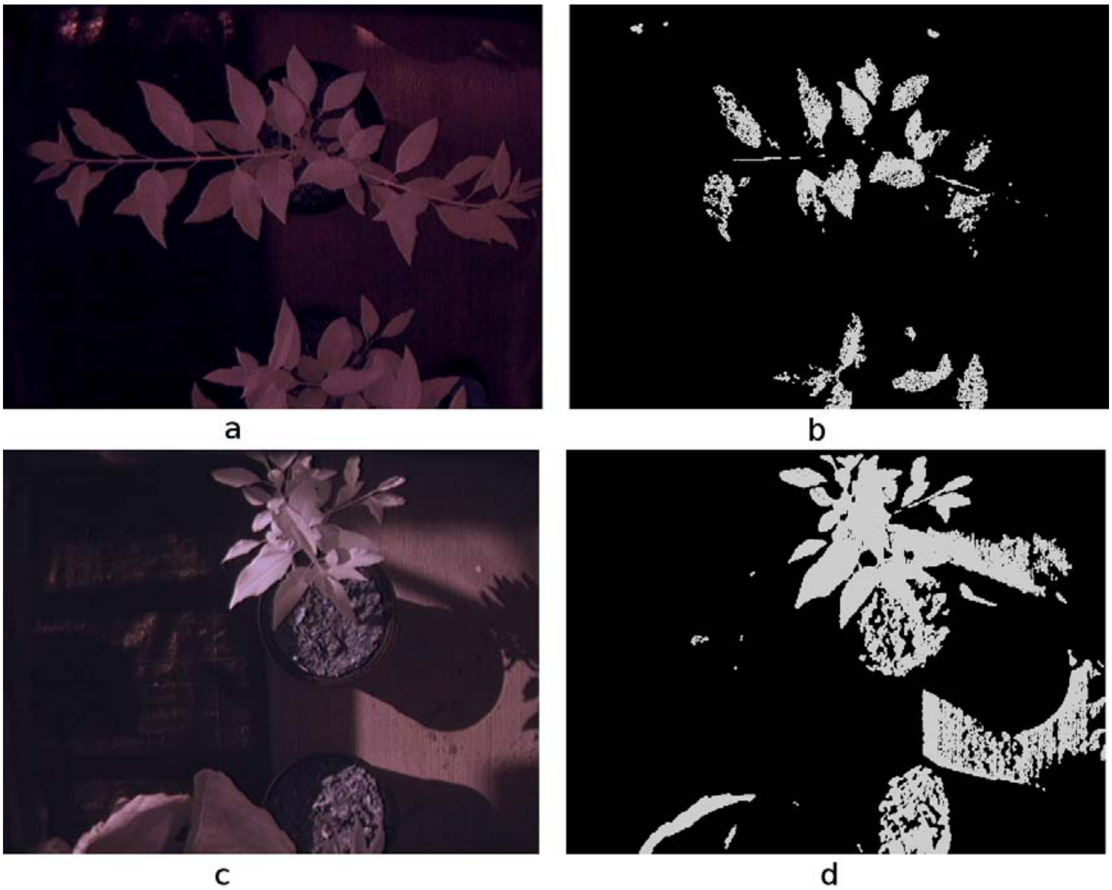


Figure 7.7 Incident light effect on camera system percentage plant calculation. a) NearIR image of plant in shade, b) Thresholded shade image at NDVI of 0.4, c) Near IR image of plant in sunlight, and d) Thresholded sunlit image at NDVI of 0.4 (showing the inclusion of concrete background in the thesholded area).

Investigation of the Skye Sensor System showed it not to be so sensitive to sunlight in this manner. Therefore we have concentrated in results presented in this report on the Three Sensor System.

Alternate Vegetative Index SAVI

We are also investigated the use of alternative vegetative index, the Soil Adjusted Vegetative Index SAVI. (Heute 1988). This index is supposed to be particularly good at correcting for varying background soil conditions. SAVI is calculated using the equation below,

$$SAVI = \frac{(1+L)(R_{NIR} - R_{VIS})}{(R_{NIR} + R_{VIS} + L)}$$

where *L* is an adjustable parameter between 0 and 1. That is related to the vegetation cover for high vegetation cover L is normally set to 0 then SAVI= NDVI and for low vegetation cover *L* is set to 1. For the results below we used a value of *L*=0.5.

Some test results

NDVI versus SAVI

The combined handheld scanner Figure 7.2 was used to scan rows of forsythia plants of varying sizes on a concrete background. The NDVI and SAVI were calculated using the Skye Single Channel sensors and compared to the measure of percentage plant recorded by the camera system. The results are shown in Figure 7.8.

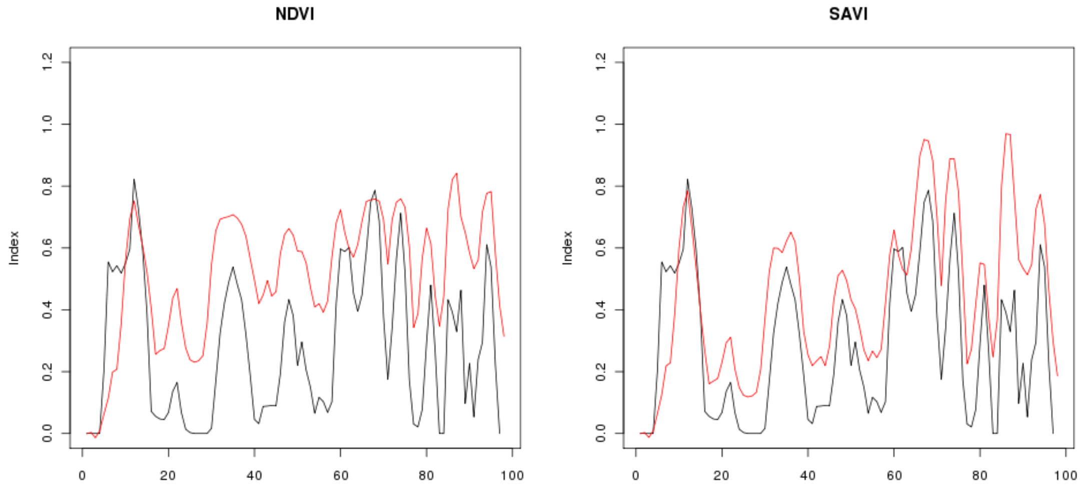


Figure 7.8 Skye Sensor calculated NDVI (red line - left) and calculated SAVI (red line - right) as compared with the camera system measured percentage plant (black lines) showing the generally excellent relationships, especially when using SAVI.

Both SAVI and NDVI capture the general features of plant size and gaps between the plants. It is noticeable that NDVI tended over estimate canopy cover when the canopy was thin and in the gaps between plants where as SAVI with the correction of *L*=0.5 matched the low density canopy better.

Environmental Variables Effect on Focal Temperature

In order to test the consistency of SAVI and NDVI measures over varying environmental conditions a test was run using the experimental setup shown in Figure 7.4 where a single well watered forsythia plant was placed under the fixed combined sensors and monitored continuously for a period of 8 days. On the fourth day the plant was moved to adjust the canopy area in the sensors' field of view. During that period there were four relatively sunny days and three overcast rainy days. During each day the incident light on the experimental plant varied due to clouds and changing shadow of roof structures such a support struts and extractor fans.

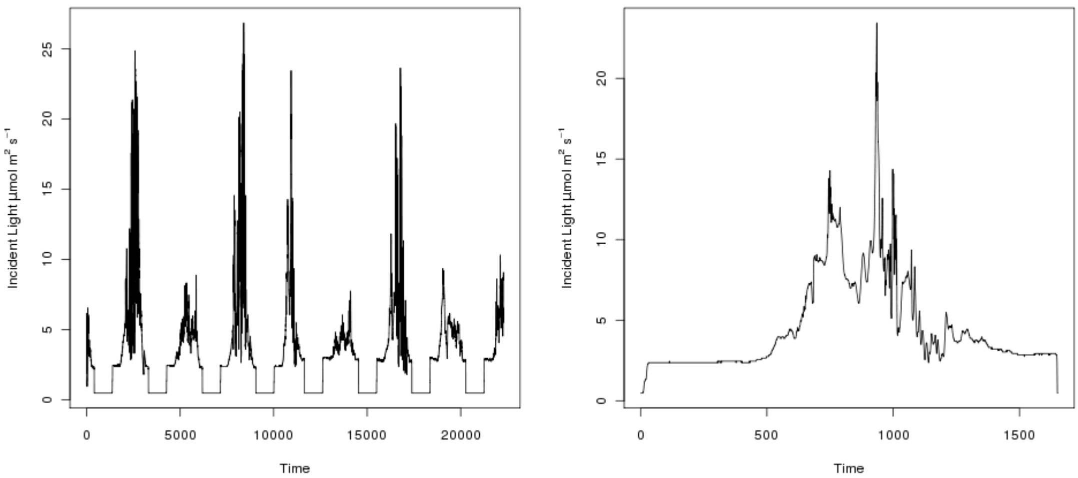


Figure 7.9 Fluctuations in incident light over a period of 7 days (left) and within the 4th day (right)

As a supplementary test, an IR sensor was also used to monitor canopy temperature over the period and a dry reference was also monitored using a thermistor. The glasshouse was temperature controlled with an automatic cooling fan and the activity of the fan is noticeable in the regular periodic fluctuations in the plot of dry reference temperature in Figure 7.10 . Figure 7.10 also shows a plot of dry reference temperature against incident sunlight, variation in sunlight explain 53% ($p<0.001$) of the variation in temperature. The glasshouse fan is likely to account for a large proportion of the unexplained variation in temperature.

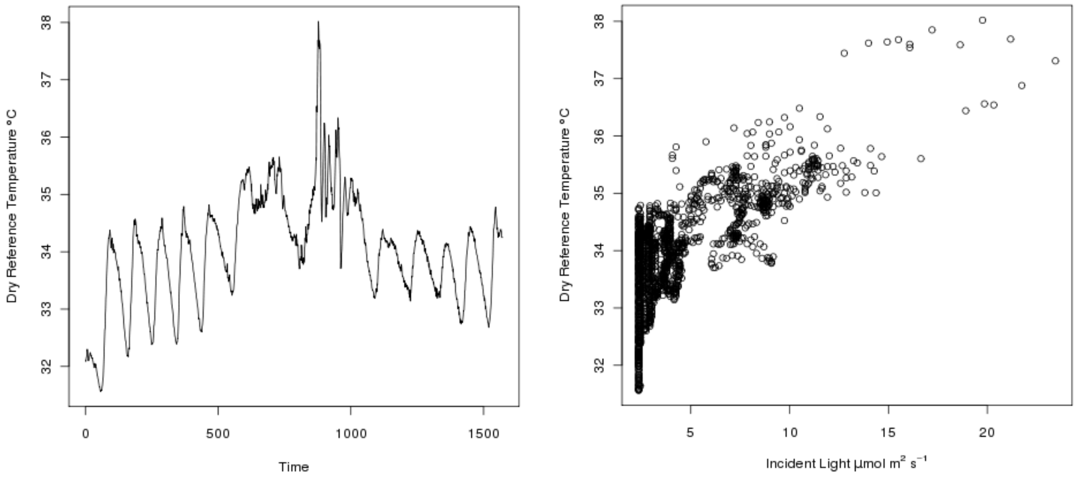


Figure 7.10 (left) Dry reference temperature fluctuations over time (right) Dry reference temperature against incident light

At low light intensities the NDVI/SAVI readings cannot be made. We therefore reduced the dataset by removing all values for times when the focal visible light sensor reading was less than 1 mV (in an operational system an even higher threshold would be likely).

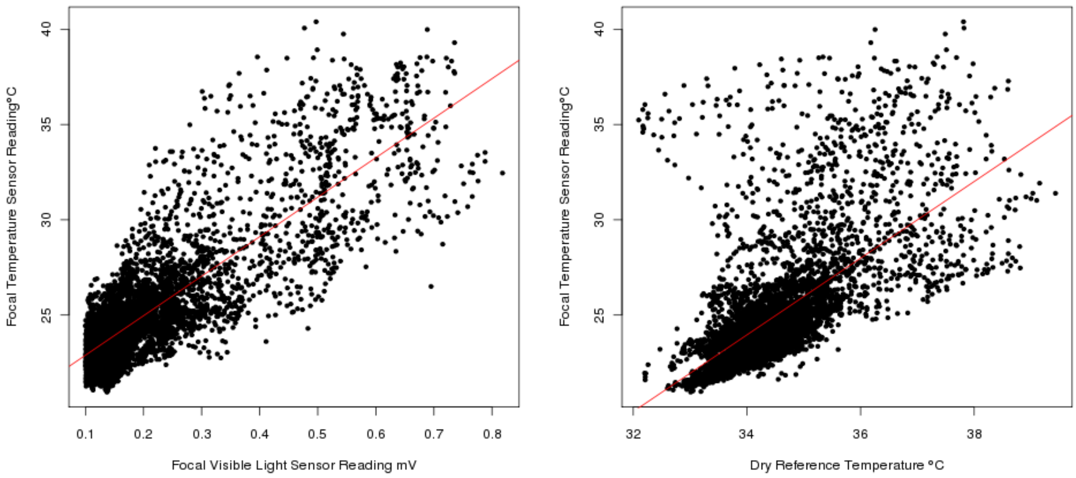


Figure 7.11 Focal Temperature Sensor reading against Focal Visible Light reading (left) and Dry Reference Temperature (right)

Figure 7.11 (left) shows clear relationships between the temperature of the focal area and the visible light reflected from the area. This is expected as the temperature of the focal area will be related to the incident radiation falling on the area and the reflected light will also be related to the incident radiation. The variation in reflected light (and hence incident light) explains 68% of the variation of the temperature of the focal area. A slightly lower proportion of the variation in canopy temperature is explained by using the dry reference temperature instead (Figure 7.12 right). The remaining variation is probably both attributable to (a) variation in air temperature (e.g. as a result of greenhouse control), (b) variation in canopy cover during the experiment, (c) diurnal changes in canopy stomatal conductance, and (d) thermal lags of the different materials.

In order to reduce the unexplained variation in focal area temperature when using only dry reference temperature or focal reflected visible light, we have tested a simple linear model combining dry reference temperature T_{td} and focal area reflected light R_{fv}:

$$T_f = \beta_1 T_{td} + \beta_2 R_{fv}$$

With this we can explain 75% of the variation in the focal area temperature T_f. This model can be further expanded to account for changes in percentage of canopy cover (on the 4th day of this experiment). The model above was expanded to include a term for focal area NDVI or SAVI reading (N) in the model:

$$T_f = \beta_1 T_d + \beta_2 R_{fv} + \beta_3 N$$

This explains 85% of the variation in the focal area temperature. For this data using the NDVI rather than the SAVI is marginally better but only by 1%. The further inclusion of an interaction term between Rfv and N (because the plant canopy and the background will have different reflective properties) increases the explained variation to a little more to 87%, with all terms being highly significant ($p<0.001$):

$$T_f = \beta_1 T_d + \beta_2 R_{fv} + \beta_3 N + \beta_4 R_{fv} N$$

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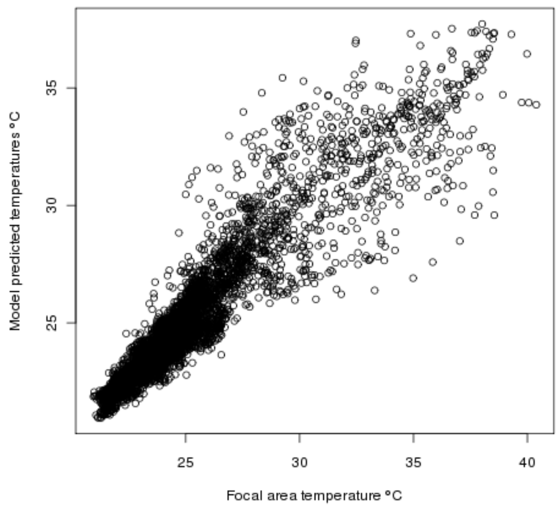

Figure 7.12 Plot of fitted model values against measured temperature values for full linear model.

A more mechanistically inspired model that has three terms, the focal reflected light and the dry reference temperature and an interaction term between dry reference temperature, the wet reference temperature T_w, focal reflected light and NDVI can also explain 87% of the variation

$$T_f = \beta_1 T_d + \beta_2 R_{fv} + \beta_3 NR_{fv} T_d T_w$$

Although there is relatively more scatter in the plot at higher temperatures, the overall fit seems reasonable and adequate for irrigation control purposes when one considers that there remains a real component of variation due to diurnal stomatal aperture changes, indeed it is this variation that one would be utilising in a control system, so the scatter is a measure of the signal that one would be using.

Conclusions

Our studies have confirmed that the proposed control system should include the following sensors:

(a) An array of downward-facing sensors on boom to estimate **plant** temperature

(1) Infrared temperature (long wave thermal sensor)

(2) Visible light (e.g. around 650 nm)

(3) Near Infra-Red (e.g. 800 nm)

(b) A set of additional sensors to allow the determination of the Crop Water Stress Index (see previous reports) for irrigation control. These could be located anywhere

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in the glasshouse, though there may be benefits in having some of these mounted on the boom to obtain local data. These would include essentially

(1) Air temperature

(2) Air humidity (or possibly a wet reference surface), but the former is easier to automate

(3) Dry reference surface temperature

(4) A measure of incident radiation (though this could be approximated using the reflected radiation from (a2) above).

There is a need for downward facing visible red light (650 nm) and near infrared (800 nm) sensor pairs to enable the boom to detect the presence/absence of plants and to correct the temperature for the canopy density; it will also provide a measure of reflected visible light as a proxy for incident radiation to correct for the local effects of sunshine and shade. A key to the success of the system will be the need to minimise errors in leaf temperature estimation as variation due to differing water status may only be a degree or so in extreme shade conditions (see Figure 7.1) though larger differences will be common in summer.

Further testing or calibration is required

(a) to determine the most robust conversion between NDVI/SAVI and leaf fraction in the focal area using R/NearIR sensors, optimised to the new cheaper sensors being developed by PERA

(b) to investigate the impact of differing time lags in thermal responses of background, canopy and air temperature in a real production environment.

(c) to finalise the control algorithm to be based on calculated plant temperature and the ancillary variables mentioned above.

Reference

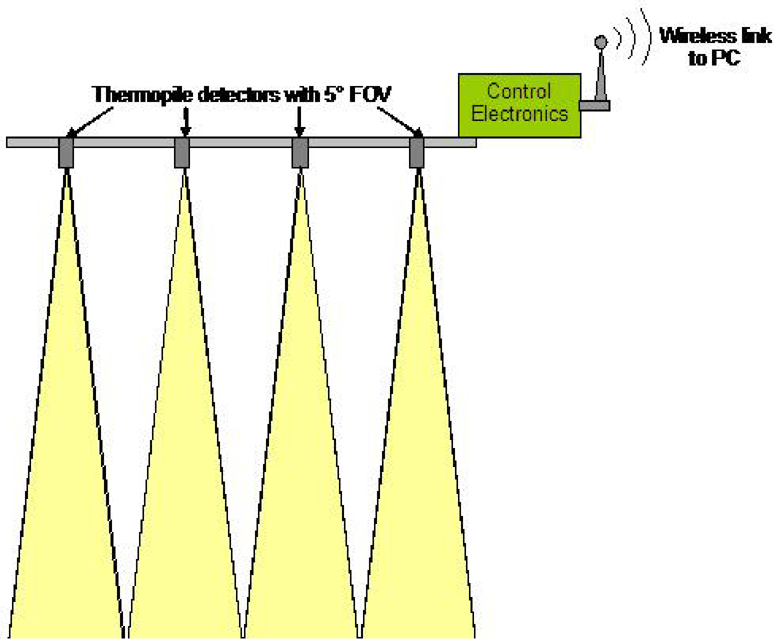
Huete, A. R. (1988) 'A soil-adjusted vegetation index (SAVI)', Remote Sensing of Environment, 25, 53-70.

<u>Pera</u>

Pera joined the project as a Scientific Researcher to assist by studying the options for automated control of irrigation utilizing a system of sensors. We are collaborating with the Department of Applied computing at Dundee University in developing their digital imagery system to assess plant stress, by building test rigs to allow a preliminary evaluation of the practicalities and potential of this approach for industry application.

Work Package 7. Is moving into the Modification and recommendation phase of the project, work is to continue with testing of the system and making design improvements

A schematic of the thermopile system.



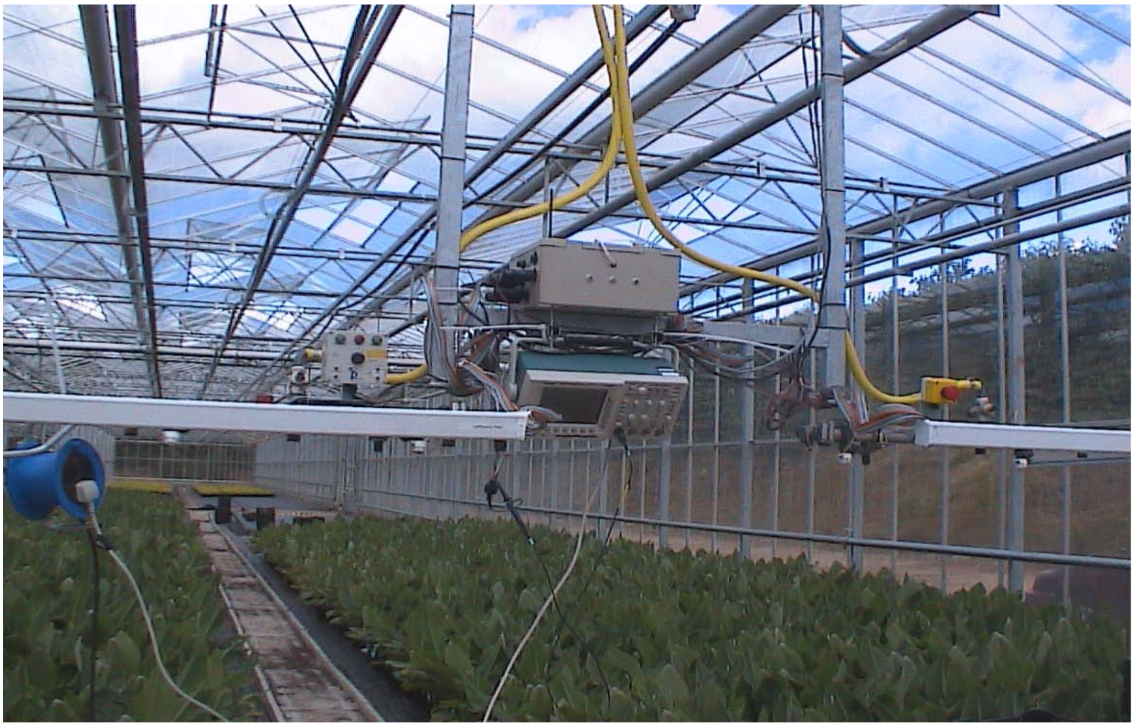
Representative Crop testing

Small thermopile test boom developed in year 2

The thermopile system with remote monitoring was developed to mount on the gantry watering system installed by Denton Automation a partner company at a Hilliers Nursery. A series of tests in a greenhouse environment was conducted to assess the performance and accuracy of the system, the readout from the system was transmitted wirelessly and proved to be very effective.

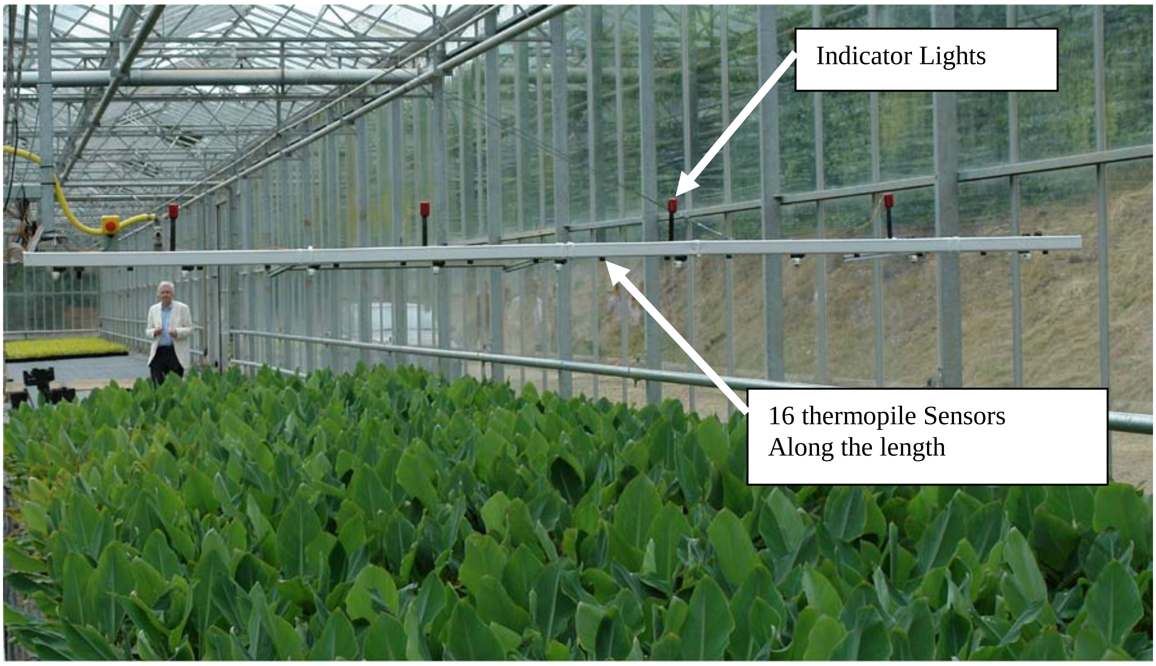
The thermopile system with remote monitoring mounted on a gantry watering system

Full bay width sensor boom now fitted to the watering gantry at Hillier's.



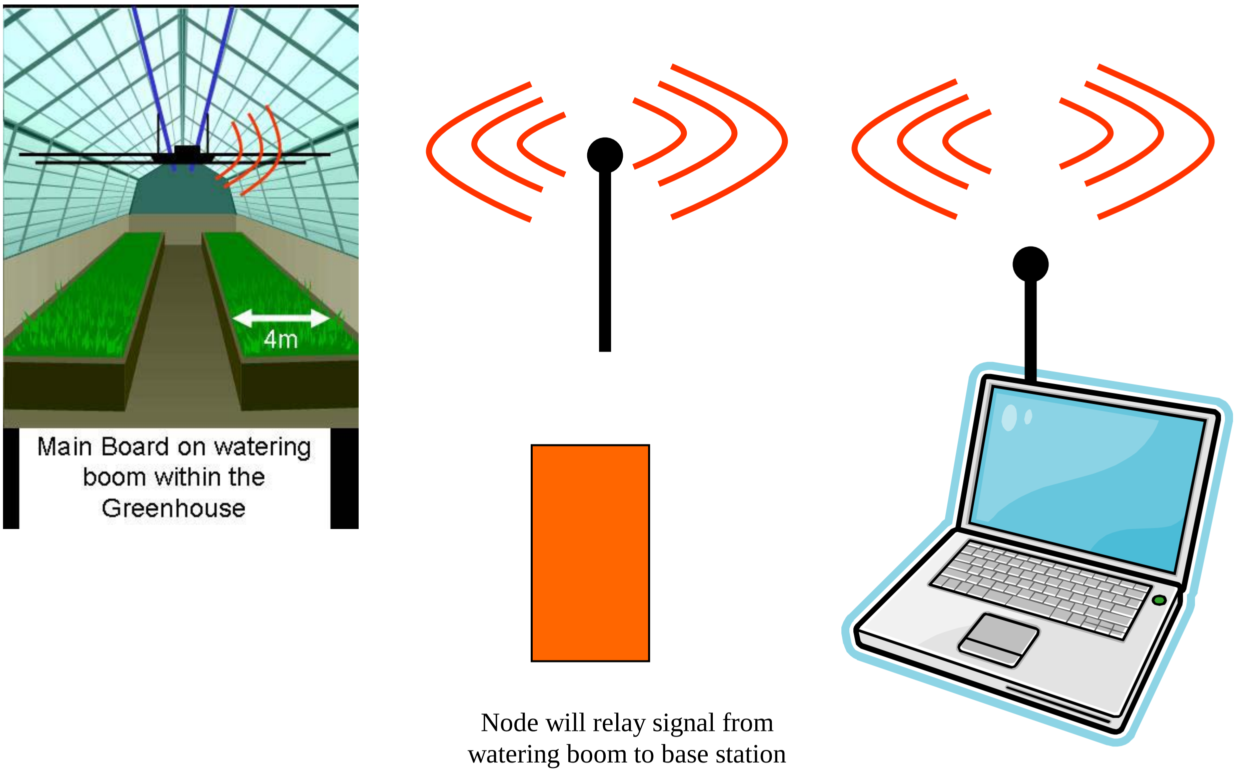
The sensor boom was installed at the end of June 2008; the sensors are performing well and appears to be unaffected by the watering process.

One of two 4 Metre sensor booms fitted to the watering gantry



The boom is fitted with 16 thermopile sensors and 5 Indicator lights, should the plants in area below the sensor be classified as being stressed and requiring additional water the indicator light will come on.
This light arrangement lets plants of varying condition to be placed under the boom to test the plant watering selection algorithm.

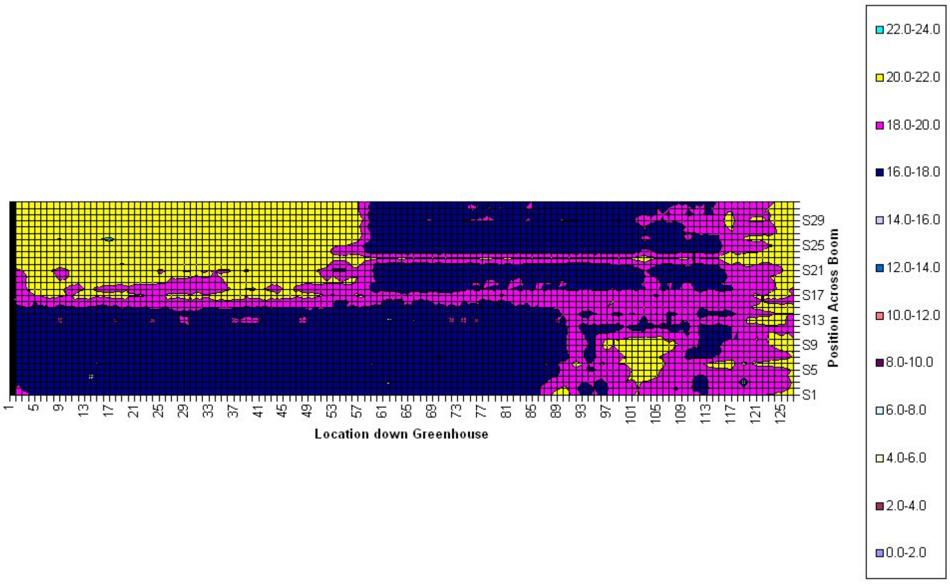
The wireless communications between the boom and a laptop computer have been an area that has proved to be problematic, due to the distance that boom now travels being 200 metres; this has been causing a loss of data. We are currently getting ready to fit the bay with a wireless node which will ensure there is no signal loss, even if the travel of the boom is extended.



Node will relay signal from watering boom to base station

The results over a shorter distance 50 – 100 metres have been most promising, as shown in Fig 1 there is a high contrast image with a 2 deg step in separation.

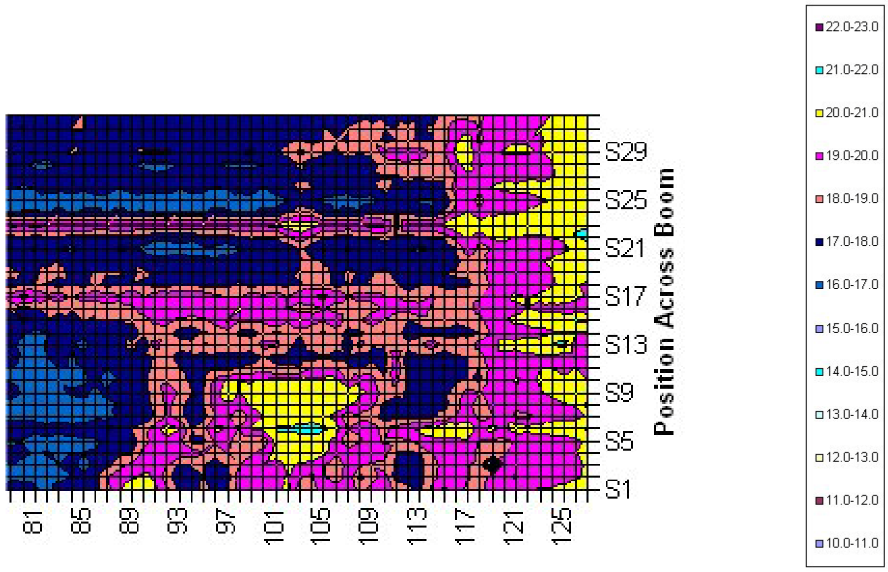
Fig 1



The yellow area shown in the Fig 1 graph is the hottest zone of the glasshouse which is the black membrane on the floor, the plants positions were cross referenced to the data collected and displayed in the graph and are very accurate. Where plants have been removed from the bed, a yellow area appears on the graph as this is where the floor membrane is exposed.

In figure 2 shown below, the scale is set to a step of 1deg. From the colours denoting plant temperature, the plants in the bottom half of the graph require attention as their temperature ranges from 16 to 20 degrees. It was noted that the plant stock in this area needed to be assessed as to their condition.

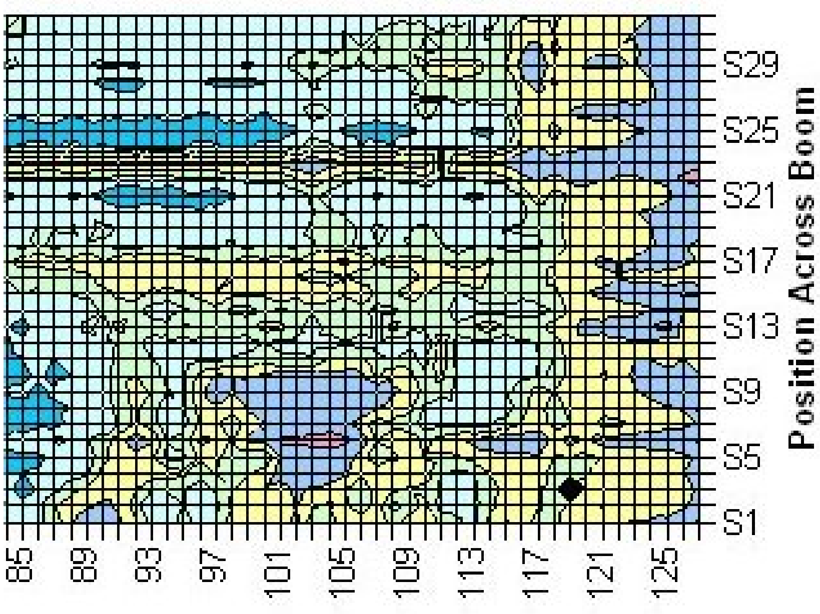
Fig 2



From the data collected the graph shows that the boom is functioning as intended and therefore next steps are to install the new wireless communications and updated software. After the upgrade a new set of trials are to be conducted where additional watering would be applied with the system fully automated. A manual check of the plants condition will be carried out where the additional water would have been applied.

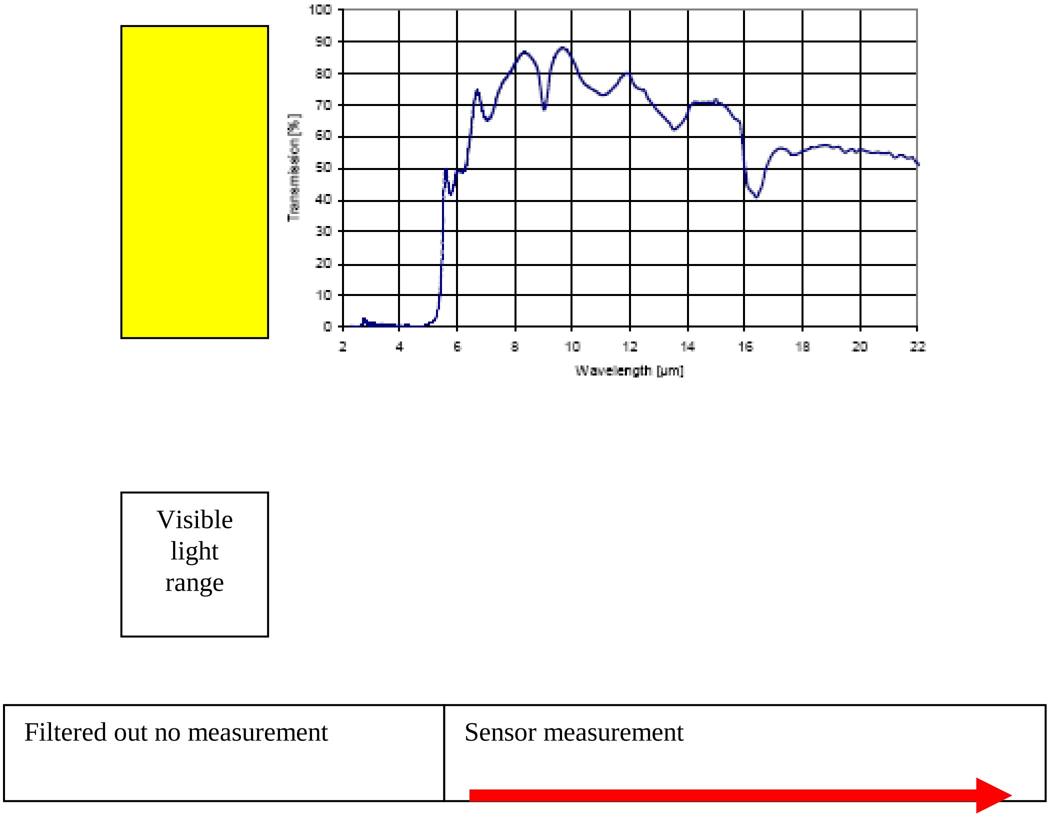
In fig 3 shown below with a colour change set for each 0.5 deg C a highly detailed mapping can be produced.

Fig 3



At the last meeting the issue of shadows falling across the beds of the greenhouse was raised as a possible problem in obtaining correct reading for shaded areas. The main supports of the greenhouse do throw a strong shadow in bright sunlight; the smaller components have very little effect due to the way light propagates.

The plant measurements are taken in the far infrared and not in the visible light range so the shadowing factor is not as dramatic as it may appear. No boom sensor readings taken to date have exhibited shadow patterns and a number of runs have been made in bright sunlight.



To verify the effects we have carried out a number of tests relating to plants in shadow to assess if there is any effect on the readings, and we are confident from the tests conducted on shadowed plants that the system will be able to provide us with accurate information.

<u>Plant, No Plant Detection</u>

We are also working on the plant, no plant sensor system with Dundee University, currently we are constructing a compact 3 sensor head, containing sensors for visible and infrared light which will used to detect if there is a plant present and a thermopile to take a temperature reading.

This unit when tested will be mounted in the sensor boom with all 3 sensors looking at the same area below the boom.

Conclusions from the testing so far

The tests conducted so far have determined that the thermopile system is accurate in a growing environment.

The temperature measurement boom at the size required can be directly mounted on a watering boom without requiring structural modification. The processed data can be directly fed into the control of the watering gantries PLC and positional data can be received from the plc

Data from the system can also be wirelessly transmitted to a PC on site, records of beds/ plants can be monitored and stored along with other data such as weather, feeds, temperature, humidity, sunlight, treatments, and pruning. This will create a valuable database which can be used in a number of ways predicting and controlling plant growth.

OBJECTIVE 9

Perform cost/benefit analysis of different methods of irrigation, stress sensing and plant growth control to inform investment decisions on nurseries. Report on conclusions of the study.

Introduction

It is important to make an economic assessment of the technology that will be coming to the market as a result of this project. More generally, the industry needs help to make rational investment decisions in relation to irrigation infrastructure (sprinklers, drainage systems, water recycling, etc.) and control systems (timers, soil moisture sensors, Evaposensor, etc.). Cost benefit analysis provides a systematic way of predicting the effect of an investment on the wealth of a company in terms of Net Present Value (NPV), Payback Period (PP) and Internal Rate of Return (IRR).

Methods

Cost information has been gathered for equipment that is already on the market. Data on reduction in hand watering achieved by improved water distribution have been provided by Palmstead Nurseries. Further data are being obtained using a questionnaire to gather best estimates of relevant costs and benefits, including intangibles, from experienced growers.

Results

Investing in equipment to apply water more uniformly (e.g. more/better sprinklers) or to avoid applying more water than the crop requires (e.g. Evapsensor/ GP1 control) will reduce water use but the price of water (even mains) is too low to produce a positive NPV. However, large investments will be justified if labour costs can be substantially reduced or revenues can be increased as a result of improved quality and/or reduced wastage. For example, a preliminary analysis of the economic feasibility of a gantry irrigator showed a large positive NPV from selling just 1% more crop due to reduced wastage and reduced need for hand watering and maintenance (Table 9.1). NPV increased as area irrigated by the gantry increased above a minimum economically viable area of about 500 m^2.

The outcome of a cost benefit analysis depends on local conditions and the equipment already available. Therefore, a software tool is under development which will help growers do cost benefit analyses themselves, tailored to their own facilities, crops, staffing and business context. It is being developed in Microsoft Excel and the aim is to make it both flexible and easy to use. The first version will be ready soon for evaluation by a sample of growers.

Table 9.1. Cost benefit analysis of an irrigation gantry, based on experience with the Denton gantry in a glasshouse at Hillier Nurseries, irrigating 1550 m^2 of crop (~ 200 m run). The table shows projected cash flows over a 5 year planning horizon. A discount rate is applied to future cash flows to allow for the time value of money. A rate of 15% was used, substantially more than inflation and interest rates to allow for the risk that predictions are overoptimistic. Notice that the gantry is predicted to have paid for itself after 2 years (i.e. PP = 2 y) and the accumulated net benefit after 5 years (i.e. NPV) is £7,203

Year	1	2	3	4	5	Total
Costs	**£s**	**£s**	**£s**	**£s**	**£s**	**£s**
Initial cost	6000	0	0	0	0	6000
Running cost	15	13	23	10	88	150
Benefits						
Tax relief	179	117	76	50	32	455
Water saving	15	13	11	10	8	57
Labour saving	2118	1842	1602	1393	1211	8165
Increased crop revenues	1213	1055	917	798	694	4676
Annual net benefit	-2490	3013	2583	2240	1857	**7203**
Cumulative net benefit	-2490	523	3106	5345	7203	

Some benefits of improvements in irrigation infrastructure are indirect or even intangible. For example, providing more uniform irrigation produces the indirect effect of enabling staff to schedule irrigation more precisely. State-of-the art systems raise staff morale and provide an environment in which staff can aim for higher standards of quality and uniformity, thereby raising staff productivity. We are exploring ways in which a monetary value can be put on that sort of benefit but it will often be better to consider those factors subjectively, *alongside* the results of the cost-benefit analysis, when making investment decisions.

Conclusions

A software tool for cost-benefit analysis will soon be available to growers in the consortium to evaluate.

Technology transfer

Presentations

H G Jones presentation on “Intelligent irrigation using infra-red sensing of plant stress" at “Horticulture: from science to appliance” Waitrose Supply Chain training day – University of Lancaster, 29 April 2008

H G Jones, presentation to meeting on “Water and its measurement in controlled environments” to the UK controlled environment User Group, Dundee, 1 – 10 September 2008.

Presentation at PISA08 international conference on “Plant responses to environmental stresses”, Elena, Bulgaria, 12-18 May 2008. “Thermal and other remote sensing of plant stress” (H G Jones and P Schofield).

H G Jones, seminar to CSIRO Plant industry, Adelaide, Jan 11, 2008 “Optimising irrigation”

Thermal imaging in precision irrigation. Invited oral presentation by OM Grant at the First Horticultural Symposium in Europe, Vienna, February 2008.

Efficient use of water in controlled environment grown crops – controlling plant growth and quality. Invited oral presentation by Chris Atkinson at the Controlled Environment Users Group (CEUG) meeting at SCRI, Invergowrie, September 2008.

R.G.Sharp Presentation to the ISHS 1st International Symposium on Woody Ornamentals of the temperate Zone in Pruhonice, Czech Republic

R.G.Sharp presentation at “Horticulture: from science to appliance” Waitrose Supply Chain training day – University of Lancaster, 29 April 2008

W.J. Davies presentation at “Horticulture: from science to appliance” Waitrose Supply Chain training day – University of Lancaster, 29 April 2008

W.J. Davies, Saving water in Agriculture, to Gordon Conference on Drought, Montana, USA. August 2008

W.J. Davies, Optimising irrigation and other water saving techniques, to launch meeting of Defra's Sustainable Agriculture Innovation Network, Yang Ling China. Oct 2008

Publications arising from the project

Dodd, I.C., Davies, W.J. Belimov, A.A. and Safranova, V.I. (2008) Manipulation of soil plant signalling networks to limit water use and sustain plant productivity during deficit irrigation *Acta Horticulturae* 792, 233-240.

Guilioni, L., Jones, H.G., Leinonen, I. and Lhomme, J.P. (2008) About the relationships between stomatal resistance and leaf temperatures in thermography. *Agricultural and Forest Meteorolog*y, 148, 1908-1912.

Jones, H.G. (2008) Irrigation Scheduling – Comparison of Soil, Plant and Atmosphere Monitoring Approaches. *Acta Horticulturae* 792, 391-403.

Loveys, B.R., Jones, H.G., Theobald, J.C. and McCarthy, M.G. (2008) An assessment of plant-based measures of grapevine performance as irrigation-scheduling tools. *Acta Horticulturae* 792, 421-427

Wilkinson, S. and Davies, W.J. (2008) Manipulation of the apoplastic pH of intact plants mimics stomatal and growth responses to water availability and microclimatic variation. *Journal of Experimental Botany* 59: 619 - 631.