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| **Project Title** | Enhancing the quality of hardy nursery stock and sustainability of the industry through novel water-saving techniques |
| **Project number:** | HNS 97b **/** HL0168 |
| **Project leader:** | Prof. Bill Davies, Lancaster University |
| **Report:** | Final Report, March 2010 |
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| **Date completion due:** | 31 March 2010 |
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# AUTHENTICATION

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

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# CONTENTS

# GROWER SUMMARY

## Headline

Evaposensor and moisture probe irrigation scheduling methods have been developed, tested and are now available commercially.  These offer partial automation of irrigation management that could lead to significant improvements in plant quality in addition to significant labour and water savings.  Practical techniques to control plant growth, including regulated deficit irrigation and the use of environmentally safe pH buffer treatments have also been further developed.

The potential for thermal imaging and thermometry for monitoring and controlling irrigation is now better understood, but requires further research and development before it can be offered to the market place.

## Background and expected deliverables

Using water more efficiently is important to the long term profitability and sustainability of the HNS industry.  Direct water cost savings can be important especially where mains water is applied, however, of more significance to HNS is improving profitability through better crop quality, reduced wastage and lower labour costs, in addition to the environmental benefits of better irrigation management.

Uniform water delivery is an important pre-cursor to effective scheduling of irrigation and for growth control via controlled application methods (e.g. Regulated Deficit Irrigation or RDI).  Sprinkler irrigation remains the most widely used method on nurseries compared to more costly, but potentially more uniform systems such as drip, flood and drain, capillary sand beds and gantries.  A better understanding of the factors affecting net delivery of water to containers from overhead irrigation was required to get the best out of existing systems.

The previous LINK project, HDC project HNS 97, had identified the potential for using both soil moisture probes, and evapo-transpiration sensors for irrigation scheduling in container-grown nursery stock.  Both these technologies required further development and evaluation for use on the nursery with a range of irrigation systems and for implementing RDI.  HNS 97 had successfully demonstrated that more compact plants of a range of subjects could be produced under RDI with uniform drip irrigation.  Practical methods for applying deficit irrigation on nurseries using sprinklers were now needed that minimised risks of crop damage.  HNS 97 had also indicated that it might be possible to mimic the growth control effects of RDI on plants through the application of novel 'fertiliser' treatments, but without the risks associated with water deficit irrigation.  These treatments were explored further as part of the project.

Many plants will control their level of transpiration by closing leaf pores (stomata) to conserve water in the early stages of water stress before visible wilting occurs.  This causes foliage temperatures to rise slightly compared to well-watered (non-stressed) plants where more evapo-transpiration keeps foliage cooler.  Detection of foliage canopy temperature, through the use of either infra-red thermometry, or thermal imaging, thus has potential for sensing crop moisture status and regulating irrigation. A further aim of the project was to see how thermal sensors / imagers could be used to detect dry plants or zones within a crop bed and apply water where needed using a precision delivery system based on gantry irrigation.

The output from the nine objectives of the project are detailed in the following Summary section.

## Summary of the project and main conclusions

### 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 (e.g. flood and drain, drip or gantry).*

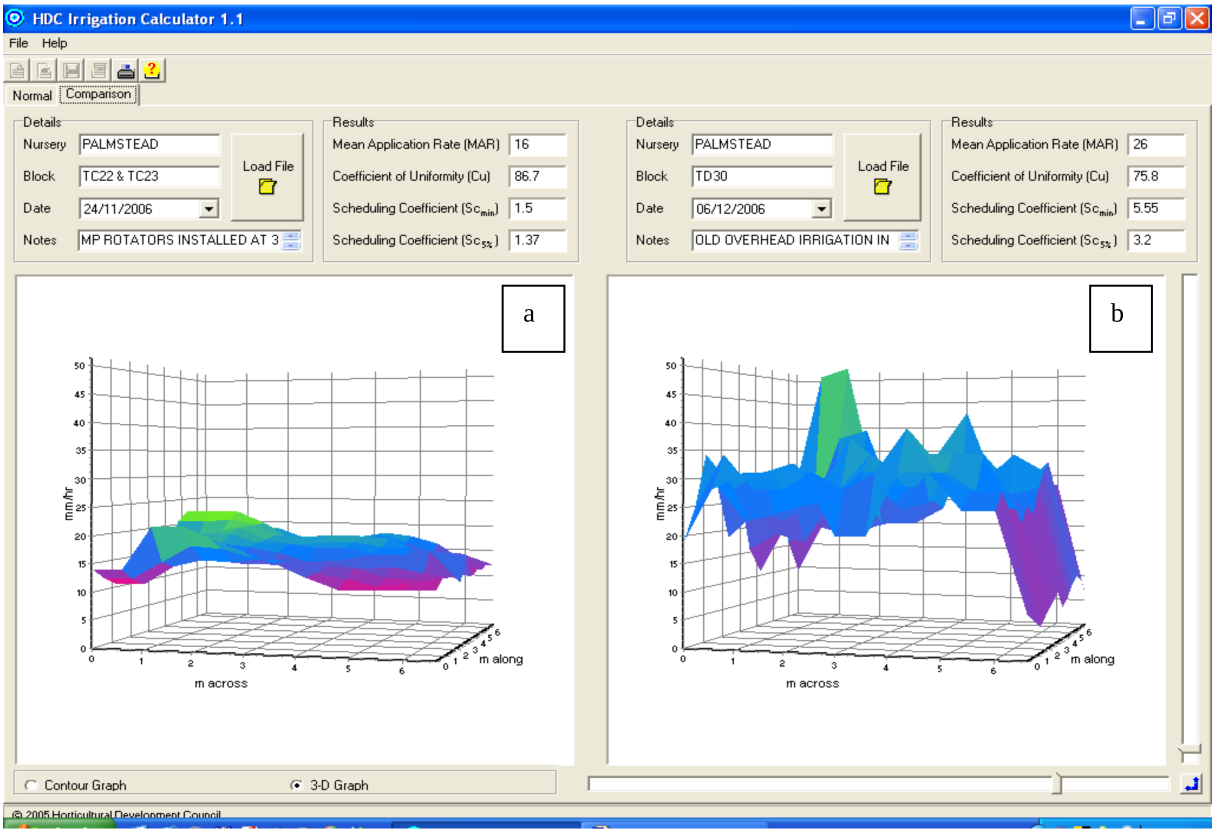
*Desk-based study on irrigation systems*

A desk-based study was used to gather information on the efficiency of different irrigation systems using a range of manufacturers' literature and websites.  The irrigation systems included various overhead sprinkler and spray line types, drip and mini spray-stake applicators, gantry and flood-and-drain systems.  The desk study report (2006) is available from the HDC, by request.

*Irrigation uniformity*

Improving uniformity of deposition from sprinklers does not guarantee uniform delivery to the container, but is an important starting point to get right first. Systematic variation in deposition can be due to poorly designed layouts often with too few or incorrect spacing of sprinklers with insufficient overlap of the spray pattern giving poor coverage, particularly along bed edges and corners. The wrong water pressure or excessive exposure to wind will also disrupt deposition from otherwise well designed systems.

Figure G.S. 1 shows how irrigation uniformity in a tunnel was improved by changing the sprinkler design and layout at Palmstead Nurseries, Kent. The poor deposition along the tunnel edge under the old system resulted in about 10 times the amount of hand watering during the summer compared to the new layout, indicating the economic importance of optimising sprinkler arrangements.



Details
Nursery: PALMSTEAD
Block: TC22 & TC23
Date: 24/11/2006
Notes: MP ROTATORS INSTALLED AT 3

Results
Mean Application Rate (MAR): 16
Coefficient of Uniformity (Cu): 86.7
Scheduling Coefficient ($Sc_{min}$): 1.5
Scheduling Coefficient ($Sc_{5\%}$): 1.37

Details
Nursery: PALMSTEAD
Block: TD30
Date: 06/12/2006
Notes: OLD OVERHEAD IRRIGATION IN

Results
Mean Application Rate (MAR): 26
Coefficient of Uniformity (Cu): 75.8
Scheduling Coefficient ($Sc_{min}$): 5.55
Scheduling Coefficient ($Sc_{5\%}$): 3.2

**G.S. Figure 1.** Irrigation deposition and uniformity measurements under MP Rotator 3000 sprinklers fitted at 3 m spacing in a new tunnel (a) and under Eindor vibro-spin nozzles hanging from the roof of an older tunnel (b) at Palmstead Nurseries. Low water capture was seen along the side of the tunnel in (b) as a result of the position of the sprinklers and their trajectory hitting the curved side of the tunnel.

A more detailed discussion of sprinkler deposition uniformity, measurement standards and suggested ways to make improvements can be found in the HDC Factsheet 16/05 ‘Measuring and improving performance of overhead irrigation for container-grown crops.’

*Standing base*

The project showed that the type of standing base could have a large impact on the net uptake (both quantity and uniformity) of water delivery to the container. Experiments showed that up to 50% of water uptake can be via the base of the container on a non-permeable bed surface (such as polythene covered by Mypex). The proportion of basal uptake was usually greater when plants were small (e.g. soon after potting), and interception of irrigation by the plant canopy was less. Compared to a free draining bed surface with no capillary action (such as gravel) where little or no basal uptake can occur, a non-permeable standing base can result in more uniformity of net uptake, but only if the bed surface is smooth and free from bumps and hollows. A slight slope across a non-permeable bed (e.g. 1 – 2%) allows surplus irrigation (and rainfall if outdoors) to run off (and be captured for re-use) and reduces puddling from minor surface irregularities. There was evidence, though, that too steep a slope resulted in a gradient in average pot moisture from driest to wettest down the slope.

A Mypex covering over the polythene layer not only protects the surface but was shown to have a significant ‘wicking’ effect, helping to spread water laterally and into the base of the container, thus extending the container’s catchment area, and limiting the rivulets and uneven flow that occurs with an uncovered polythene surface. The minimal water holding capacity of Mypex, compared to capillary matting, is an advantage when applying small doses of water.

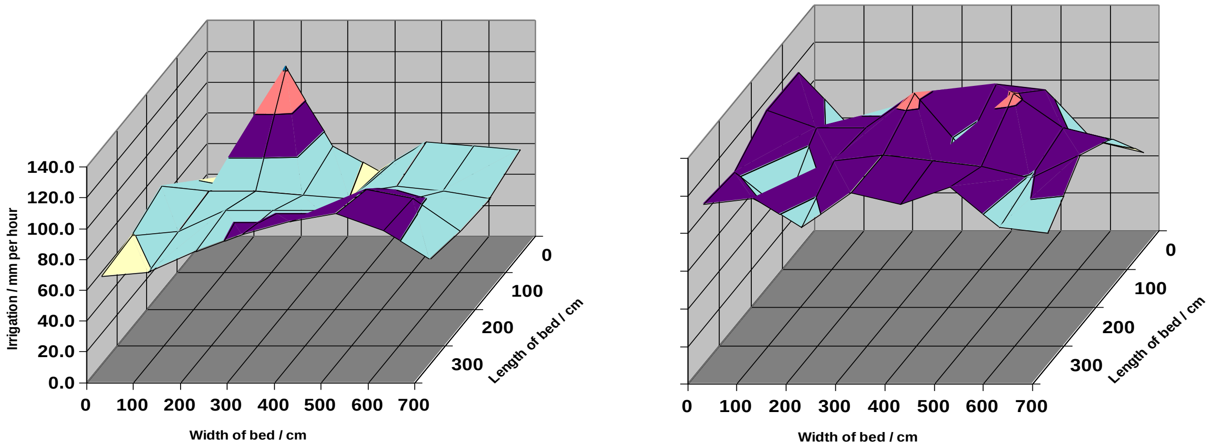
*Foliage canopy*

The foliage canopy has a significant impact on the proportion of uptake between the top and base of the container, and this will vary through the season as the crop grows. Even when foliage is not conspicuously funnel shaped (e.g. *Forsythia*), substantial amounts of water can be intercepted and directed into the container by running off leaves and down stems. With large *Griselinia* plants, delivery of water into the top of the container was almost five times greater than with a container without a plant. Unlike rain, water from many sprinkler systems does not fall vertically onto the crop but in a low trajectory. Plant height, as well as leaf area, therefore showed a strong positive correlation with water capture. Less water was 'collected' if foliage was wilting or had a drooping habit beyond the container, especially at a wide plant spacing where less of the shed water was intercepted by neighbouring containers.

While there is potential for the foliage canopy to disrupt irrigation deposition patterns resulting in non-uniform delivery from plant to plant, this may be ameliorated over repeated irrigation events, and by uptake through the standing base.

*Overhead sprinklers versus gantry system*

Trials compared overhead gantry and pin jet irrigation of ornamental banana, *Musa lasiocarpa* and showed that broadly similar measures (co-efficient of uniformity, CU and scheduling coefficients, SC) could be achieved.



**G.S. Figure 2.** Uniformity of uptake of pots on standing base for pin jet bay (left) (CU 84%; $SC_{5\%}$ 1.34) and gantry bay (right) (CU 89%; $SC_{5\%}$ 1.39).

A major advantage of a gantry over fixed systems, for HNS growers needing to mix crops within a bed, is being able to vary delivery of water down the bed to better match the water needs of different subjects. Varying run speeds or frequencies of irrigation along different sections can be programmed into the gantry controller with the use of position sensors. Irrigation from a gantry is also confined widthways to the target zone without needing overlap from lines over adjacent beds to achieve uniformity.

**Objective 2**

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

*Measuring evapotranspiration to schedule irrigation*

Evapotranspiration is the process where moisture is returned to the air by evaporation from the soil (substrate), and transpiration by plants via their stomata. The Evaposensor, invented at HRI East Malling (now East Malling Research), gives a measure of the evaporative demand on a crop (also known as potential evapo-transpiration, ETp). It is an elegantly simple and reliable device which can replace a costly weather station and computer. The sensor compares the temperature of wet and dry artificial 'leaves', the difference, known as the 'wet leaf depression' (WLD), being proportional to ETp. Just like plant leaves, the Evaposensor responds to radiation, wind speed, temperature and humidity, and it can be easily mounted where it will be exposed to the same environment as the crop.

In HNS 97, Skye Instruments developed the Evapometer to integrate the WLD values from an Evaposensor and display an accumulated degree hour (°C hr) total or 'Previous 24 hr total' to aid irrigation scheduling. A calibration procedure was required to turn a °C hr reading into the amount of irrigation for a specific crop and irrigation system. The original calibration proved too complex for busy growers, so a simpler alternative was sought.

*Alternative method for estimating Evaposensor crop calibration factors*

Working with a range of 12 HNS subjects of contrasting form and growth habit, it was found that most of the variation in water use could be predicted from plant height and percentage cover, i.e. the percentage of ground hidden by the crop. Percentage cover combines the separate effects of leaf area per plant and pot spacing and, with the help of a simple visual key, can be estimated accurately enough by eye, looking down on the crop from above. The analysis generated a formula for calculating the calibration coefficient required to convert Evaposensor readings into estimated irrigation requirement of any HNS crop. The formula for protected crops is slightly different for the formula for outdoor crops and, in both cases, provide a starting point for irrigation scheduling which could be then be adjusted if crop inspections indicated under- or over- watering.

*Automating the use of an Evaposensor for irrigation scheduling*

Nurseries typically have many irrigation zones or valves operated by multi-station controllers. Frequent manual adjustment of timers for each station is often difficult and impractical. So, towards the end of this project, a system for automated adjustment of daily irrigations based on an Evaposensor was developed and successfully demonstrated. It exploited the Evaposensor Control Interface (Electronic and Technical Services Ltd) that was developed in HDC projects HNS 159 / 159a for controlling mist propagation environments. The interface converted Evaposensor WLD to a voltage signal which was fed to a multi-station controller (Heron Electric Company Ltd) fitted with an analogue input card. The Heron integrated the signal and triggered an irrigation dose once a threshold WLD-sum had been met. 'Evapo-irrigation' control was tested on a single commercial bed of *Syringa* 'Red Pixie' under protection initially, but as confidence in the system grew, this was extended to a variety of subjects on six additional beds running off the same Heron, but using different dose settings for each station according to relative crop need. The starting point settings for irrigation dose times were approximated using the grower's previous experience of crop needs and sprinkler output rather than using a formal calibration procedure. These were then fine-tuned following weekly crop inspections.

Evapo-irrigation control makes management much easier and accurate, as the daily fluctuations in water requirement due to the weather are automatically adjusted for. This allows the grower to concentrate on more gradual adjustment of base settings to cope with plant development and fine tuning for different crop types etc.

*Post-project commercial developments*

Irrigation scheduling is a combination of dose and frequency. 'Little and often' is typically required for capillary matting with trickle lines and small pots / cell trays, whereas large containers will need heavier doses only every 1 – 4 days or more. Evapo-irrigation scheduling can now adopt two basic modes; a) fixed interval / evapo-varied amount, or b) fixed amount / evapo-varied interval. Modern Heron controllers can be configured by the manufacturer with software versions capable of either mode depending on grower needs. For mode a), program valve times could correspond to a 24 hr WLD-sum set-point (e.g. 100 °C hr for a 'standard' sunny summer day); the actual Evaposensor integral over the day would adjust all valve times by a 0 – 250% factor accordingly for the next irrigation. In mode b), an irrigation program is triggered whenever the WLD-sum set-point is exceeded; which might be several times a day when the set-point is low or a few days interval when high. In mode b), growers may wish to restrict overhead sprinkler irrigation, for example, to specific times of the day or night. This can be achieved by using 'stored starts' which are held to run later during an allocated time slot. Being able to apply a series of short stored starts as 'pulsed irrigation' instead of one large dose can also improve water absorption and reduce run-through. In either mode, base times for each valve or station in the controller program will reflect the differences in crop requirements under each station, and it is these that the grower will fine-tune in a gradual controlled way as guided by crop monitoring.

An important aim has been to enable growers to economically upgrade their existing controllers to evapo-irrigation where feasible. Recently, E&TS have launched a dedicated evapo-irrigation interface (Eii) with a built-in integrator with user-definable WLD-sum set point. One model of the Eii can also store 'starts'. The Eii can be fitted to a wide range of irrigation controllers provided that they accept a 'remote start' input. See www.ets-controls.co.uk for further details.

Although the Evaposensor will clearly register little or no WLD while exposed to rainfall, evapo-irrigation will not automatically account for water gain by the crop. Rainfall sensors available for some irrigation controllers, including the Heron, give some rough compensation by reducing valve times by a factor dependent on rainfall over a preceding period. Alternatively, the grower would manually override irrigation for example by clearing any stored starts on the Eii.

**G.S. Figure 3.** Evaposensor and E&TS Evapo-irrigation interface with display showing current WLD reading, °C hr set-point, and accumulated °C hr.

### *Measuring substrate water content to schedule irrigation*

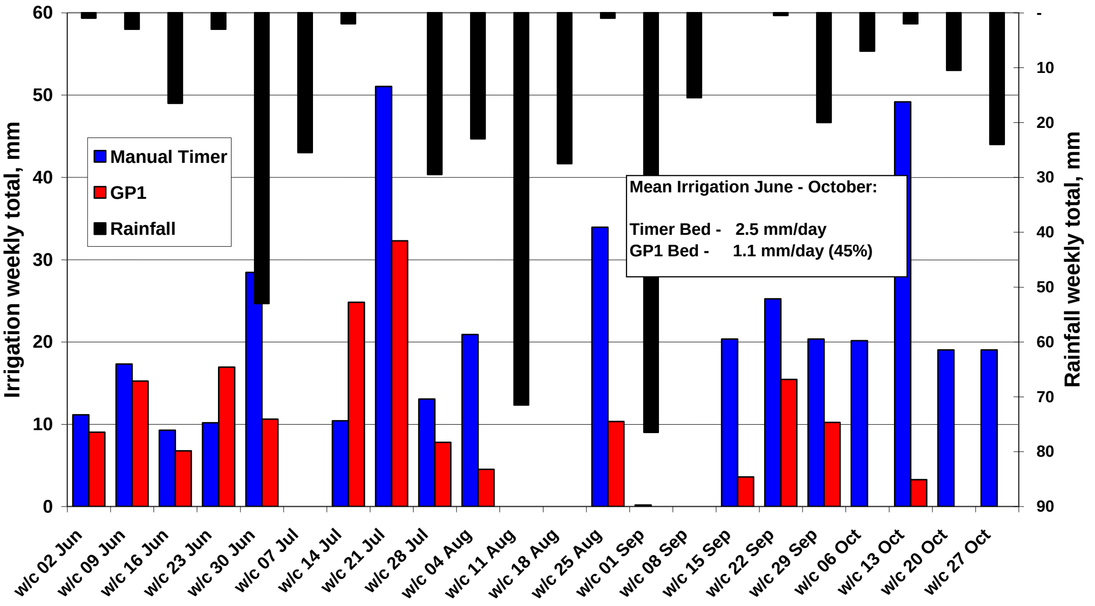
Scheduling irrigation using a moisture probe is a closed-loop control system with feedback from the probe enabling the complex of factors affecting water delivery and loss to the growing medium to be accounted for. Thus irrigation frequency and duration will automatically adjust according to weather (including rainfall), variations in irrigation rate, crop growth, interference from foliage canopy etc. Following project HNS 97, Delta-T Devices Ltd developed a relatively compact moisture probe, the SM200 and a compact logger / controller, the GP1, which were further evaluated in this project for precise irrigation control including RDI regimes.

The principles of moisture probe irrigation control are straightforward. Moisture content of the growing medium in a representative container is sampled by the GP1 e.g. every 0.5 – 1.0 hours. An upper and lower percent volume / volume moisture content is set by the user (typically a narrow 1 – 5% band), and when moisture falls below the lower level, the GP1 controller relay closes and allows the bed's irrigation solenoid valve to operate until the upper moisture set-point is exceeded. Numerous trials including those on commercial nurseries demonstrated that, providing the irrigation system and crop water requirement over the bed was reasonably uniform, a moisture probe in a single container could automatically control a large irrigated bed of 500m$^2$ or more. This is because the moisture status of the control container typically fluctuated in parallel with the rest of the crop. The choice of container for the probe was not critical provided it was not very atypical of the crop. For beds containing subjects with slightly different water requirements, it was best to install a probe in the subject requiring most water but adjust settings so that this ran slightly dry rather than too wet, thus ensuring other subjects received sufficient water. Starting set-points on the GP1 sometimes needed fine-tuning based on crop monitoring after one or two irrigation cycles, but then often needed no further adjustment for several months.

The Delta-T probes use a sophisticated technique measuring the soil's dielectric properties and are little affected by soil pH or fertiliser content, unlike simple probes based on electrical resistance measurements. Probes can be used in containers down to 1 litre, and the sensor's pins are best situated in the central zone (horizontally and vertically) within the growing medium. Moisture measurements are very sensitive to probes being disturbed, so the connecting wires should be securely fixed to the pots with tape.

The GP1 can link with the solenoid valve circuit of any irrigation system. Where nurseries restrict irrigation to particular times of the day, irrigation called for by the GP1 outside that time slot is simply delayed until the circuit becomes 'live'. It was important to allow enough duration of 'irrigation opportunity' in the main controller program for sufficient irrigation under GP1 control to be applied. The GP1 requires connection to a netbook, laptop or PDA device to interrogate logged data and adjust set-points etc. The GP1 allows 'pulsed' irrigation cycles to be used, as well as more sophisticated control parameters involving inputs from two or more moisture probes if desired, or temperature probes. Input from a water meter can also be logged, and critical examination of the stored data can give growers useful feedback about how water is being used by the crop and whether changes in schedules are required.

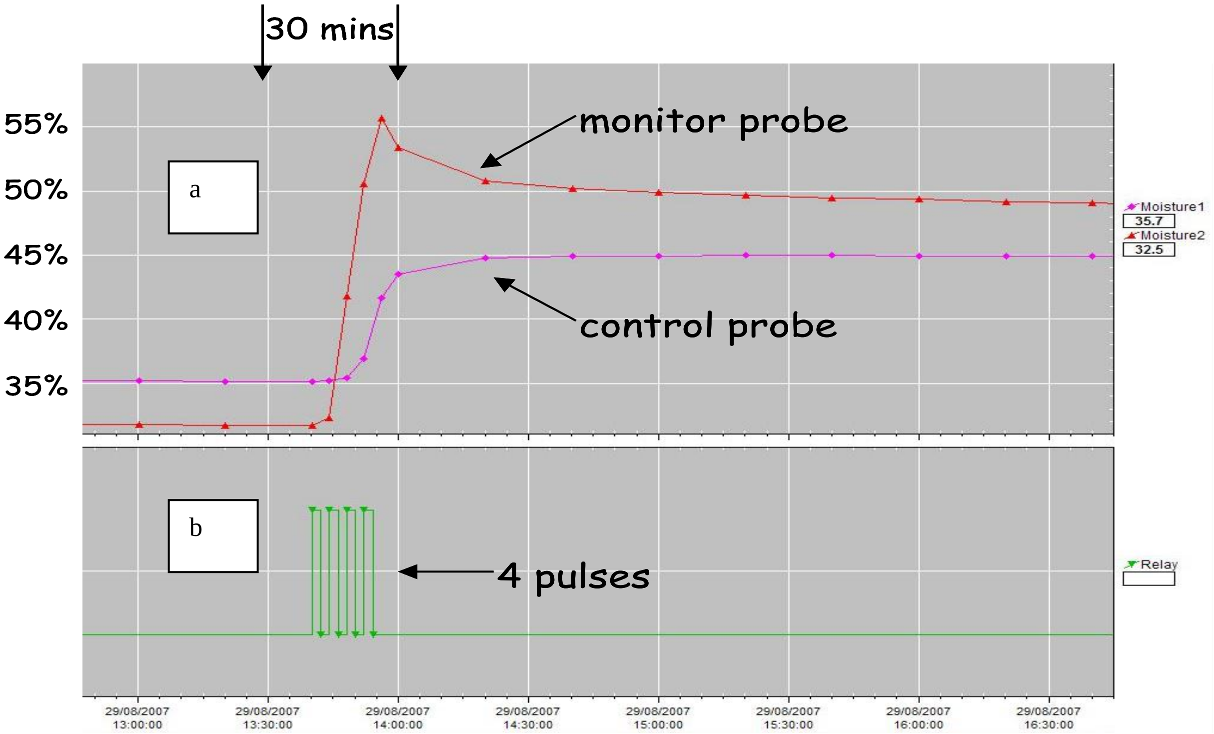
Significant savings in water use were shown in several of the nursery trials where GP1 / SM200 irrigation scheduling was compared to manually adjusted timer regimes. On large outdoor beds with 3 litre crops at Wyevale Nurseries, the GP1 beds used only 45% of the water over the summer on *Ligustrum ovalifolium* in 2008 and 64% on *Prunus lusitanica* in 2009, with less labour needed for irrigation management.



**G.S. Figure 4.** Weekly irrigation and rainfall totals on GP1 versus manual timer scheduled crops of *Ligustrum* in 2008 at Wyevale Nurseries.

The GP1 was used to trigger irrigation on gantry irrigated crops under glass at Hillier Nurseries (G.S. Figure 5) as well as those under pin jet spray lines.

**G.S. Figure 5.** GP1 logger / controller operating with gantry irrigation on a crop of *Musa lasiocarpa* at Hillier Nurseries. SM200 moisture probe inserted in 3 litre pot (insert).



**G.S. Figure 6.** Detail of one irrigation event for the pin jet bay at Hillier nurseries, with the program moisture set-points at 35% on / 40% off. Four × 2 minute pulses were applied (b); the scheduling pot (centre of bed) and monitoring pot (edge of bed at bottom of slope) continued to wet up after the irrigation stops (a).

G.S Figure 6 shows how logged data can provide details of the wetting up of containers following a pulsed irrigation event.

*Using moisture probes to implement RDI regimes*

Regulated Deficit Irrigation (RDI) is the process where plant growth is controlled by restricting irrigation (see Objective 4). The RDI irrigation level applied is usually expressed as a percentage of potential evapo-transpiration (ETp), i.e. the amount of water needed to maintain a reference set of plants in a well-watered and stress-free state. An Evaposensor can be used to schedule RDI regimes after calibration with the well-watered crop sample. Experiments in HNS 97 and this project have shown that 50% - 70% RDI treatments have given effective growth control on a range of contrasting HNS subjects.

This project compared using the GP1 and SM200 and Evaposensor to implement RDI regimes on crops of *Forsythia x intermedia* 'Lynwood', *Cornus alba* 'Elegantissima' and *Lonicera periclymenum* 'Graham Thomas'. Both scheduling methods under both drip and overhead irrigation successfully achieved growth control under the deficit regimes used. RDI cannot be defined precisely in terms of percentage moisture content as this varies with growing media and where measured in the pot, but in an experiment using a 100% peat medium, substrate moisture of about 28% corresponded to imposition of 50% RDI.

Deficit irrigation regimes were also achieved using gantry irrigation triggered by a GP1 giving growth control in commercial crops of climbing *Solanum,* and *Tradescantia*. The GP1 and probe gave a standard irrigation to one side of a glasshouse bay under one arm of the gantry boom, which received water from forward and return passes, repeated as required. The deficit irrigated half bay was watered from passes in one direction only, thus getting only 50% of the standard irrigation treatment.

To maintain closed-loop control, a separate GP1 and moisture probe(s) is needed for each irrigated station / valve, and so will incur a higher capital investment for controlling multiple beds than an evapo-irrigation system. Nevertheless, for large commercial beds, particularly if carrying crops of similar water requirement, the system may be an effective and viable option.

*Post-project commercial developments*

Delta-T Devices have discontinued manufacturing the SM200 probe, but this has been replaced by the SM300 incorporating temperature measurement and other improvements. The SM150 is a recent addition; the same dimension as the SM300 but without a temperature sensor, its accuracy is well suited for irrigation control and it offers a less expensive option for the grower. Software upgrades for the GP1 include additional features for more sophisticated irrigation control and data logging. See www.delta-t.co.uk for details.

Both evapo-irrigation and GP1 / moisture probe scheduling offer significant improvements in irrigation management, are available commercially, and have been adopted by several HNS nurseries since the end of the project.

**Objective 3**

*Determine the theoretical and actual performance of thermography and infra-red thermometry in direct comparison with other techniques for monitoring HNS irrigation.*

*Using thermography to measure plant water use*

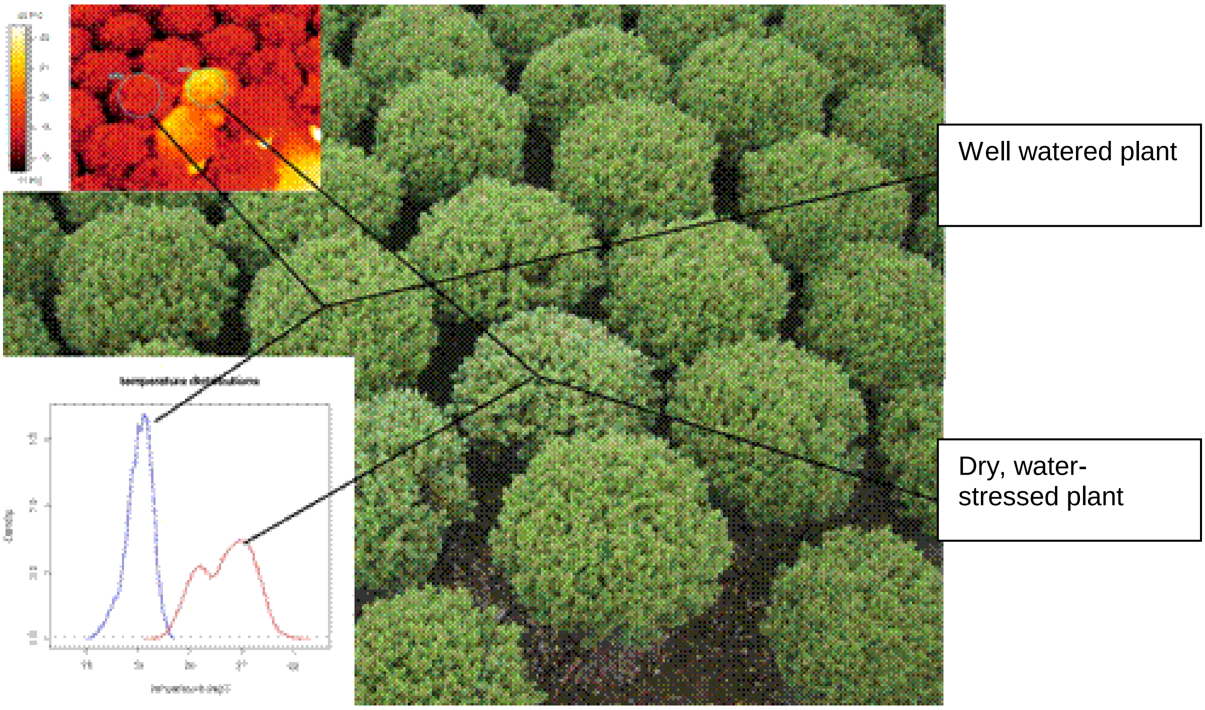
Thermal cameras can be used to measure whether plants are drought stressed and require irrigation, this is called thermography. The project explored the use of thermography in HNS under a range of conditions.

The stomata are pores in the leaf that are used for exchange of gases. Plants can control their level of transpiration by opening or closing their stomata and even prevent drought by closing the stomata to prevent transpiration. Thermal cameras were used to show variation in the leaf temperature when the stomata open (which causes plants to cool down) and close (which causes plants to warm up). Success in using thermography for monitoring HNS irrigation depends upon the extent to which stomata (and transpiration) are controlled as the substrate dries (see Objective 6). Leaf temperatures also depend upon a range of additional variables e.g. non-droughted plants in full sun are warmer than droughted plants in overcast conditions.

*Potential for using thermal imagers on the nursery*

Using a high resolution handheld thermal imager it was possible to identify not only individual plants in the early stages of water stress, but also uneven irrigation and specific irrigation failures on nursery crop beds, even when no variation in foliage was apparent to the naked eye.

G.S Figure 7 below shows the analysis of the images of *Hebe pinguifolia* ‘Sutherlandii’ taken by a high resolution thermal imager (FLIR Systems, Wilsonville, USA).



**G.S. Figure 7**. Normal and thermal images of *Hebe pinguifolia* ‘Sutherlandii’ using high resolution FLIR device. Insert top right: Thermal image clearly identifying water stressed (yellow) plants. Insert lower left: Analysis of temperature distribution of two plants showing stressed plant (pink line) is warmer by almost 1 °C.

These very high resolution cameras (e.g. 320 x 240 pixels) are currently prohibitively expensive for nursery use. Lower resolution imagers from InfraRed Integrated Systems Ltd, Northampton were also tried. A mid-range instrument, the Irisys 4010 with 160 x 120 pixels, was also capable of identifying stressed plants when observing relatively few plants at a time, but not very successful when attempting to scan large bed areas.

Greatest thermal sensitivity of plants under water stress occurs under conditions of low humidity, high irradiance and low wind speeds. Use of thermal imaging was less successful under dull conditions for example, or under glass on a sunny day where shadows from roof structure caused variation in foliage temperatures. There was also considerable variability between plant subjects in their thermal response to water stress and hence suitability to this technique.

### Objective 4

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

*The use of Regulated Deficit Irrigation (RDI) to control plant form*

Regulated Deficit Irrigation (RDI) has been shown to be an effective means of saving water without deleterious consequences to the crop for a wide range of species. HNS 97 showed that with HNS subjects, RDI could be applied to produce more compact and saleable plants in controlled experiments under precision irrigation systems. This needed further testing using overhead sprinkler irrigation and with substrates other than those based on 100% peat.

In this project it was found that RDI could successfully control growth in two *Forsythia x intermedia* cultivars, *Lonicera periclymenum* ‘Graham Thomas’ and *Cornus alba* ‘Elegantissima’ without reducing crop quality, whether overhead or drip irrigation was used, and whether plants were grown in 100% peat or a peat / bark (60% : 40%) growing medium.

Delaying the application of relatively severe deficit (50% RDI) until after pruning of *Forsythia* in June was very effective in maintaining plants in a compact form. A more moderate deficit treatment (70% RDI) throughout the growing season resulted in high quality crops in two separate experiments. Such a moderate stress treatment reduces the risk of damaging individual plants that receive less water than the crop average (as a result of non-uniformity of application and or uptake).

The density of flowering (flowers per length of stem) on *Forsythia* held over to the following spring was enhanced by RDI treatments due to reduced internode length (G.S. Figure 8).

**G.S. Figure 8.** *Forsythia × intermedia* 'Weekend' in flower during the spring following either RDI after pruning (at severe level (50%) and a moderate (70% level) through the whole growing season compared to full irrigation (150%).

The project has shown that, despite variation in delivery of water under overhead irrigation, RDI can be applied successfully with existing irrigation systems on certain plant subjects (under protection from unwanted rainfall). If applying RDI, particular care needs to be taken to place crops that need very similar watering requirements together under the same irrigation regime, and that other factors affecting uniformity of water delivery (Objective 1) are optimised as far as possible. Evapo-irrigation or moisture probe scheduling both offer a practical method of applying RDI. Even if strict RDI is not attempted, applying drier than normal set-points in a controlled way can be tested to save water and possibly achieve some useful growth control.

### Objective 5

*Identify physiological mechanisms underlying plant responses to Regulated Deficit Irrigation (drought) and novel 'fertiliser' treatments in order to optimise practical exploitation of such techniques.*

*Exploiting pH changes in the xylem sap*

Some plants respond to drought by altering the pH of their sap, but the naturally occurring xylem sap pH changes as a response to soil or substrate drying varied considerably across 22 species tested. For example, *Buddleja davidii* significantly increased xylem sap pH, in *Physocarpus opulifolius* pH was decreased and *Lonicera periclymenum* exhibited no change in xylem sap pH. Well watered plants of these subjects showing a contrasting response were then sprayed with a potassium phosphate buffer at pH 6, 7 or 8 to try and artificially modify xylem sap pH. After a single foliar spray, stomatal closure and leaf temperature rises were exhibited by all three species sprayed with pH 8 buffer, demonstrating that the treatment can induce ABA-regulated drought stress responses in well watered plants, even in some subjects where sap pH is not alkalised naturally following actual water stress.

This response to artificially raising sap pH with a corresponding effect on stomatal closure has potential use in the horticultural industry where reductions in transpiration, growth control and water consumption could be achieved more easily and safely than using RDI.

In another experiment on a commercial nursery, an alkaline buffer (pH 8) was sprayed on to *Euonymus fortunei* plants in 2 litre containers, to see whether water savings could be made. The degree of saving on irrigation water achieved depended on the prevailing evaporative demand in the growing environment. An average water saving of 11% was achieved relative to untreated plants, but this rose to around 20% during hot and dry periods. An experiment with *Forsythia x* *intermedia* showed that reduction in stem growth equivalent to a 70% RDI treatment was achieved using a root drench of pH 8 buffer.

Further work is required to develop the use of alkaline buffer treatments for a wider range of HNS subjects. However, current indications are that a 5 – 20 millimol concentration potassium phosphate buffer made to pH 8.0 should be suitable. The addition of an adjuvant appears unnecessary, and the buffer solution can be applied as a spray or as a drench (e.g. through dripper or spray lines). Effects from a single treatment may persist for 2 – 3 weeks. Potassium phosphate at this concentration should be harmless to the environment and could therefore be classified as an inorganic fertiliser.

*Using rhizobacteria to counteract undesirable effects of plant stress on crop quality*

Ethylene is an important plant hormone produced by plants to control various processes such as senescence, abscission and fruit ripening. Ethylene, or its precursor compound ACC, is also involved in plant responses to stress from wounding, drought or flooding. The inhibition of growth and promotion of senescence or abscission in response to stress may be undesirable for commercial propagation or production, so ways of reducing ethylene production or the transport of ACC from plant roots could be of benefit in horticulture and agriculture.

Specific plant growth-promoting rhizobacteria (PGPR) such as *Variovorax paradoxus* ‘feed’ on ACC produced by the roots by breaking it down with the enzyme ACC deaminase, and in sufficient concentration in the soil or growing media, can reduce ACC levels in the plant. In turn, this will reduce ethylene production, and could help protect the plant against stresses such as drought or flooding, or physical wounding including root damage. In this project, growing media was inoculated with PGPR *V. paradoxus* 5C-2. *Cytisus x praecox* is quite susceptible to leaf drop in summer when exposed to drought. PGPR inoculated plants given a drought treatment (50% RDI) showed significantly less leaf drop and enhanced flowering than non-inoculated controls. Likewise, late season leaf senescence on the herbaceous perennial *Aquilegia x hybrida* was reduced following an interrupted irrigation regime.

The results demonstrated that such rhizobacteria may have real potential use in horticultural propagation and production situations where plant stresses are unavoidable.

Further research is required to establish the life expectancy of bacteria in standard growing media, the optimal inoculation concentration and responses with other crop subjects, how persistent the effects on plant growth are and whether such approaches could become economically viable.

### Objective 6

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

*Understanding water loss and canopy temperature for use in irrigation scheduling*

Much of this work was designed to obtain basic information on the relationship between plant water status, growth and leaf temperature. Several species were grown under different irrigation treatments and average container moisture status, leaf temperature and stomatal conductance were then measured. Leaf temperatures, compared to reference temperatures of a standard surface in the same environment, were used to derive a Crop Water Stress Index (CWSI).

It is well known that some plants show particularly good control of plant water status by stomatal control. These so-called isohydric plants are ideal subjects for thermography (see Objective 3) because the leaf temperature is affected by stomatal opening or closure. Non-isohydric plants show only limited or slower stomatal control of water loss as the substrate dries and as such are less well-suited to the use of thermography for irrigation scheduling.

In the trials where the plants regulated water status well by stomatal control, the plant temperature was successfully detected by both the low-resolution IRISYS imager and the higher-resolution FLIR camera. *Hebe pinguifolia* 'Sutherlandii' was found to be particularly suited to the use of thermal imaging to monitor plant water status. Other promising species investigated include *Viburnum tinus*, *Hydrangea macrophylla* and *Forsythia x intermedia*. *Berberis darwinii* and *Choisya ternata*, however, did not show a good relationship between plant temperature and substrate moisture levels in these experiments. Generally, the growth stage of the plants appeared to be quite important in terms of stomatal response (and hence leaf temperature) to water stress, with differences best detected in smaller, more actively growing plants.

With species to species variation in response, the influence of growth stage etc., it is going to be difficult to use thermography alone to *define* irrigation regimes. It may be more promising to use thermography to provide feedback to adjust irrigation regimes set by another method for some plant subjects. However, clearly there is much further work to be done before this can be practically applied to control irrigation on the nursery.

**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 or local level.*

*Development of a test rig for automated irrigation using infra-red stress sensing*

Work focused on developing software and algorithms to extract plant temperature from thermal images or from point thermal sensors (as adopted in preference to imagers) later in the project. After a review of previous work on the use of thermal imaging for scheduling irrigation, a two-camera system was developed in the first two years, designed to acquire three images (visible, infra-red, and thermal) necessary to distinguish plant material from background. This two camera system was particularly useful for calibration purposes, but was considered likely to be too expensive for a production system. Therefore a thermopile sensor system (cheap temperature sensor) was developed as part of this system to reduce the cost of developing a commercially viable system. In addition, a plant sensor system was developed to ensure that the system only irrigates plants and not bare areas containing no plants such as paths or gaps in the bed. The original PERA sensors tested had too much 'noise' to provide reliable percentage plant data, though the sensors from Skye Instruments Ltd were excellent. Further effort is needed to source a cheaper set of light sensors.

The temperature measurement boom was directly mounted onto the irrigation boom of the gantry (Denton Automation Ltd) installed at Hillier Nurseries, where it could scan a bed of plants to determine the temperature status of a matrix of zones (approx 0.5m square) down the bed.

**G.S. Figure 9.** A temperature sensing boom containing 16 thermopile sensors mounted in front of one arm of the irrigation boom on a Denton Automation gantry.

**G.S. Figure 10.** Results from a scan of *Heuchera* plants on a sloping bed using the gantry mounted thermopile array. It shows dryer / warmer areas at the top of the slope (yellow / orange) and wetter / cooler areas at the bottom of the slope (green / blue).

Scanning tests demonstrated that temperature differences between ‘dry’ and ‘wet’ areas on a bed or those devoid of plants could be detected, and processed data could be wirelessly transmitted to a PC on site. This could then be monitored and stored along with other data such as weather, feeds applied, pruning treatments etc.

The next development stage required is to use the processed data to enable water delivery by the boom to be varied both across and down the bed. This could be achieved through the use of individually operated solenoid valves for each nozzle on the boom. This could help match irrigation delivery more precisely to dryer or wetter areas of the bed, but individual dosing of containers in this way presents a much greater challenge. It is likely that the fast data processing possible would allow the temperature scan and irrigation delivery to be achieved in one pass of the gantry. A design-for-manufacture study is now required to assist in taking the system to the market place.

### Objective 8

*Develop user-friendly guidelines for application of different methods of stress sensing and plant manipulation in nursery practice.*

Guidelines were presented at various technology transfer events throughout the duration of the work and will be continued to be delivered through key organisations, such as the HDC and East Malling Research.

### Objective 9

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

Many benefits of more accurate delivery and scheduling of irrigation were identified under four broad headings: (a). cost savings for labour, (b). maintenance and (c). water, as well as (d). an increase in crop revenues due reduced wastage and / or higher grade out. Savings in labour can arise in many ways, some obvious (e.g. less need for hand watering) and others less so (reduced moss and liverwort problem and therefore less hand weeding). Savings on the cost of water alone, even when mains water is used, are usually too small to justify substantial investment. However, there are some benefits that are hard to value in money terms, such as a company’s environmental reputation or a staff ethos of attention to detail. These must be weighed up alongside the economic benefits.

A cost benefit analysis tool was developed and used to study the economics of investing in three of the technologies investigated in the project: automatic irrigation scheduling, either by Evaposensor or by soil moisture probe, and gantry irrigation. The output summarised in G.S. Table 1 is a representative example but will not apply to all crops or all nurseries. It shows that investment in any of the three technologies is economically attractive, particularly the two systems for automatic scheduling.

Automatic scheduling was estimated to reduce water use by 25% but the saving on the cost of the water contributed little to the financial benefit. Even using mains water, the saving on water cost is much less than the saving on labour, particularly when careful restriction of irrigation is used to reduce the need for hand weeding. By avoiding over-irrigation, automatic scheduling can also reduce plant wastage, but this was not a factor in the trials at Hillier Nurseries where manual scheduling of irrigation was well managed.

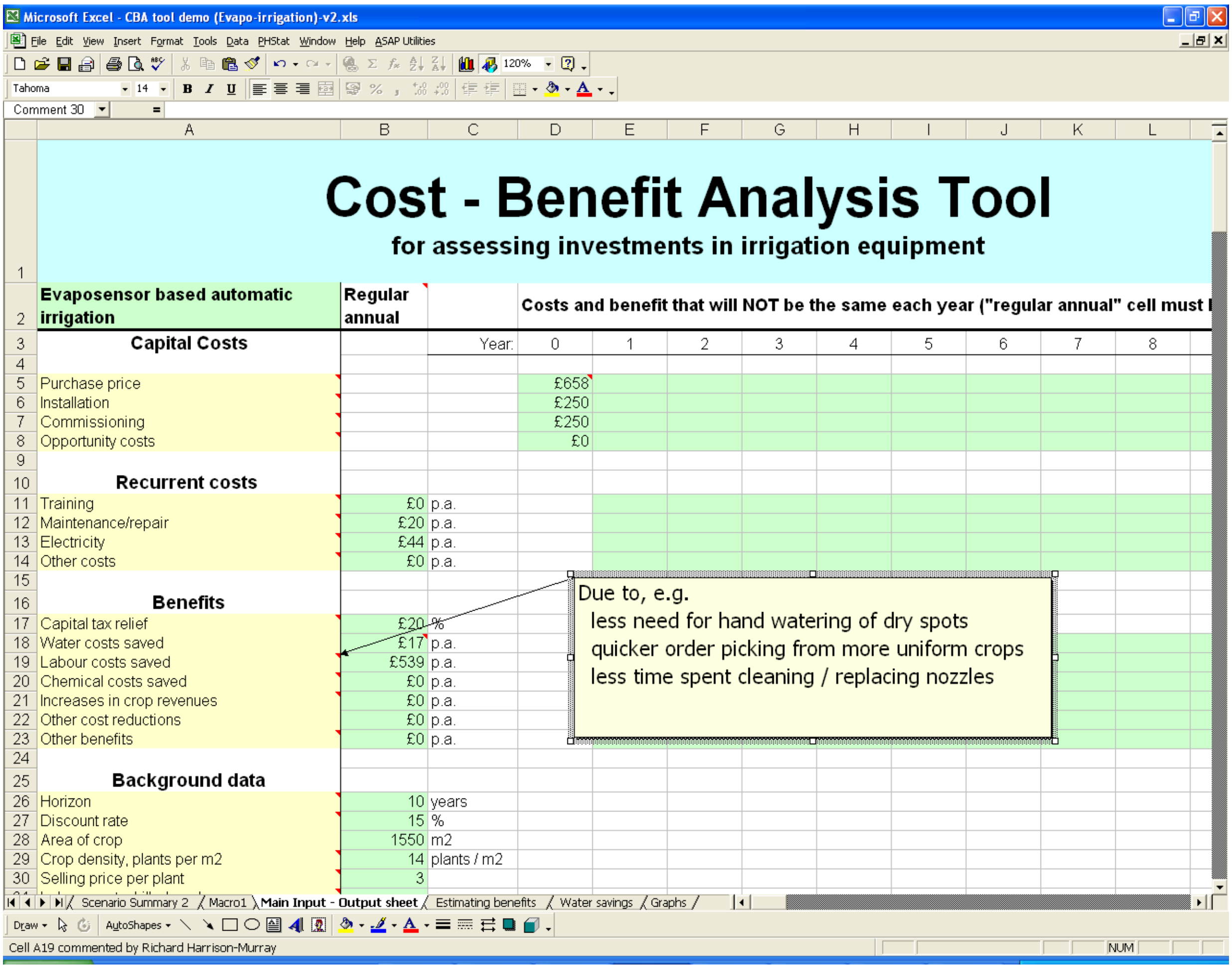
Based on experience during the trials, two factors were particularly important in offsetting the large capital outlay for a gantry: (i) less plant wastage, probably due to more uniform watering and (ii) avoiding the labour of maintaining a large number of overhead nozzles. Whether such benefits are large enough for a gantry to be a good investment will vary from one nursery to another, depending on local factors such as how non-uniform is the current irrigation system. The cost benefit analysis tool is designed to help growers compare the cost benefits of different systems under their particular circumstances.

In most cases, the initial capital investment is the major cost of improving irrigation, but using cost - benefit analysis helps ensure that the cost of running and maintaining equipment is not overlooked. Over a 10 year planning horizon even the consumption of just 50 watts of electricity by a small control panel is surprisingly large.

**G.S. Table 1.** Cost-benefit analysis of adding three alternative irrigation technologies to one bay (1550 $m^2$ of crop) of the glasshouse at Hillier Nurseries, showing predicted costs and benefits over a 10 year planning horizon.

| | **Gantry** | **Evaposensor** | **Soil moisture** |
|---|---|---|---|
| **Costs, £s** *(at present value)* | | | |
| Purchase price | 6,015 | 658 | 515 |
| Installation | 250 | 250 | 250 |
| Commissioning | 250 | 250 | 250 |
| Maintenance/repair | 104 | 100 | 50 |
| Electricity | 88 | 220 | 80 |
| **Benefits, £s** *(at present value)* | | | |
| Capital tax relief | 556 | 61 | 48 |
| Water costs saved | 82 | 85 | 85 |
| Labour costs saved | 5,291 | 2,707 | 2,707 |
| Increases in crop revenues | 3,162 | | |
| **Investment indices** | | | |
| NPV (Net Present Value) | £2,384 | £1,375 | £1,694 |
| PP (Payback Period, years) | 6 | 3 | 3 |
| IRR (Internal rate of return) | 24% | 43% | 53% |

(Figures for the gantry system based on the assumption that scheduling would be controlled by a soil moisture probe. A discount rate of 15% was used, substantially more than inflation and interest rates, to allow for the risk that predictions are over optimistic).



Cost - Benefit Analysis Tool

for assessing investments in irrigation equipment

| | A | B | C | D | E | F | G | H | I | J | K | L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | |
| 2 | **Evaposensor based automatic irrigation** | **Regular annual** | | **Costs and benefit that will NOT be the same each year ("regular annual" cell must** | | | | | | | | |
| 3 | **Capital Costs** | | Year: | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 4 | | | | | | | | | | | | |
| 5 | Purchase price | | | £658 | | | | | | | | |
| 6 | Installation | | | £250 | | | | | | | | |
| 7 | Commissioning | | | £250 | | | | | | | | |
| 8 | Opportunity costs | | | £0 | | | | | | | | |
| 9 | | | | | | | | | | | | |
| 10 | **Recurrent costs** | | | | | | | | | | | |
| 11 | Training | £0 | p.a. | | | | | | | | | |
| 12 | Maintenance/repair | £20 | p.a. | | | | | | | | | |
| 13 | Electricity | £44 | p.a. | | | | | | | | | |
| 14 | Other costs | £0 | p.a. | | | | | | | | | |
| 15 | | | | | | | | | | | | |
| 16 | **Benefits** | | | | | | | | | | | |
| 17 | Capital tax relief | £20 | % | | | | | | | | | |
| 18 | Water costs saved | £17 | p.a. | | | | | | | | | |
| 19 | Labour costs saved | £539 | p.a. | | | | | | | | | |
| 20 | Chemical costs saved | £0 | p.a. | | | | | | | | | |
| 21 | Increases in crop revenues | £0 | p.a. | | | | | | | | | |
| 22 | Other cost reductions | £0 | p.a. | | | | | | | | | |
| 23 | Other benefits | £0 | p.a. | | | | | | | | | |
| 24 | | | | | | | | | | | | |
| 25 | **Background data** | | | | | | | | | | | |
| 26 | Horizon | 10 | years | | | | | | | | | |
| 27 | Discount rate | 15 | % | | | | | | | | | |
| 28 | Area of crop | 1550 | m2 | | | | | | | | | |
| 29 | Crop density, plants per m2 | 14 | plants / m2 | | | | | | | | | |
| 30 | Selling price per plant | 3 | | | | | | | | | | |

Due to, e.g.
less need for hand watering of dry spots
quicker order picking from more uniform crops
less time spent cleaning / replacing nozzles

Cell A19 commented by Richard Harrison-Murray

**G.S. Figure 11.** Part of the main spreadsheet of the cost - benefit analysis tool, illustrating an example of the pop-up help comments.

## Financial benefits

The financial benefit that will accrue from this project depends on the value of the knowledge and technology to the thousands of diverse enterprises that make up the HNS industry. Irrigation is a key input for that industry and water is becoming an increasingly scarce and expensive resource. Therefore, in the long term, improving the efficiency of water use is essential to the survival of an industry worth in excess of £450 million per annum (Defra, Basic Horticultural Statistics, 2004) to the UK economy. In the shorter term, there is no doubt that profitability and competitiveness can be greatly increased by ensuring that water is used in a way that promotes high quality and uniform crops. The outputs from this project give growers the tools to make these improvements.

However, reaping financial benefits from the project clearly depends on the willingness of growers to invest time and money to apply the results to improving the precision of their irrigation. To encourage such investments, an easy-to-use spreadsheet tool was developed that allows growers or their advisers to run a cost - benefit analysis for their particular circumstances. Applying this tool to data gathered at Hillier Nurseries showed that automatic irrigation scheduling, either by Evaposensor or soil moisture probe, will generally pay for itself within a few years. The larger investment in gantry irrigation will also pay off in some circumstances.

Other technologies emerging from the project, such as gantry irrigation incorporating infra-red sensing of crop water requirement, require further development before they reach the market. They cannot yet be subjected to cost-benefit analysis because we do not yet have figures for either costs or benefits, but it is likely that some will prove to be of real economic benefit to the industry in the future.

## Action points for growers

***Irrigation systems***

1. Look critically at your current irrigation system. Achieving adequate uniformity of irrigation delivery to a crop is an essential pre-cursor to irrigation scheduling (matching dose and frequency to crop needs).
2. Minimise systematic variation in the uniformity of water deposition from irrigation sprinklers due to poor sprinkler layouts, choice of nozzle and other factors. See HDC Factsheet 16/05 ‘Measuring and improving performance of overhead irrigation for container-grown crops’ for further details.
3. Remember that uniformity of irrigation delivery to containers will also depend on the material, drainage / capillary characteristics and quality of the standing base. A quarter to half of water uptake can occur via the base of the container. Bumps and hollows, particularly if drainage is impeded, must be minimised. Use of a woven geotextile material such as Mypex over a *smooth* impermeable polythene covered base can give better results than a gravel base by helping redistribute water between containers. Bed gradients to help drain / recycle surplus water should be no steeper than about 1:100 to minimise a gradient in container water status.

4. The size and habit of foliage canopy also has a significant impact on the proportion of uptake from the top and base of the container, and this will vary through the season as the crop grows as well as differences between crop species. This needs to be taken into account when setting and adjusting irrigation schedules, guided by regular crop monitoring.

***Irrigation scheduling***

5. For successful scheduling, crops with similar water requirements must be grouped on the same beds or irrigation stations as far as possible.
6. Seriously consider adopting evapo-irrigation and / or moisture probe scheduling. These technologies are now commercially available, can be flexibly integrated with many existing irrigation timer based control panels, and can offer significant irrigation management benefits.
7. Evapo-irrigation offers cost effective semi-automatic irrigation scheduling. A single sensor and interface per control panel can cover all the crops under a single environment (e.g. outdoor or protected). The grower will enter initial dose / frequency irrigation settings for each irrigation zone based on their experience which are then fine-tuned following approximately weekly crop inspections. Meanwhile evapo-irrigation automatically adjusts irrigations to take care of day to day weather fluctuations.
8. When monitoring crops, consider tagging sample containers to be either formally weighed or picked up to estimate water status. Use a ‘run-through’ test to establish what irrigation dose is needed to achieve correct wetting up without excessive drainage (see HDC Factsheet 19/05 ‘Methods and equipment for matching irrigation supply to demand in container-grown crops.’). Make changes to set-points periodically after inspections to allow for crop development and keep written records for reference.
9. GP1 scheduled irrigation is a closed-loop system which automatically takes account of the actual moisture status of the crop, and once initial set-points are established can often need little further adjustment for weeks or months. This method is most economically viable for large irrigated blocks of crop requiring a similar irrigation regime as normally a separate GP1 and probe will be required for each irrigation valve.
10. SM150 probes from Delta-T Devices have now replaced the SM200. For most container sizes (minimum 1 litre), probes should be inserted so that the pins are in the central zone of the container. The connecting wire should be

securely fixed to the pot with tape to minimise the chance that the probe is disturbed.

11. In most situations, only a single probe in a representative container is required to monitor and control a large bed. With mixed crop beds, use the probe in the subject requiring most water (but run this as dry as possible) thus ensuring remaining species receive adequate irrigation.

12. The GP1 logger / controller requires a handheld PDA, netbook or laptop connection to adjust set points and view / download logged data. Use this data to provide valuable feedback on the effects of irrigation regimes. The software within the logger enables some sophisticated irrigation control options including ‘pulsed’ water applications and will accept additional inputs from e.g. temperature probes and water meters.

***Applying RDI and growth control***

13. Both evapo-irrigation and moisture probe control are suitable where growers may wish to apply Regulated Deficit Irrigation for growth control. For success with RDI, overhead sprinklers, as well as drippers, can be used providing delivery is uniform. Rain protection is also needed. RDI is best applied to one plant subject per irrigation zone as slight differences in water requirements become more critical under very dry regimes.

14. Delaying the application of relatively severe (50% $ET_p$) RDI until after pruning of *Forsythia* in June was effective in maintaining them as compact plants. However, a more moderate RDI treatment (70% $ET_p$) throughout the growing season can give high quality and growth controlled crops. Such a treatment entails less risk of damaging individual plants that receive less water than average (as a result of non-uniformity of uptake).

15. Using a pH 8.0 buffer spray or drench of potassium phosphate may limit excessive transpiration and thereby cut down the need for irrigation when water supplies are limited, and may also offer growth control without the need to apply deficit irrigation treatments. Species response will vary, and further development work is needed, but this would be well suited to nursery based trials.

16. Inoculation of growing media with rhizobacteria such as *Variovorax paradoxus* also have potential to mitigate drought or other stress symptoms in some HNS subjects. However, further research on the survival of bacteria

in growing media, inoculation concentrations, species responses and economic viability is needed before commercial uptake is possible.

### *Thermography and thermometry for irrigation management*

17. Medium to high resolution hand held thermal imagers are technically capable of being used to monitor cropping beds for individual stressed plants or dry zones under ideal conditions (high irradiance, low humidity and low wind speeds). But the variation in response between subjects, the current high cost of suitable instruments and the range of nursery environments and growing conditions means they are presently not a viable option for most growers.
18. Considerable progress was made in understanding relationships between plant responses to drought, effects on foliage temperature and developing technologies to detect this with thermal imaging cameras. However, with species variation in response, influence of growth stage etc., it will be difficult to use thermography alone to define irrigation regimes. Much further research is required, but using thermography to provide feedback and adjust irrigation scheduled by another method offers more promise.
19. A relatively low cost system based on thermopiles for remote monitoring of plant positioning and plant temperatures related to water stress was developed and mounted on the watering boom of a gantry. Further development work is needed to translate the detection of dry areas down the bed into individual operation of irrigation nozzles so that water delivery can be matched more closely to the crop need.

### *Evaluation of irrigation equipment investments*

20. Use the Cost - Benefit Analysis spreadsheet tool (available via HDC) to evaluate irrigation equipment investment decisions. It provides a logical structure for growers to think about and input appropriate data for their circumstances. The Excel spreadsheet handles the necessary calculations enabling different scenarios to be compared.

21. Contact details for irrigation equipment suppliers used in the project:

Evapo-irrigation interface and Evaposensor: www.ets-controls.co.uk.
GP1 and SM150 moisture probes: www.delta-t.co.uk.
Gantry irrigation: www.dentonautomation.co.uk.

# SCIENCE SECTION

## Introduction

This project was aimed at the provision of more R&D to achieve substantial and reliable water saving for producers, while at the same time minimising the risk of potentially catastrophic plant water deficits and crop losses. A variety of novel sensing technologies were 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). Soil water content and evaporative demand were assessed using new, commercially-available technology and this was then used to schedule irrigation with a view to saving water and increasing uniformity and quality of the crop. 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). These treatments were further developed within the project to allow exploitation of plant signalling to the benefit of the producer. Many of the techniques described above are available for immediate low cost exploitation.

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 informed the development of optimal control systems. Detailed mechanistic studies, particularly of plant signals involved in responses to drought and nutrient treatments guided the development of protocols for novel management options to control growth, crop quality and crop water use.

## 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

The efficiency with which irrigation is applied on the nursery is now seen as an important component of the sustainability of the HNS sector. Moreover, uniform crop production requires uniform irrigation. In particular, the feasibility of using overhead irrigation for scheduling deficit irrigation (see Objective 4) clearly depends on achieving uniformity of water deposition, in order that the degree of water deficit applied will be reasonably uniform across the crop. Sprinkler manufacturers publish data on the performance of their sprinklers and some provide software to predict the uniformity that will be achieved by a particular layout. There is also commercial software available to do this (SPACE program, http://cati.csufresno.edu/cit/software/). How valuable this software is depends on how accurately it can predict actual performance.

In this objective, we aimed to obtain a body of reliable data on the performance of different irrigation systems, investigate discrepancies between uniformity of water deposition and water uptake, and encourage growers to critically examine the irrigation systems on their nurseries with a view to optimising irrigation.

## Materials and methods

### *Desk-based study*

Information was collected from a range of manufacturers' literature and websites covering the main irrigation application products appropriate for container nursery stock. This included various overhead sprinkler and sprayline types, drip and mini spray-stake applicators, gantry, and flood-and-drain systems. The operating principles were described, pros and cons summarised, and some examples with specifications illustrated.

### *Data collection and trials to test performance of irrigation systems*

Trials were undertaken on nurseries to measure precipitation uniformity from different irrigation systems, and net water uptake (via base as well as the top of the pot), and drainage run-through.

To measure water distribution from overhead irrigation systems, the procedure described in HDC Factsheet 16/05 using pot drip trays was used in conjunction with the HDC Irrigation Calculator software. To measure net uptake into containers, typically 32 pairs of pots (four rows of eight pairs) were weighed before and after irrigation. A row normally extended over the full width of the cropped bed or bay being monitored. One ‘run-through pot’ in each pair was placed in a smaller container lined with a polythene bag (e.g. 3 L in 2 L) to collect any drainage, as well as isolating the crop pot from the standing base. The ‘standing base pot’ in the pair could take up water from both above and via the base. Irrigated area and water meter readings, irrigation time, before and after irrigation weights, drainage volumes, and pot top diameter were entered into a spreadsheet template. These allowed calculation of:

1. Irrigation in mm applied to irrigated area (L / area of glasshouse bay or tunnel in $m^2$) and mean application rate (MAR). This approximated to the mm dose and MAR as measured by a tray test

2. The mean total dose captured from above by the run-through pots based on the surface area of the pot (i.e. pot weight gain plus drainage volume divided by pot surface area). Comparison with 1, above, gives an indication of whether the foliage canopy is tending to shed water away from, or funnel water into, the pot surface. This can also be expressed as MAR

3. Net uptake by both standing base and run-through pots. This can be expressed as mm based on surface area of the pot and compared with (1) and (2) above

4. Proportion of net water uptake via the base for standing base pots, and for run-through pots, the proportion of drainage of that captured from above

In addition to these mean values for the sampled area, net pot uptake uniformity was observed by displaying values in a 3D chart and Coefficient of Uniformity (CU) calculated in the same way as tray deposition test results.

At Hillier nurseries, ornamental banana, *Musa lasiocarpa*, in 3 L pots were grown in one 36.5 m × 9.6 m glasshouse bay section with 3 lines of pinjet irrigation per bay (Fig. 1.1a). Irrigation lines were spaced 3.2 m apart, designed to give overlap with adjacent bays. A similar sized section of a different bay with *Musa* was irrigated with the Denton gantry system (Fig. 1.1b). In both bays pots stood on a smooth and firmed base covered with a layer of Mypex over polythene, which sloped slightly towards the central path. Surplus water was collected via sub-surface drainage for re-cycling. Palmstead Nurseries updated a polytunnel in order to compare one set of sprinklers in that tunnel with a different set in a newly built tunnel. In the 'old' tunnel Ein dor Vibro-spin nozzles (160 L h$^{-1}$; Fig. 1.2a) were in use, while in the new tunnel two rows of MP3000 Rotator sprinklers (827 L h$^{-1}$) were fitted either side of the stanchions down the centre, one row to irrigate either side of the twin-span tunnel (Fig. 1.2b). Water use was monitored under both systems. Irrigation tests were also run at Johnson's of Whixley and Wyevale.

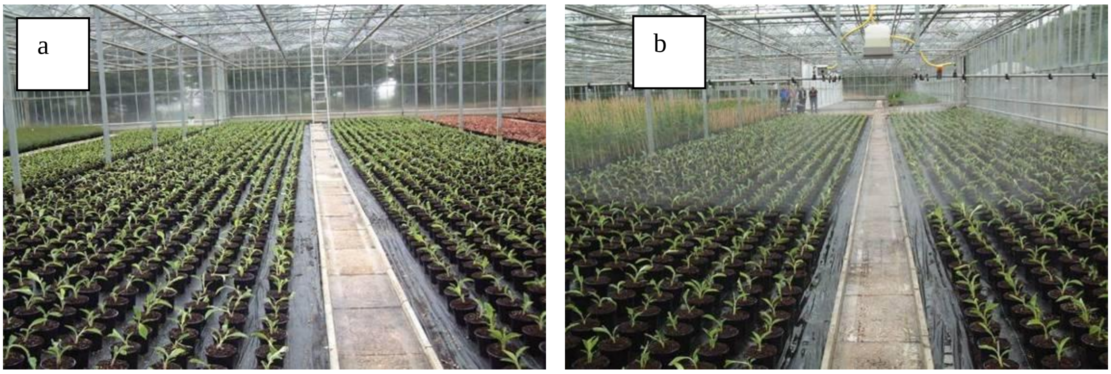


**Figure 1.1.** Hillier Pinjet bay (a) and Gantry bay (b) cropped with *Musa lasiocarpa*, in 2007

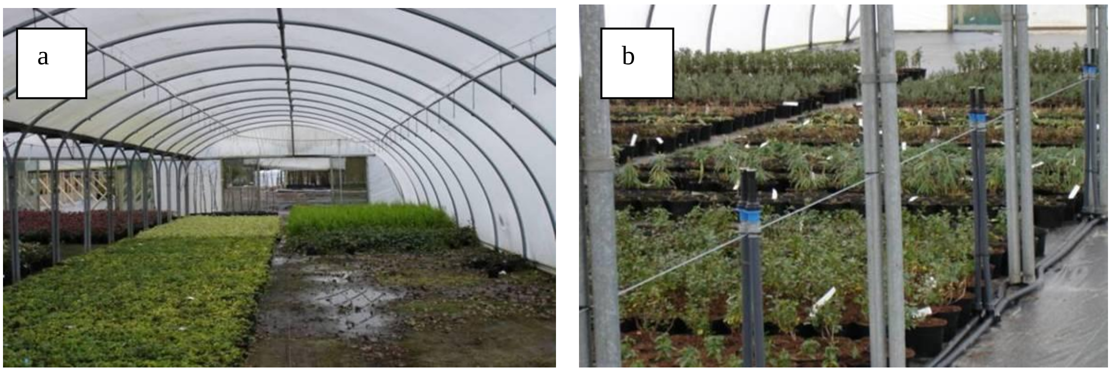


**Figure 1.2.** Ein dor Vibro-spin nozzles in one half of an "old" polytunnel (a) and MP3000 Rotator sprinklers in a new tunnel (b) at Palmstead Nurseries

*A "standard absorbency pot" for reproducible measurement of water delivery*

It is difficult to make a pot containing a plant a reproducible system for a systematic study of water delivery. The plant canopy may 'funnel' water into the pot or 'deflect' it away from the pot and this effect will change as the canopy develops. Also, it is difficult to achieve consistent initial water content and therefore absorbency of the substrate, and it is generally necessary to allow at least a day between measurements for transpiration to draw down the water content sufficiently. For these reasons, a wad of capillary matting firmly compressed into a pot was used to provide a standard absorbency for water delivery measurements. The matting was in the form of a strip, 200 × 17 cm, with a dry mass of 85 g, which was folded many times and pushed into the bottom of a 2 L pot. Initially, the capillary matting was well-wetted, excess water was wrung out and then water was added to bring the mass of the pot (42 g) and moist matting to a standard 300 g starting mass. This was then capable of absorbing up to around a further 250 g of water through the holes in the base of the pot (i.e. surface uptake). To prepare for another test the strips can be wrung out again or else 'drip-dried' for about hour before adding water to restore the standard starting mass. An inverted saucer was used as a lid to prevent water deposition directly into the top of the pot. Water deposition was measured separately by placing a 17 cm saucer on top of the lid. Both water deposition and surface uptake were converted to mm $h^{-1}$, based on the area of the top of 2 L pot (227 $cm^2$). Water delivery was then calculated as delivery = deposition + surface uptake

*Factors affecting surface uptake*

A series of measurements with the standard absorbency pots were used to study the effects of:

1. Evenness of the standing base. Measurements were made before and after thoroughly rolling gravel with a garden roller to produce a smooth looking surface

2. Polythene under Mypex. Measurements were made with and without a layer of polythene covered by another layer of Mypex

3. Amount of irrigation. Surface uptake cannot start until the standing surface is well wetted. By varying irrigation times the amount of irrigation was varied from about 1 to 5 mm. Applications at the lower end of this range are characteristic of deficit irrigation regimes

*Variation in water delivery to individual plants*

Using *Forsythia* 'Lynwood' plants irrigated with deficit irrigation (DI: 50% or 70% $ET_p$, see Objective 4), 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.

The following year, water delivery to pots of *Forsythia* × *intermedia* 'Weekend' and *Griselinia littoralis* 'Variegata' was measured by weighing plants before and after irrigation. For comparison, water deposition into empty saucers provided an estimate of how much water would have fallen directly into the top of the pot. Factors such as the size, water status and spacing of the plants were varied over the course of three experiments. Irrigation was from Eindor 861 mini-sprinklers, 50 L $h^{-1}$, mounted at a height of 1 m. After irrigation, plants were weighed before and after shaking to remove much of the water on the foliage. Removing remaining water from samples of detached shoots, by dabbing with paper tissue, showed that shaking removed about 50% of the water on the leaves.

## Results and Discussion

A desk-study was produced in the first year of the project. Comparisons of different irrigation systems showed how uniformity of water delivery can vary between systems. With the gantry irrigation system at Hillier nurseries, typically one or two passes were required at the slowest or medium speed to achieve an adequate irrigation dose. The nursery found it was helpful to be able to vary irrigation part way down the bay to cope with different water demand by two different crops. There was a significant proportion of uptake through the pot base under both gantry and Pinjet irrigation (Table 1.1). A comparison of the two systems is summarized in Table 1.1 and Fig. 1.3.

**Table 1.1.** Water uptake and run-through test for *Musa* in Hillier pinjet and gantry bays – 18/7/07

| Irrigation performance | Pinjet | Gantry |
|---|---|---|
| 1. Irrigation applied to area | 5.5 mm | 6.3 mm |
| 2. Total capture by run-through pot (including drainage) | 7.1 mm | 5.4 mm |
| 3. Net uptake by standing base pots | 9.9 mm | 10.3 mm |
| 4. Net uptake by run-through pots | 7.1 mm | 5.4 mm |
| 5. Proportion uptake via pot base (4 as % of 3) | 29% | 47% |
| 6. Proportion run-through (4 as % of 2) | 0% | 0% |

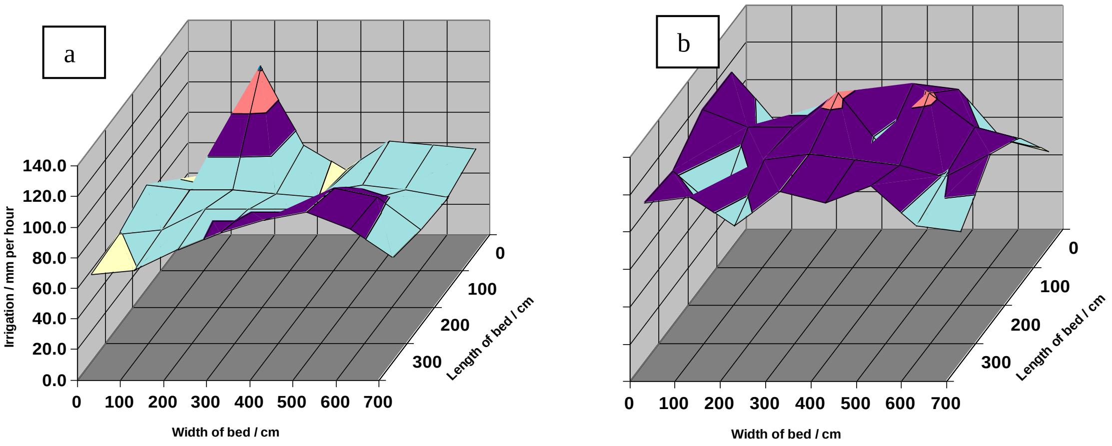
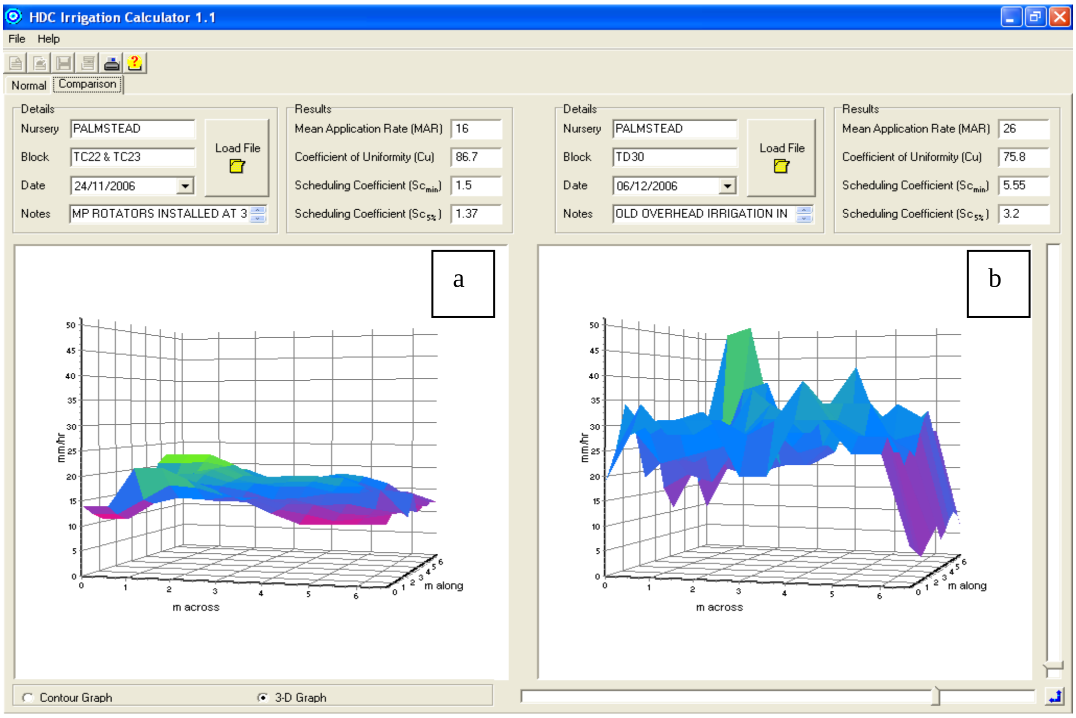


**Figure 1.3.** Uniformity of net uptake of pots on standing base for pinjet bay (a) and gantry bay (b) 18/7/07. The pinjet bay had a MAR of 71.0 mm $h^{-1}$, CU of 84.2% and $SC_{5\%}$ of 1.34. The gantry had a CU of 88.8% and a $SC_{5\%}$ of 1.39.

Irrigation uniformity was found to be higher in the new polytunnel using MP 3000 Rotator sprinklers than in an old tunnel using Ein dor sprinklers, at Palmstead Nurseries (Fig. 1.4). Lower uniformity with the Ein dor sprinklers relates partly to water hitting the plastic rather than falling on the plants at the side of the tunnel. There were also problems with an uneven floor surface and poor drainage. When this was corrected, coefficients of uniformity for water deposition, water delivery, and water uptake were very similar in the two systems, but nonetheless water did not reach the edges of the tunnel with the old system (Fig. 1.5). The two different systems led to little difference in total water use during the summer. However, the length of time that had to be spent hand-watering under the new system was far less (about one-tenth) than that under the old system, indicating the economic importance of optimising sprinkler arrangements. In the old tunnel, plants along the tunnel edge received insufficient water from the Ein dor sprinklers, and therefore had to be watered by hand. Labour savings in a hotter year could be greater.



Details
Nursery PALMSTEAD
Block TC22 & TC23
Date 24/11/2006
Notes MP ROTATORS INSTALLED AT 3

Results
Mean Application Rate (MAR) 16
Coefficient of Uniformity (Cu) 86.7
Scheduling Coefficient ($Sc_{min}$) 1.5
Scheduling Coefficient ($Sc_{5\%}$) 1.37

Details
Nursery PALMSTEAD
Block TD30
Date 06/12/2006
Notes OLD OVERHEAD IRRIGATION IN

Results
Mean Application Rate (MAR) 26
Coefficient of Uniformity (Cu) 75.8
Scheduling Coefficient ($Sc_{min}$) 5.55
Scheduling Coefficient ($Sc_{5\%}$) 3.2

○ Contour Graph
● 3-D Graph

**Figure 1.4.** Irrigation capture and uniformity measurements under MP Rotator 3000 sprinklers fitted at 3 m spacing in the new tunnel (a) and under Ein dor vibro-spin nozzles hanging from the roof of the older tunnel (b) at Palmstead Nurseries. Low water capture was seen along the side of the tunnel in (b) as a result of the position of the sprinklers and their trajectory into the curve of the tunnel

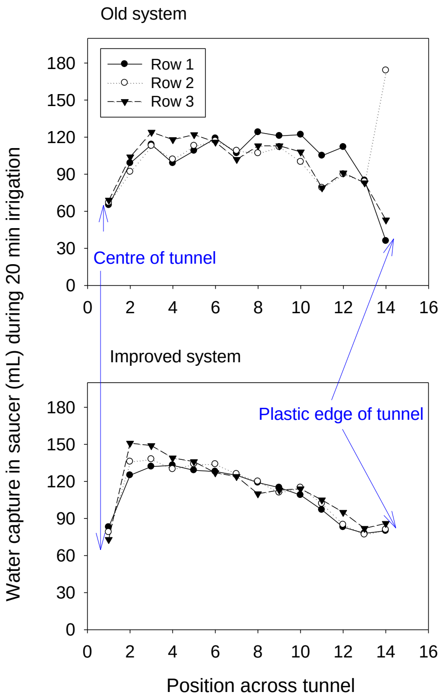
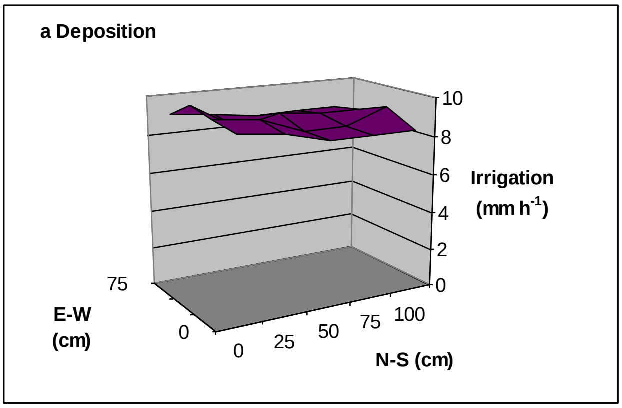


**Figure 1.5.** Irrigation water captured into saucers spaced from the centre to the plastic edge of two tunnels at Palmstead Nurseries during 10 (top graph) or 20 (lower graph) minutes of irrigation, after the uneven surface in the old system had been corrected

*Factors affecting surface uptake*

Surface uptake was found to be much more variable than water deposition, indicating that care in setting up irrigation equipment to achieve uniform water deposition is no guarantee of uniform water delivery (Fig. 1.6). CU of water delivery was just 56% compared with 96% for water deposition. When irrigation time was reduced from 10 mins to 5 mins so as to apply just 0.7 mm, the CU of water delivery dropped further, to 44%. Similarly, when it was increased from 10 to 30 minutes (from 1.5 to 5 mm) the CU for water delivery increased from 56% to 85%. If the polythene under the Mypex was removed, surface uptake was reduced by about three quarters but was more variable, so that the coefficient of uniformity for water delivery was only 77%. The covering of Mypex over compacted gravel, even without the polythene under it, was enough to restrict the free-flow of water sufficiently for some water to move over the surface and into the base of the pots. The amount of surface uptake was reduced from 16.9 mm $h^{-1}$ to 4.6 mm $h^{-1}$ but it became even less uniform (CU fell from 28% to 16%).



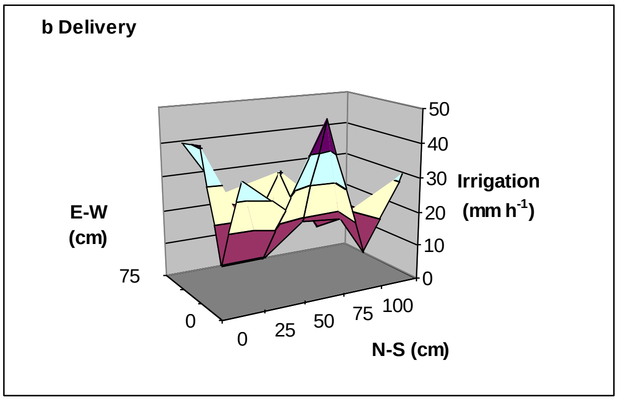


**Figure 1.6.** Results from standard absorbency pots on Mypex over polythene laid over a base of compacted gravel. Despite highly uniform water deposition (a, CU = 96%) water delivery was uneven (b, CU =56%) because uptake through the base of the pot (surface uptake) was extremely variable.

Rolling the gravel base to eliminate visible unevenness improved uniformity of surface uptake slightly so that CU of water delivery rose from 56% to 63%. Before rolling, hosing down the surface revealed low spots and it was found that surface uptake correlated quite well with the depth of the puddles which formed ($R^2 = 0.66$). Rolling eliminated these puddles but did not eliminate the correlation. It is likely that slight unevenness must have remained and that this was enough to direct water flow to certain positions but not create a visible puddle. It is also reasonable to assume that the same factor was underlying the correlation between water delivery to *Forsythia* plants in the same positions (Fig. 1.7).

The variability of surface uptake reflects the fact that the 'catchment area' from which an individual pot can draw water is not clearly defined and pots are 'competing' with their neighbours for the water which falls on the standing surface. Placing each pot in a 25 cm saucer provided a clearly defined catchment area but failed to achieve uniform water delivery because much of the water falling into these saucers was not taken up by the pots standing at their centre.

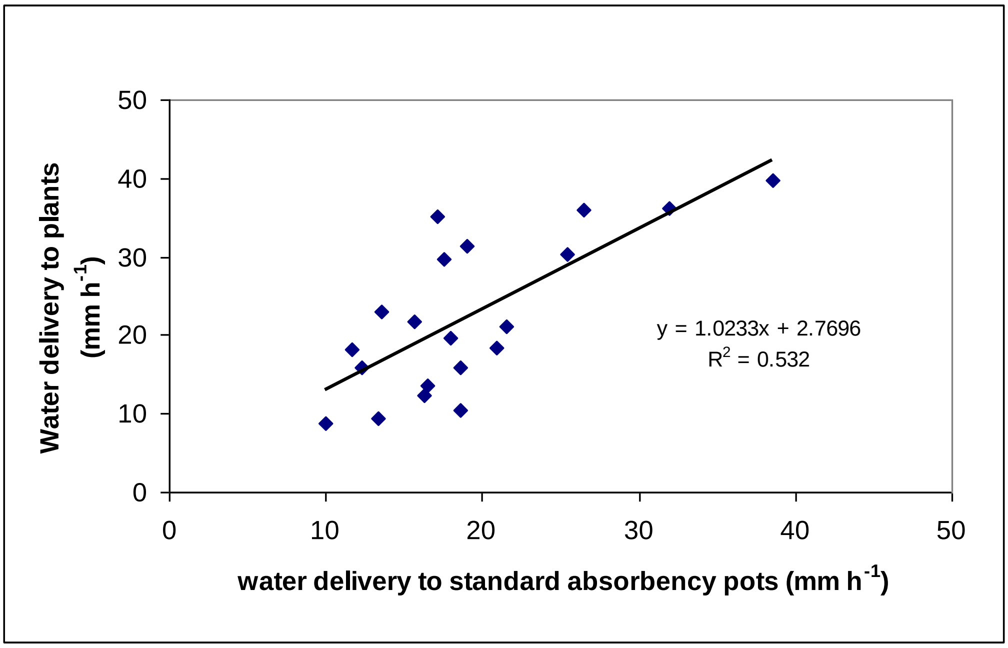


**Figure 1.7.** The relationship between water delivery to recently potted *Forsythia* plants (in peat in 3 L pots) and water delivery measured using the standard water absorbency pots in the same positions (Mypex over polythene after rolling).

A separate experiment showed that this problem can be overcome by a covering of Mypex over the base of the saucer (Fig. 1.8 and Table 1.2). It is evident from this result that a layer of Mypex over polythene or other impermeable surface not only protects the surface but also helps transport water laterally over the surface. In this wicking action it is behaving like capillary matting but it has the advantage of having minimal water holding capacity. It was shown in HNS 97 that the water holding capacity of capillary matting is a severe disadvantage when the amount of irrigation applied is small, as is the case with deficit irrigation.

**Figure 1.8.** Experiment with standard water absorbency pots to determine the effects of Mypex and a sloping surface on moving water across the surface towards the pot. Puddles of free water are visible in the saucers which are horizontal and without a Mypex disc.

**Table 1.2.** Surface uptake of water measured using standard absorbency pots standing in 25 cm pot saucers. Pots were either placed at the edge with the saucer inclined towards the pot, or centrally with the saucer horizontal. A disc of Mypex covered the base of some saucers to act as a ‘wick’, to move water to the base of the pot. Tabulated values are means (n = 5) ± standard errors

| **Inclination (degrees)** | **Mypex** | | **Mean** |
|---|---|---|---|
| | **–** | **+** | |
| 0 | 4.2 ± 4.2 | 15.2 ± 1.7 | 9.7 ± 2.8 |
| 7 | 27.4 ± 0.5 | 22.8 ± 0.8 | 25.1 ± 0.9 |
| Mean | 15.8 ± 4.4 | 19.0 ± 1.6 | 17.4 ± 2.3 |

*Variation in water delivery to individual plants*

Variation in water use appeared to largely mask variation in water delivery as the substrate dried down during deficit irrigation. 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.

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 1.3). 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 1.3.** 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 |

Water delivery was significantly correlated ($P < 0.001$) with plant height (which ranged from 0.2 to 0.5 m) amongst *Forsythia* when irrigated to replace 50% $ET_p$, at a spacing of 0.25 × 0.25 m. Vertical projected foliage area (i.e. as viewed from the side) correlated with water delivery less well. In this experiment, pots were standing on Mypex over polythene so that surface uptake through the base of the pot contributed to water delivery.

In a second experiment, single isolated plants were used and surface uptake was eliminated by standing pots in close fitting saucers. Nonetheless, the amount of water delivered to plants averaged about four times that deposited into the pot directly (Fig. 1.9). This indicates that the foliage was ‘collecting’ additional water even though its appearance does not suggest it will act as an efficient ‘funnel’. When leaves were wilting, far less water was ‘collected’, unless the branches were tied up above the pot. Visual observation and water deposition into the surrounding saucers indicated that more water dripped off leaves that were wilting. This explains why tying branches upright only increased water delivery if the foliage was wilting.

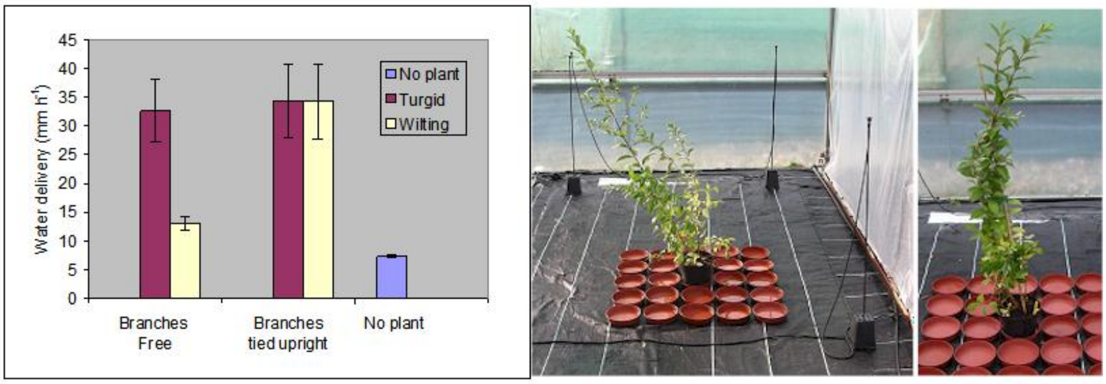


**Figure 1.9.** Mean rate of water delivery to isolated *Forsythia* plants, compared with water deposition into an empty pot or saucer (data are means ± se, $n = 3$ to 5), and the system used for measuring the effect of foliage on water delivery to the pot and water deposition onto the ground around it. In the photo on the right, branches have been temporarily tied up to simulate a very upright habit.

In a third experiment, water delivery to a set of six plants, contrasting in size and shape, was measured once in each of six positions on the bed, spaced at 1 × 1 m. There were large and significant ($P < 0.001$) differences in water delivery to the six plants, which broadly related to their size (Fig. 1.10 and 1.11). The large *Griselinia* ‘collected’ almost 5 times as much water as was deposited directly into the pot. This was 70% more than the largest *Forsythia*, despite being much shorter, presumably because it was more branched and leafy (Fig. 1.11). However, further evidence for the importance of height came from tests with ‘artificial plants’, consisting of a bare tripod of 1.2 m canes, which increased 3-fold the volume of water collected in a saucer. A single set of measurements with plants spaced at 0.25 × 0.25 m showed no evidence of interaction between plants, even though their foliage overlapped substantially. Differences in mean water delivery at the six positions on the bed were significant ($P < 0.01$) but the range of values was five times smaller than for the different plants, and the coefficient of uniformity was 92% compared with 65%.

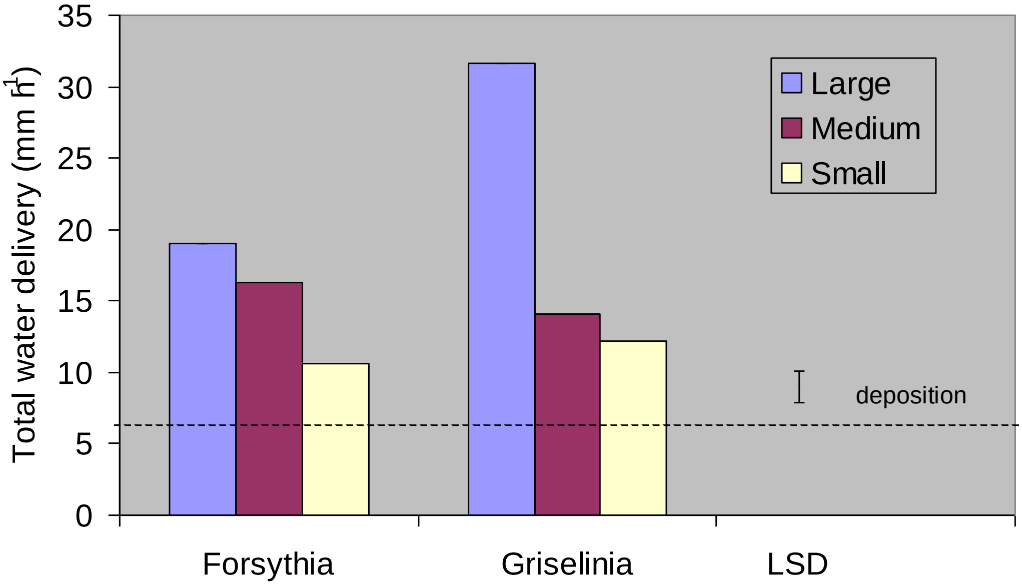


**Figure 1.10**. Mean rate of water delivery to the 6 plants in experiment 3, compared with the rate of water deposition. Error bar is LSD $_{(P=0.05,\ 25\ \mathrm{d.f})}$. The heights of the *Forsythia* plants were 1.15, 0.93, and 0.55 m and those of *Griselinia* were 0.65, 0.43, and 0.35 m respectively.

**Figure 1.11**. The *Griselinia* plants used in Experiment 3, arranged from largest to smallest

In conclusion, even when the foliage is not conspicuously funnel shaped, water running off leaves and down stems means that plants can ‘collect’ substantial amounts of water and direct it into the pot. Unlike rain, water from sprinklers usually is not falling vertically because it is emitted as a fairly low trajectory stream. Therefore, the amount of water intercepted is influenced by plant height, leaf area and the proportion of water that is transferred from leaves onto main stems and thus into the pot. This creates the potential for great variation in water delivery from plant to plant on the same bed, even where a good irrigation system is achieving high uniformity of water deposition. It is essential that these large effects of foliage on water delivery are taken into account, along with potential for variation in surface uptake, as we try to develop more precise irrigation and to use it for regulation of growth.

### Conclusions from irrigation tests on nurseries

The type of standing base has a significant effect on net uptake – a quarter to almost half of water uptake may occur via the base of the pot on impermeable surfaces (such as Mypex over polythene).

A non-permeable standing base may result in better uniformity of net uptake than a free-draining gravel base, but only if it is smooth and free from bumps and hollows
The foliage canopy also has a significant impact on the proportion of uptake from the top and base of the pot, and this will vary through the season as the crop grows.

The foliage canopy will not necessarily reduce the uniformity of net uptake, especially if it *funnels* water into the container instead of *shedding* it away from the pot.

Both the foliage canopy and type of standing base will need to be taken into account for irrigation scheduling using open-loop control methods such as the Evaposensor (see Objective 2). This is also true when considering the type and design of precision delivery nozzles on a gantry.

Overhead sprinklers gave very uniform water *deposition* but *delivery* to plants was much more variable than with drip, partly due to variation in surface uptake. Nonetheless, plant growth was not any more variable under overhead than drip, probably because there are many other sources of variation in growth of HNS.

## Objective 2

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

## Introduction

Certain sensors have shown considerable promise in the assessment of water requirements of different crops (Stirzaker 2005). One method of scheduling irrigation is based on evaporative demand. This depends on the weather conditions where the plants are grown and in addition on plant spacing and other factors. An alternative is to base scheduling on the moisture content of the growing substrate. Tensiometers have now been used for decades for monitoring soil water status (Stirzaker 2005), but their uptake by commercial growers, particularly growers of container plants, has been poor. More "user-friendly" capacitance devices have come on the market relatively recently (Charlesworth 2005).

The Evaposensor, produced by Skye Instruments Ltd, is a portable evaporimeter based on a prototype leaf-model evaporimeter described by Harrison-Murray (1991a, b). It measures wet leaf depression sum in units of degree hours, where 1°C h equates to a difference in temperature of 1°C for a duration of 1 h between wet and dry artificial leaves. The SM200 is the latest in a range of soil moisture sensors developed by Delta-T Devices. It is a small probe, well suited to use in pots used in HNS production, and its output in voltage, or, more usefully, percentage of volumetric soil moisture, can be either read instantly using a hand-held meter (HH2 meter), or any one of Delta-T's range of loggers, including the GP1. The GP1 has the additional function of controlling irrigation scheduling, so that irrigation is turned on when soil moisture content falls to a lower threshold, and turned off when an upper soil moisture content threshold is reached.

To ensure that these sensors can be taken on board by HNS growers, the limits of both needed to explored, and the potential of both further developed. For the Evaposensor, this included determining the scale of variation in readings depending on location of the sensor relative to the crop, irrigation, etc. The major requirement with the Evaposensor, however, was to overcome the issue of not knowing the relationship between the actual water use of a given crop at a given development stage and the Evaposensor readings. For HNS production, the actual evapotranspiration of the crop ($ET_A$) can be calculated from evapotranspiration from a short grass crop reference ($ET_o$) and a crop coefficient ($K_c$) that defines the relationship between the two: $ET_A = ET_o \times K_c$. However, $K_c$ values are not generally known for ornamental plants, on account of the hundreds of species and thousands of cultivars in production (Beeson 2005). The Evaposensor, by measuring evaporative demand, provides the reference, and thus takes into account daily fluctuations in weather. The water use of any crop is directly proportional to the Evaposensor readings. The actual water use of very different cultivars, however, clearly differs substantially. Therefore much effort has been invested in establishing, and ultimately validating, a generic system for estimating approximate crop coefficients.

Uptake of the Evaposensor by the industry has been limited by the need for the user to read the meter, convert the reading into irrigation required, and manually adjust an irrigation timer. The advent of the E&TS Evaposensor – mist controller, developed during HNS 159, created opportunities for automatic irrigation. It incorporates an analogue output (0-20 mA), proportional to the measured Wet Leaf Depression, allowing it to be used to interface the Evaposensor to a wide range of other equipment. Thus, in 2009, an Evaposensor was linked to a Heron irrigation timer, via the E&TS controller, to create a system that automatically adjusted daily irrigation dose in proportion to potential evapotranspiration registered during the preceding 24 hours.

For the soil moisture sensor, the focus of this research has been in understanding the scale of variation in soil water content across a crop under regulated deficit irrigation (RDI), and using this information along with an increased understanding of the rate of drying down of the substrate, as guidance for optimal use of soil moisture sensors for scheduling RDI on nurseries.

## Materials and Methods

### *Evaposensor*

*Scale of variation in Evaposensor readings depending on location*

Evaposensors were set up in different locations under a polytunnel – within a canopy, near the edge of the tunnel, at the centre of the tunnel, close to overhead irrigation, far from overhead irrigation etc. – and in different locations on and around an open bed of 3 L container plants.

*Establishing a system to estimate crop coefficients*

Plant material

*Escallonia* 'Donard Radiance' in 100% peat in 2 L black polyethylene pots were donated by Palmstead Nurseries Ltd. (Kent, UK) in July 2005. In the following three years, plants were purchased as liners and potted up in 100% peat (medium grade), with 1.5 kg $m^{-3}$ limestone and 6 kg $m^{-3}$ CRF (Osmocote Plus) incorporated at the time of potting up, in 2 L pots. The cultivars were:

1. 2006: *Choisya ternata* 'Sundance', *Cornus alba* 'Elegantissima', *C. alba* 'Gouchaultii', *Escallonia* 'Donard Radiance', *Hydrangea macrophylla* 'Blue Wave', and *Lonicera* × *heckrottii* 'Goldflame'
2. 2007: *Buddleia* 'Lochinch', *Ceanothus thyrsiflorus* var. *repens*, *C. thyrsiflorus* 'Autumn Blue', *Choisya ternata*, *Cornus alba* 'Gouchaultii', *Cotoneaster* 'Coral Beauty', *Escallonia* 'Donard Radiance', *Griselinia littoralis* 'Variegata', *Hydrangea macrophylla* 'Blue Wave', *Lonicera* × *heckrottii* 'Goldflame', *Philadelphus* 'Beauclerk', and *Physocarpus opulifolius* 'Dart's Gold'
3. 2008: *Buddleia* 'Lochinch', *Cornus alba* 'Gouchaultii', and *Griselinia littoralis* 'Variegata'

Growing environment

In 2005, 2006, and 2007, plants were split equally between an outdoors experiment and an experiment under a polythene tunnel. In 2005, the tunnel was of the Spanish, open-sided, form, but from 2006 onwards a completely covered tunnel was used. In 2008, only one experiment was conducted, and this was in the plastic tunnel. In 2005, pots were placed on a gravel standing surface, whereas from 2006 onwards they were placed on a Mypex surface. During measurement of evapotranspiration, however, pots were placed in saucers, to ensure that there was no surface uptake of water from the standing base. Plants were established using drip irrigation. During measurement of evapotranspiration, however, irrigation water was applied by hand from a measuring cylinder.

Manipulation of evapotranspiration

In 2005, the impact of canopy variables on evapotranspiration was studied in a two-factor experiment. The factors were pruning and spacing, with two levels of each, with each level replicated four times in a block design:

1. Pruning: Severe pruning (shoots pruned to within the pot edge) vs. light pruning (shoots pruned to within 10 cm of the pot edge)
2. Spacing: Narrow spacing (pot edges touching) vs wide spacing (25 cm between centres of neighbouring pots; pots were 16 cm in diameter)

Each replicate consisted of nine plants, in three rows of three. The position of plants within a group was occasionally changed, to ensure the same plant was not at the centre of the group throughout.

### Multi-cultivar experiments

In 2006 and 2007, the only factor was cultivar, with each cultivar being replicated four times in a block design. Each replicate consisted of nine plants, in three rows of three, with 25 cm between the centres of neighbouring pots. The position of plants within a group was occasionally changed, to ensure the same plant was not at the centre of the group throughout.

The three cultivars studied in 2008 were monitored separately. They were arranged at 25 cm spacing in single large blocks of 72 pots arranged in four rows. The outer plants acted as guard plants. Of the remaining 32 plants, eight were selected randomly for each set of measurements.

### Evapotranspiration and crop coefficients

Evapotranspiration of the central plant in each group was determined by weighing the pot every 24 hours. A known quantity of water (verified by weighing the pot again after adding it) was added after weighing to ensure that drying of the substrate and hence stomatal closure never occurred.

The accumulated degree hours logged by the Evapometer between consecutive pot weights was recorded. Crop coefficients were calculated for each plant as evapotranspiration per degree hour. In general, crop coefficients over a period of two weeks were averaged for each plant.

### Canopy measurements and stomatal conductance

Plant height, leaf area, various measures of canopy cover, and stomatal conductance were recorded for the central plant of each replicate plot during each set of measurements of evapotranspiration, in 2005-2007. In 2008 plant height and cover were recorded. Leaf area was estimated by counting leaves in ‘small’, ‘medium’, or ‘large’ size classes, and measuring the area of a selection of representative leaves of each class with a portable leaf area meter (LI-3000A, Licor, USA). Cover refers to the percentage cover in the 25 cm × 25 cm square around the central plant and was estimated in several ways:

1. By measuring the interception of photosynthetically active radiation (PAR) with a linear PAR ceptometer (AccuPAR, Decagon Devices Inc., Pullman, WA, USA) – four parallel readings were averaged
2. By selecting the area covered in foliage in digital photos taken looking down on the plants, and calculating percentage cover using Photoshop (Adobe Systems Incorporated, CA, USA)
3. By visually estimating the percentage cover, using images of known percentage cover as guides

Stomatal conductance was measured with a porometer (AP4, Delta-T Devices, Cambridge, UK).

### Statistical analysis

The significance of treatment differences in the *Escallonia* experiments was assessed by analysis of variance. In the multi-cultivar experiments, the significance of correlations between the different canopy measurements or stomatal conductance and crop coefficients was determined for each month, for each cultivar, and across all months and cultivars. Multiple linear regression analysis to establish the best fit equation between the various canopy/stomatal conductance measurements and crop coefficients was performed in a forward stepwise manner; terms for which $P$ values for the $t$ test exceeded 0.05 were rejected. This was undertaken for each month separately, and then for all months and cultivars combined. All statistical analysis was carried out in Genstat software (Genstat 9.1, Rothamsted Experimental Station, UK).

### *Nursery trials of Evaposensors*

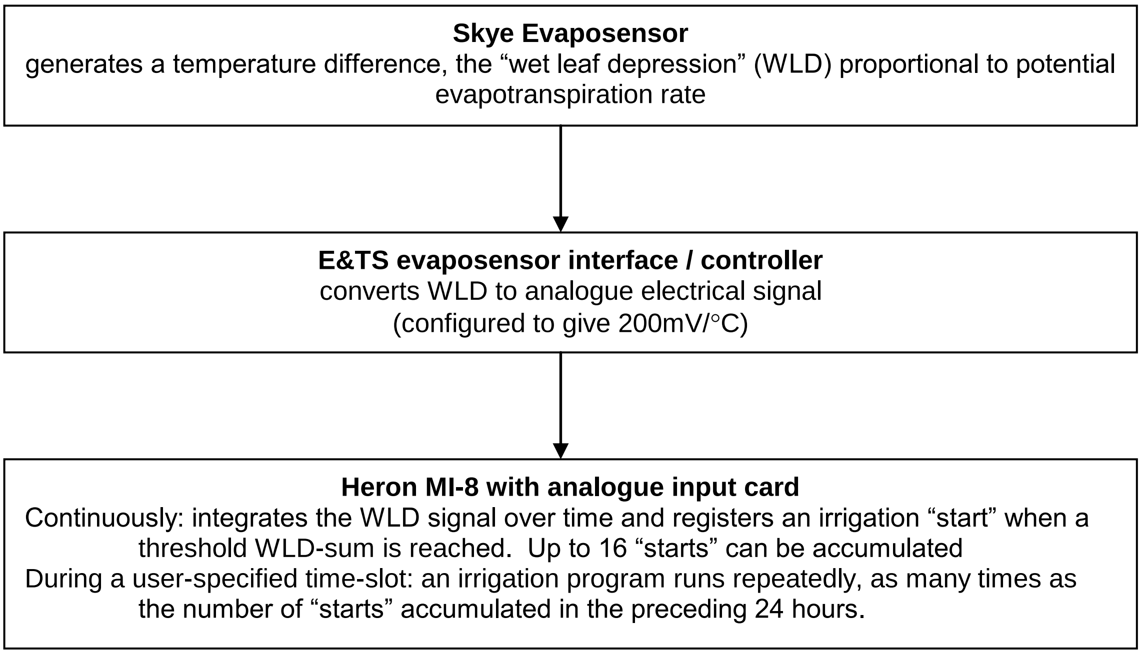
During 2006, Notcutts, Johnsons of Whixley, and Wyevale compared scheduling using an Evaposensor with an alternative method (Table 2.1). This required undertaking a two-stage calibration procedure firstly involving weighing a sample of e.g. 10 pots over a one or two day period without irrigation, and correlating mean pot weight loss (evapotranspiration) to degree hours as measured by the Evaposensor over the same period. The second stage involves measuring mean weight gain of the pot sample following a dose of irrigation applied over a known time. Thus, daily readings of degree hours ('Previous 24 hour value') were directly converted into irrigation times required to replace water lost. A spreadsheet was made available for the nurseries to help with the calibration procedure and produce a 'look-up table' that could be printed out. This enabled daily Evaposensor readings to be readily converted into irrigation times without having to use a calculator, and the irrigation manager could then adjust the irrigation control panel prior to the next irrigation event. Clearly the calibration was only directly applicable to one particular crop subject under one irrigation system, and it was expected that the calibration would need to be updated perhaps two or three times during the season to take account of relative changes in water use as the crop grew.

During 2007, the nursery comparisons of irrigation scheduling compared use of a Skye Evaposensor with timer based irrigations adjusted according to the grower's judgment. Water consumption was monitored with daily (where possible) water meter records. Litres consumed from the irrigated area were converted to mm depth on a bed area basis (i.e. L $m^{-2}$ bed area including access paths). For protected crops, where there was little non-cropped irrigated area, this gave a similar result to the 'irrigated area' based calculation using sprinkler spacings. Evapometer readings were recorded daily where possible. The Evapometer's 'Previous 24 hour total' was used e.g. from 7:00 – 7:00 or 15:00 – 15:00 depending on whether irrigations were typically set up to run in the morning from reading after 7:00, or at night from reading after 15:00. In addition, a running accumulated total was recorded, which enabled extrapolation of mean 24-hour totals to be calculated to fill in gaps in daily records. Irrigations to standard and Evaposensor-scheduled treatment areas were made independently by different staff to try to avoid the application of one treatment being influenced by the other. During the summer of 2008, Evaposensor-based scheduling was compared with timer-based watering on a crop of young *Hydrangea* in 1 L pots under glass at John Woods Nursery. Calibrations were performed in May and August.

**Table 2.1.** Scheduling trials on nurseries using the Evaposensor in 2006

| | **Notcutts** | **Johnsons** | **Wyevale** |
|---|---|---|---|
| Crop | Herbaceous spp. mainly 2 L | *Choisya* 7 L | *Choisya* 3 L |
| Bed location | Outdoors | Glasshouse | Tunnel |
| Irrigation type | Impact sprinklers | Dan micro sprinklers | Impact sprinklers |
| Scheduling comparison with | Grower determined | (1) Grower determined<br>(2) GP1 and SM200 | Grower determined |

Based on work developed in HNS 159, an interface (ET&S – developed by Electronic & Technical Services Ltd) 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 (Fig. 2.1). A system was devised that varied the number of pulses of irrigation applied overnight, from 0 to 16 pulses, in proportion to evapotranspiration registered by an evaposensor over the preceding 24 hours. It was tested in a large glasshouse at Hillier nurseries and operated as follows:



**Skye Evaposensor**
generates a temperature difference, the “wet leaf depression” (WLD) proportional to potential evapotranspiration rate

**E&TS evaposensor interface / controller**
converts WLD to analogue electrical signal
(configured to give 200mV/°C)

**Heron MI-8 with analogue input card**
Continuously: integrates the WLD signal over time and registers an irrigation “start” when a threshold WLD-sum is reached. Up to 16 “starts” can be accumulated
During a user-specified time-slot: an irrigation program runs repeatedly, as many times as the number of “starts” accumulated in the preceding 24 hours.

Within the Heron software, the user creates an irrigation program that specifies how long the irrigation will run for each ‘start’ accumulated, and thus for the amount of evapotranspiration equivalent to the WLD-sum threshold set for the integrator. Different durations can be set for each irrigation valve so that the relative amounts applied to each bed can be tailored to the needs of the crops, their stage of growth, etc. (i.e. to the crop coefficient). Initial settings were chosen by the nursery staff, based on their experience, and the values were subsequently adjusted if crop inspection indicated that the system was applying too much or too little water to maintain the substrate at the desired water content.

Taking 200 °C h as the maximum daily WLD-sum likely to be observed in the UK, the threshold of the integrator was set so that 200 °C h would result in the maximum number of irrigation ‘starts’ being accumulated i.e. to 16 starts. The threshold WLD-sum was therefore set to 200 ÷ 16 = 12.5 degree hours (°C h). To set this in the Heron software, it was first necessary to calculate how the arbitrary units used in the software relate to °C h. The Heron controlled irrigation to seven beds but initially only one was automatically scheduled by the Evapo-irrigation system, while the remainder were on conventional control, with irrigation times adjusted manually by nursery staff, based on daily inspection of crops and intuitive assessment of the effect of weather on water use. The trial bed was filled with a uniform crop of *Syringa* ‘Red Pixie’(Fig. 2.2), potted in March and irrigated conventionally while the automated system was set up and tested. The automated system took control from 29 April.

The Evaposensor was mounted on the south side of glasshouse stanchion, about 2 m above the ground. The location was conveniently close to the irrigation control panels in the boiler house but about 50 m from the initial trial bed. Loggers were used to monitor the behaviour of the system during the trial. A Delta-T DL2 monitored the duration of irrigation by counting the number of a.c. cycles applied to the irrigation valves, while a GP1 logged water flow by counting pulses from a water meter (1 pulse per litre). Other variables logged were Evaposensor WLD, substrate moisture content in two representative pots and air temperature.

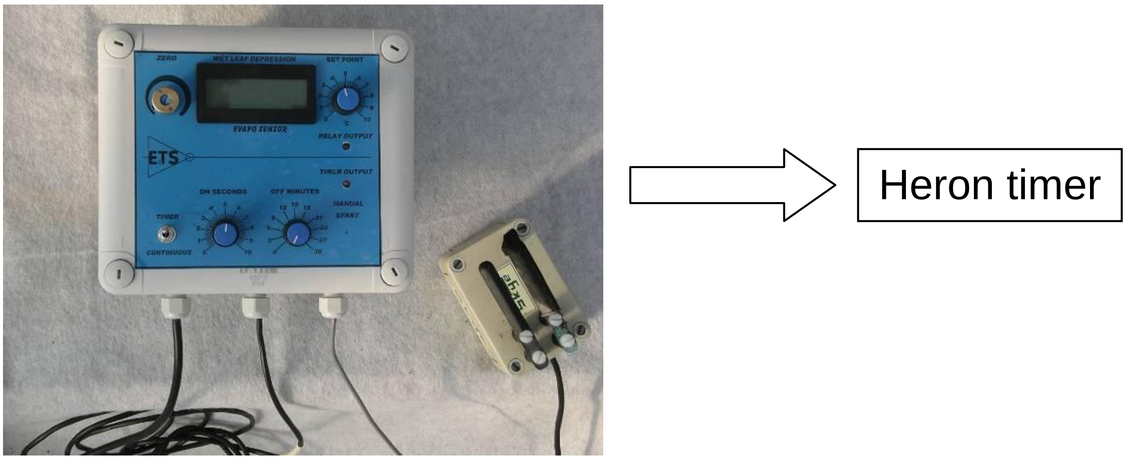


**Figure 2.1.** ETS interface and Evaposensor, which together allow automatic daily adjustment of the length of irrigation runs triggered by a Heron irrigation timer

**Figure 2.2.** The *Syringa* crop at Hillier nurseries automatically irrigated throughout the summer of 2009, using an Evaposensor linked to a Heron irrigation timer.

### *Soil moisture sensor*

*Scale of variation*

To determine the scale of variation in soil water content of apparently representative plants within a single container bed under different levels of RDI, a series of RDI experiments were set up (which were also used to investigate the potential of applying RDI on nurseries – see Objective 4).

Plant material

Experiments were conducted in 2006 and 2007, with all plants purchased as liners and potted up into 2 L pots. The cultivars were:

- 2006: *Lonicera periclymenum* 'Graham Thomas' and *Cornus alba* 'Elegantissima'
- 2007: *Forsythia* × *intermedia* 'Lynwood'

Growing environment

The experiments were run in a closed plastic tunnel. The length of the polytunnel was divided into separate bays using sheets of thin plastic to prevent overhead irrigation in one bay reaching another bay. Drains at the base of the plastic sheets prevented water hitting the plastic from reaching the ground. Pots were placed on a sheet of Mypex over a sheet of plastic. The standing surface was rolled to ensure it was as smooth as possible, minimising puddles. Pots were arranged in groups of 90 (2006) or 72 (2007) per bay, in rows of 16-18 plants, with the outer rows acting as guard plants.

Substrates

In 2006 all plants were grown in 100% peat. In 2007 half the plants were grown in this substrate, and half in a 60% peat: 40% bark mix. 1 g ammonium nitrate per L of bark was incorporated to compensate for the low nitrogen availability in bark. Peat and peat/ bark treatments were replicated randomly in each bay. Limestone (1.5 kg $m^{-3}$) and CRF (Osmocote Plus, 6 kg $m^{-3}$) were incorporated in both mixes at the time of potting up.

Irrigation

Half of the plants (three bays) were given drip irrigation while the other half were given overhead irrigation. Drip irrigation was applied via 2 L $h^{-1}$ C.N.L. Junior Drippers (Access Irrigation, Northampton, UK). This resulted in 96-98% uniform irrigation with a scheduling coefficient of 1.0 to 1.1. Six 50 L $h^{-1}$ Eindor 861 sprinklers (Access Irrigation) were used per bay to apply overhead irrigation, giving a coefficient of uniformity of 91%, a scheduling coefficient of 1.2, and a mean application rate of 7.7 mm $h^{-1}$.

Irrigation was scheduled to provide either full irrigation (FI) or RDI. Two different RDI treatments were applied each year:

- 2006: 50% $ET_p$ and 25% $ET_p$
- 2007: 70% $ET_p$ and 50% $ET_p$

Irrigation was adjusted daily according to an Evaposensor. Crop coefficients were determined every two weeks by weighing a sample of FI plants soon after irrigation and a day later. Crop coefficients were multiplied by the appropriate percentage to obtain either FI or RDI.

Substrate moisture content

Volumetric substrate moisture content was measured in each experimental plant every week with a hand-held soil moisture sensor (SM200 and HH2 meter). Additionally, in August 2007, plants and their substrate were taken out of the pots, and, for each pot, substrate moisture was measured at four locations in the top, four locations in the central, and four locations in the bottom section of the substrate. Substrate moisture content at the top and bottom of each pot was also measured at the end of the RDI experiments each year.

*Establishing protocols for use of soil moisture sensors*

In 2008, at EMR, 72 *F.* × *intermedia* 'Weekend' in 100% peat in 3 L pots were placed in each of six bays in a polytunnel. Overhead irrigation was applied to each bay, using the same sprinkler arrangement as described above. Irrigation of half the plants was scheduled using the Evaposensor, while irrigation of the other half was scheduled using in-pot SM200 soil moisture probes. A single soil moisture probe was placed in a representative pot. The soil moisture probe was connected to a GP1 irrigation controller and data-logger. Upper and lower thresholds of substrate moisture content were input into the controller, so that irrigation was triggered when the substrate moisture content fell below the lower threshold, and irrigation was automatically turned off when the substrate moisture content reached the upper threshold. Separate soil moisture sensors were used to schedule FI and two different levels of RDI. In the case of RDI, the thresholds were gradually reduced to impose a similar reduction in $ET_p$ as was being scheduled with the Evaposensor. The RDI levels were: 70% $ET_p$ throughout the growing season, compared to a shorter RDI treatment of 150% $ET_p$ until pruning, followed by 50% $ET_p$. All plants were pruned in late June, following standard nursery practice.

Several trials of the SM200 soil moisture sensors in conjunction with the GP1 irrigation scheduler on commercial nurseries were also undertaken to determine optimal use of the sensor. In 2006 the SM200 was trialled at Johnson's of Whixley, Notcutts, and Garden Centre Plants. The GP1 was used in comparison with Evaposensors on a drip irrigated tree crop (outdoors) at Notcutts and on a 7 L *Choisya* glasshouse crop at Johnsons of Whixley (Table 2.1). The GP1 was additionally assessed on sprinkler irrigated *Hibiscus* and *Hydrangea* crops in a glasshouse at Notcutts, in comparison with grower-determined irrigation.

In 2007, irrigation scheduling compared using a GP1 plus SM200 moisture probe was compared on nurseries with timer based irrigations adjusted according to the grower’s judgment. Water consumption was monitored with daily (where possible) water meter records. Litres consumed from the irrigated area were converted to mm depth on a bed area basis.

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 2008, 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 potential evapotranspiration estimated by recording daily degree hour totals using an Evaposensor. A similar experiment was run at Wyevale Nurseries in 2009 with automatic GP1 *vs* timer-based scheduling of an outdoor crop of 3 L *Prunus lusitanica*. The experiment was set up in spring 2009 and recording started in early June. The trial bed areas were 359 $m^2$ per treatment for *Ligustrum* in 2008 and 562 $m^2$ per treatment for *Prunus* in 2009 (Fig. 2.3). In each case the automatic GP1 treatment was controlled via a single representative pot containing an SM200 probe, but with additional probes simply monitoring pots on each treatment. *Prunus* is susceptible to shot hole disease (*Stigmina carpophila*), exacerbated by leaf wetting, so the aim in 2009 was to provide adequate, but not excessive, irrigation to the controlled bed and compare water use with the manually adjusted timer system.

**Figure 2.3.** GP1 scheduled (front) and Timer scheduled (rear) beds of 3 litre *Prunus laurocerasus* at Wyevale Nurseries in early June 2009

Use of GP1 to trigger gantry irrigation

At Hillier nurseries, a section of the Denton gantry (see Objective 1) was controlled using an SM200 and GP1. This was compared with control of pinjet irrigation by the GP1. The crop grown was *Musa lasiocarpa* (ornamental banana). For the gantry, the GP1 relay was wired to a stationary connection box halfway down the gantry run. This, in turn, was linked to the control box and microprocessor on the mobile gantry unit. Under normal operating mode, the gantry was stationed in its parking position at one end of the bay. When the GP1 called for irrigation and its relay closed, the gantry travelled down the bay until the start of the section containing the *Musa* crop. Irrigation then started, and the gantry applied a double pass (forwards and return) over this section, and then continued back to its parking position. The gantry software was programmed to turn on and off the irrigation valves only when positioned over the *Musa* crop. The programme then re-checked the status of the GP1 relay. If still closed (i.e. moisture level within the probed container had not reached the ‘off point’), then the irrigation cycle was repeated until the off point was reached.

To determine whether deficit irrigation could be applied to a commercial crop using gantry irrigation, scheduled using a GP1, 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.

GP1-scheduled gantry irrigation was later applied to a crop of *Tradescantia* ‘Sweet Kate’. In this case, 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.

## Results and Discussion

### *Evaposensor*

*Scale of variation in Evaposensor readings depending on location*

Some variation was seen between readings of Evaposensors in different locations across a polytunnel, with sensors close to or within canopies showing the least accumulation of degree hours. There was clearly some variation in the difference in temperature between the wet and dry sensors depending on location. Most notably a sensor on the pavement maintained a relatively large difference between wet and dry sensors at night, when the difference for the other sensors fell to close to zero.

On an outdoor bed, an Evaposensor which occasionally received irrigation spray showed a tendency to show lower temperature differences than a sensor on a gravel bed. The precise location of the evaposensor does appear to have an influence on degree hours, but problems should be avoided by placing the sensor at a height similar to the plants, above a surface similar to that on which the plants are grown, and either consistently exposed to the same overhead irrigation as the plants or never exposed to any spray – the latter is preferable as frequent exposure to overhead irrigation can result in algae building up on the wick and eventually a change in the texture of the wick which prevents it from wetting up correctly.

*Establishing a system to estimate crop coefficients*

<u>Manipulation of evapotranspiration</u>

In the *Escallonia* 'Donard Radiance' experiments, it was found that when the canopy was lightly pruned and widely spaced, transpiration rate of individual plants was high, whereas when the canopy was severely pruned and narrowly spaced, evapotranspiration was reduced (Fig. 2.4a). When expressed per unit ground area, evapotranspiration per degree hour was strongly correlated with both a visual estimate of % cover (Fig. 2.4b) and with % light interception (Fig. 2.4c). This suggested that estimating cover, alone, could be sufficient to establish crop coefficients for *Escallonia* 'Donard Radiance'.

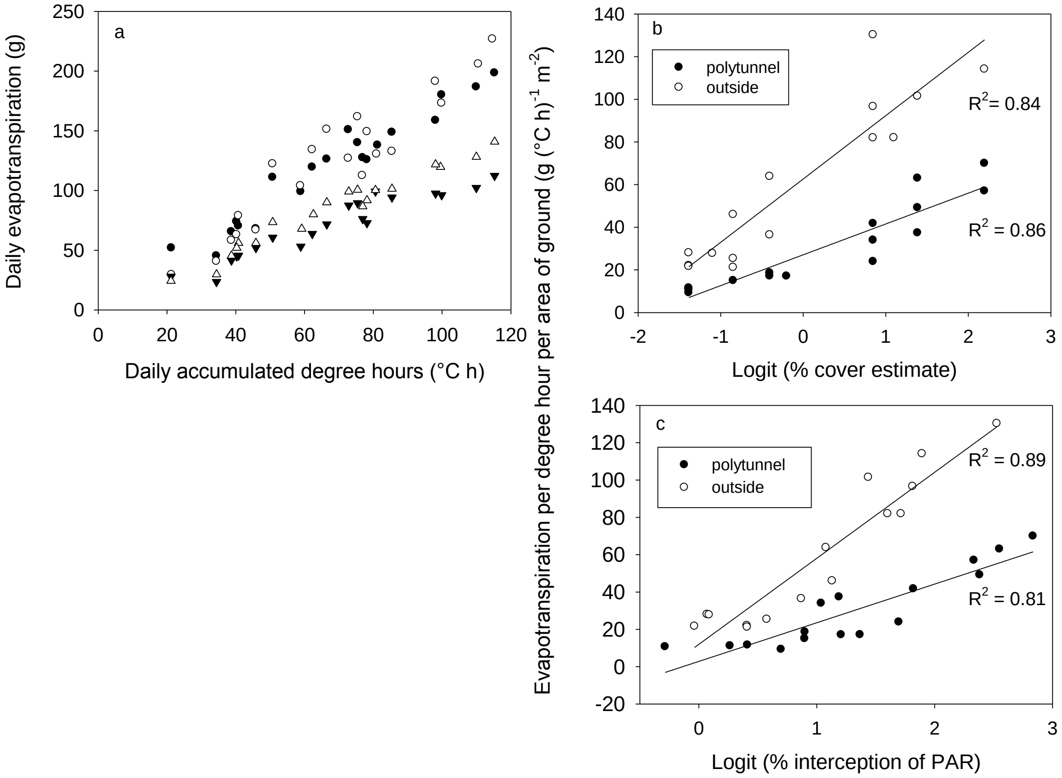


**Figure 2.4.** The relationship between daily evapotranspiration per plant and daily accumulated degree hours, for lightly (circles) or severely (triangles) pruned, and narrowly (filled symbols) or widely (open symbols) spaced *Escallonia* 'Donard Radiance' grown under a polythene tunnel (a, *n* = 4), and across these treatments between evapotranspiration per degree hour per unit ground area and an estimate by eye of percentage cover (b) or % interception of photosynthetically active radiation (PAR) (c) in plants grown either in a tunnel or outdoors

## Multi-cultivar experiments

### *Crop coefficients for a range of cultivars*

Our interest here was not just to be able to rapidly estimate crop coefficients for one cultivar, such as *E.* 'Donard Radiance', but to determine a method for estimating crop coefficients that would be applicable across a wide range of crop types, with different growth habits. When we monitored evapotranspiration per degree hour of six cultivars, total leaf area was the canopy measurement which most closely correlated with water use (Fig. 2.5).

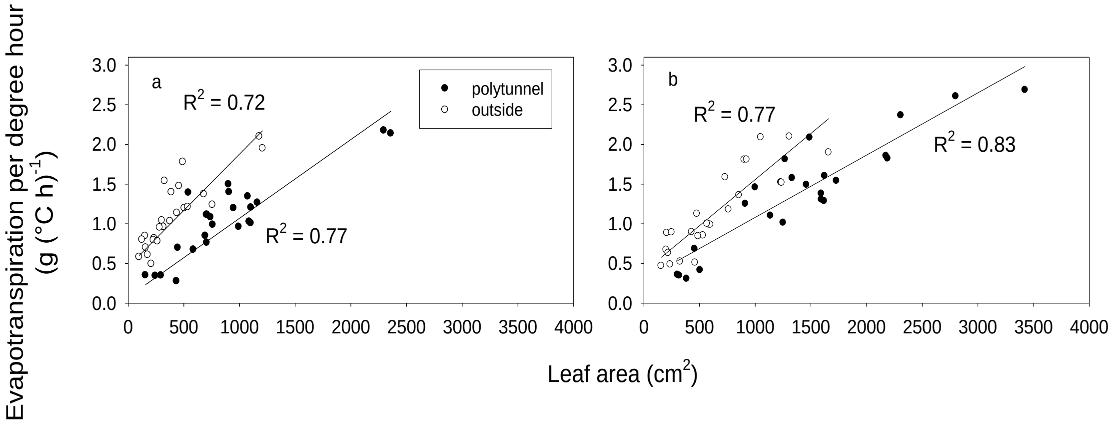


**Figure 2.5.** Evapotranspiration per degree hour of individuals of six cultivars of different habits, in relation to leaf area, in two separate months [(a) and (b)], and in two different environments

*Crop coefficients for a range of cultivars over a season*

Initial assessment suggested that the relationship between leaf area and crop coefficients was maintained as the crops grew (Fig. 2.6). Over a whole season (six months growth), however, crop coefficients appeared to depend more on certain canopy variables in some months and on other variables in other months (examples in Fig. 2.7). Combining data from the whole season, for plants grown in the plastic tunnel crop coefficients could be best explained by a combination of plant height, leaf area, and stomatal conductance: these variables together explained 76% of the total variation in crop coefficients:

$ET_A$ per degree hour = 0.73 plant height + 4.63 leaf area + 0.77 log ($g_s$) – 1.57 (2.1)

For the same cultivars grown outdoors, 62% of the variation in crop coefficients could be explained by these variables along with percentage cover:

$ET_A$ per degree hour = 0.44 plant height + 2.25 leaf area + 0.48 log ($g_s$) + 0.25 logit (eye cover) (2.2)

While it is interesting that such a large proportion (particularly in the tunnel where there was no wind) of the variation in crop coefficients across very diverse cultivars (including, for example a climber and a very prostrate creeping cultivar) could be explained by these variables, it is unlikely that growers would measure stomatal conductance or leaf area on commercial nurseries.

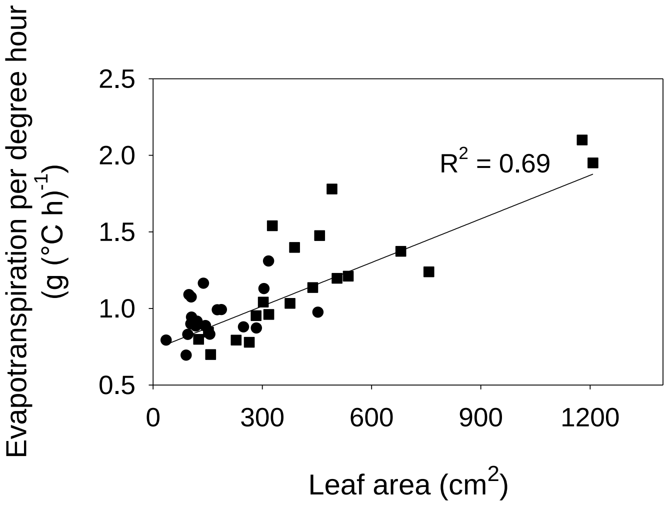


**Figure 2.6.** Evapotranspiration per degree hour of individuals of a six cultivars of different habits, in relation to leaf area, when data from two separate months (squares *vs* circles), during which there was substantial growth, are considered together (outdoors experiment)

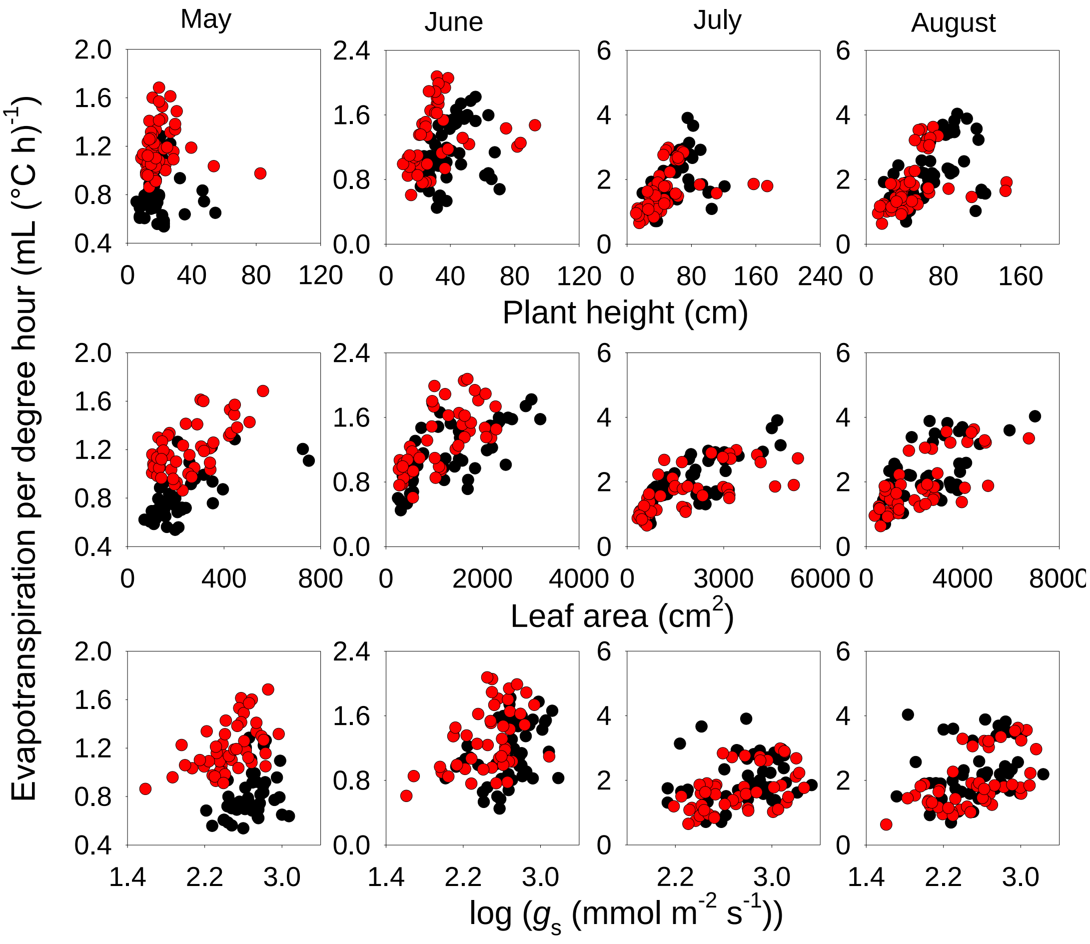


**Figure 2.7.** Evapotranspiration per degree hour of individuals of a twelve cultivars of different habits, in relation to three of the variables measured through the summer of 2008 (May-August shown here), in a polytunnel (red symbols), or outdoors (black symbols)

*A practical system for establishing crop coefficients*

Plant height and percentage cover can be easily and rapidly measured on nurseries. In the plastic tunnel, these two measures alone accounted for 64% of the variation in crop coefficients:

$ET_A$ per degree hour = 1.61 plant height + 0.29 logit (eye cover) + 0.72 (2.3)

Outside, they accounted for 57% of the variation in crop coefficients:

$ET_A$ per degree hour = 0.58 plant height + 0.43 logit (eye cover) + 1.51 (2.4)

*Validation*

Regression analysis of 2007 data was used to predict calibration coefficients on the basis of crop height and cover, for each of three cultivars, which had been found to have high (*C. alba* ‘Gouchaultii’), medium (*B.* ‘Lochinch’) and low (*G. littoralis* ‘Variegata’) water use respectively:

*Cornus*: $ET_A$ per degree hour = 3.7 plant height (2.5)
*Buddleia*: $ET_A$ per degree hour = 3.6 plant height (2.6)
*Griselinia*: $ET_A$ per degree hour = 0.22 logit (eye cover) + 0.92 (2.7)

The three cultivars were grown through the summer of 2008 to see if their water use at different heights and cover matched that predicted from the models. Despite deviations from the models, the correlation between predicted and actual crop coefficients was strong (Fig. 2.8a). Ideally, however, calibration coefficients that can be used across different species and cultivars are needed. Therefore we also determined how well the data fitted to equation 2.1 (calculated using data from all 12 cultivars studied in 2007). The 2008 data actually fitted better to this model than to the cultivar-specific models (Fig. 2.8b). It should be noted that although there is a strong regression in the case of the cultivar-specific model (Fig. 2.8a), there is a large deviation from the 1:1 line, suggesting that the three crops would be substantially over-watered if irrigated according to this model. In the case of the general model, however, the regression is much closer to the 1:1 line (Fig. 2.8b), In this case, the worst deviation was for *G. littoralis* ‘Variegata’ in October, when the general model would have resulted in overwatering the crop by 66%. Perhaps more seriously, in May, use of the general model would have resulted in underwatering *B.* ‘Lochinch’ by 36%. Nonetheless, we suspect that these deviations represent, over the whole season, a far smaller deviation from actual crop water use than occurs on the majority of nurseries. If desired, growers could use the model to estimate crop coefficients for each crop at the start of a growing season, and then increase irrigation as the crop grows, and as their monitoring of the crop suggests necessary. We hope that this will encourage growers to start scheduling irrigation using the Evaposensor.

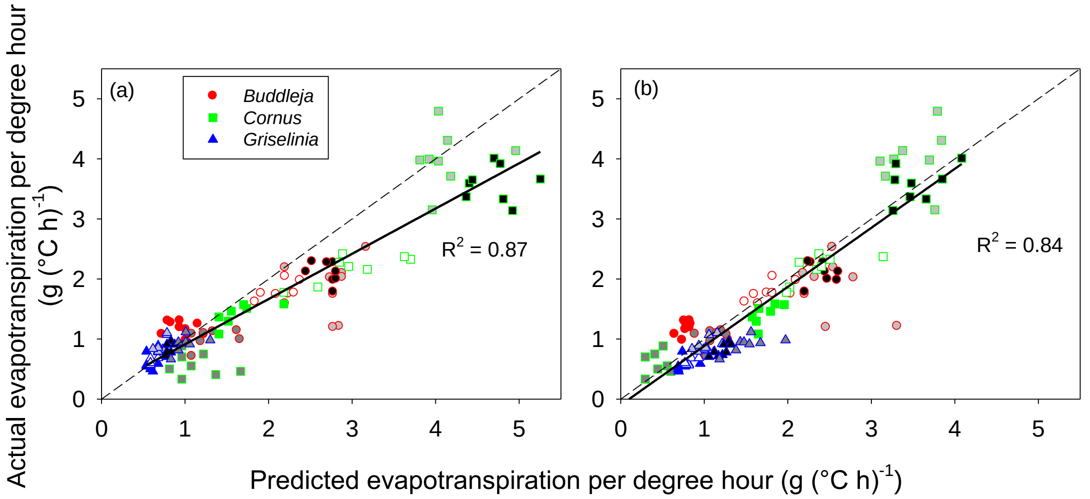


**Figure 2.8.** Actual *vs* predicted evapotranspiration per degree hour for three cultivars measured every 4 weeks from early June to late August 2008, at which point *Buddleja* ‘Lochinch’ and *Cornus alba* ‘Gouchaulti’ were pruned, and then measured once in October 2008, using either specific predictions for each cultivar (a) or a single general regression that was derived from data obtained from 12 cultivars in 2007 (b). 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. Linear regressions are through all data points; the dotted lines represent 1:1.

Effectively, we have moved from a situation where we were suggesting to growers that they needed to use pot weights to calibrate their crop water use against the Evaposensor, to a situation where we are suggesting that they use crop height and cover and our equation as a starting point. To assist in estimating crop cover, we have prepared images of known cover, for the same type of plant with different leaf areas (Fig. 2.9), and for the same amount of leaf area but different spacing (Fig.

2.10). Again, if there is sufficient interest, these could be extrapolated to different types of plant, and more leaf areas and more spacing arrangements.

The results of these experiments suggest that measuring just crop height and percentage cover (which can be estimated visually) should suffice to estimate crop coefficients and schedule irrigation across a wide range of different hardy nursery stock crops. By monitoring crops for which irrigation is scheduled in this way, growers could adjust the coefficients for individual crops if greater accuracy is desired.

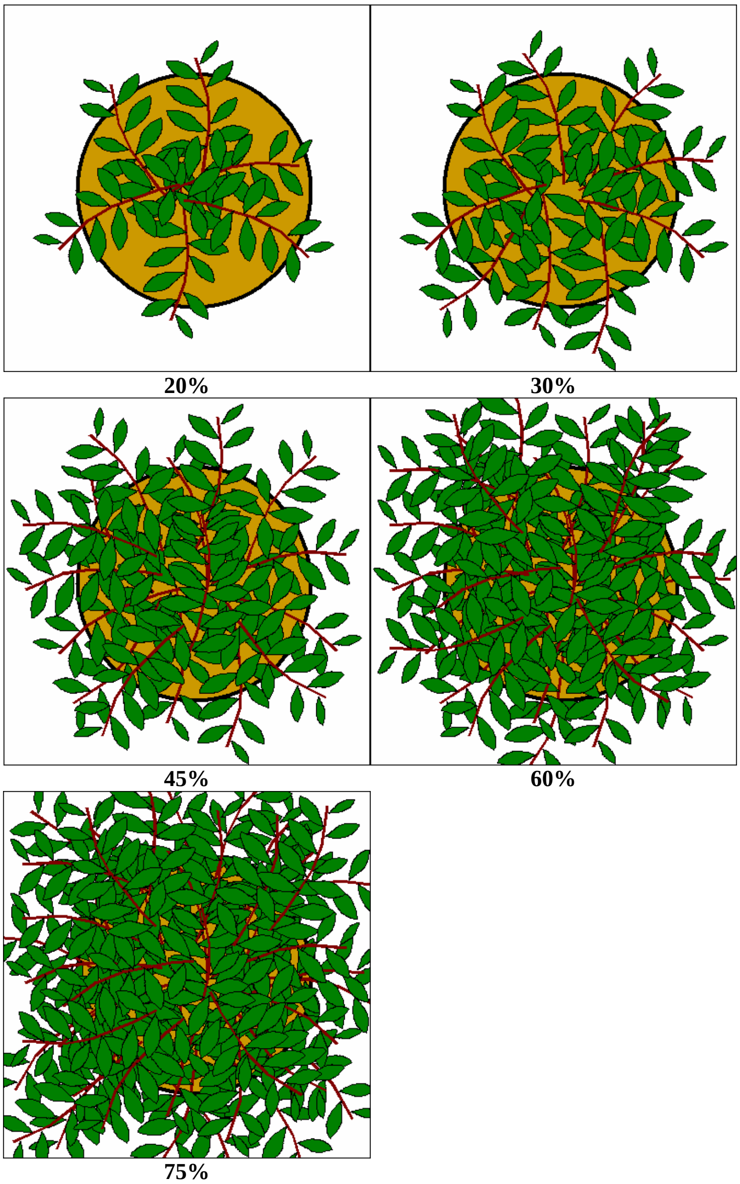
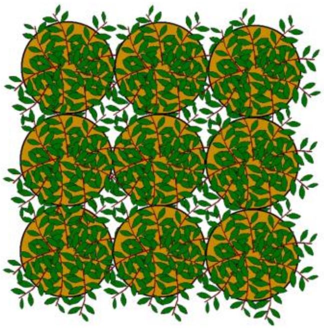
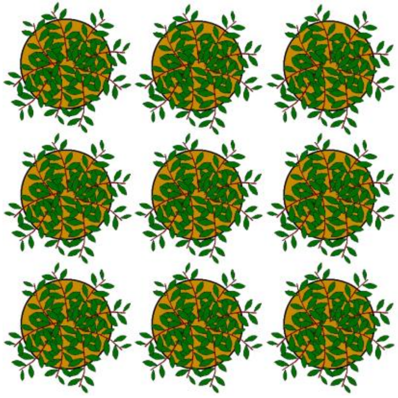


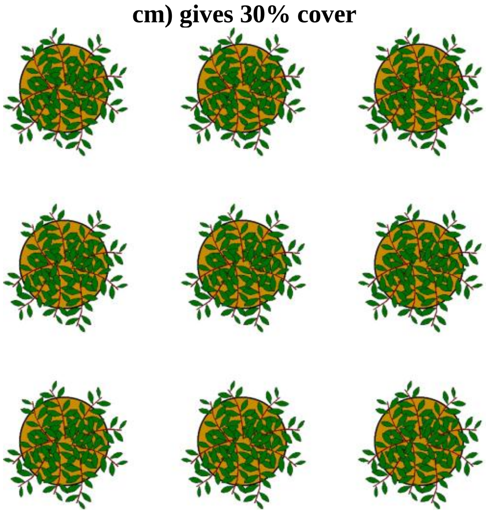
**Figure 2.9.** Examples of different percentage cover for a small-leaved type of plant in pot at spacing ratio of 1.4 (e.g. 18cm pot at 25 × 25 cm)



**60% when pot thick**



**The same plants at a spacing ratio of 1.4 (e.g. 18 cm pots spaced at 25 x 25 cm) gives 30% cover**



**At a spacing ratio of 2, cover is just 15%**

**Figure 2.10.** Examples of different percentage cover when a small-leaved type of crop is arranged at different pot spacings

*Nursery trials of Evaposensors*

On some nurseries, there were initially problems in achieving an accurate calibration of the Evaposensor for the nursery crops, because an irrigation dose that was too short to achieve sufficient weight gain, compared with what is normally applied, was used. This resulted in a calibration that called for much greater irrigation doses than was actually required. However, the calibration procedure appeared to work satisfactorily if a test dose was used that was about half to 2/3 of what was required to fully wet up the pots. It is important to apply a realistically high dose to get a good relationship between irrigation time and pot weight gain, but not so high that significant drainage of surplus occurs.

The Evaposensor appears to have been successful in scheduling the Notcutts trial on an outdoor herbaceous crop in 2006, and resulted in similar or less water use than comparative beds on which irrigation was determined according to grower judgment. The following year at Wyevale, scheduling using the Evaposensor used less water (mean 6.6 mm day$^{-1}$) than grower-determined irrigation (9.0 mm day$^{-1}$) (Fig. 2.11). In other cases where the Evaposensor was trialled on nurseries, it is difficult to tell how effective it was, because the growers did not consistently follow the Evaposensor scheduling. This was due either to finding it difficult to get a reliable calibration using pot weights, 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.

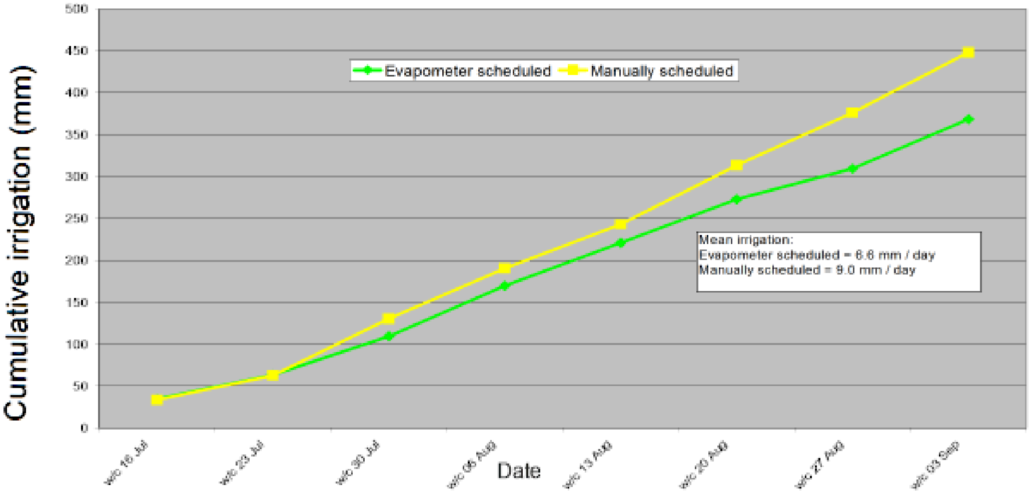


**Figure 2.11.** Cumulative irrigation in a nursery comparison of scheduling irrigation using either the Evaposensor or grower-determined timer control

Automated irrigation

At Hillier nurseries in 2009, the automatic scheduling system was compared with manual adjustment of timers by experienced nursery staff (Figs 2.12 and 2.13). Over the 15 days for which data are available, the automatic Evapo-irrigation system altered irrigation times every day, with times ranging from 3.7 to 8.7 minutes, while manual changes were infrequent and generally small. As expected, the automated system varied irrigation times in proportion to daily WLD-sum, and hence $ET_p$. In contrast, manually adjusted times showed little relationship with WLD-sum, apart from the extra irrigation applied on 23 June. Nursery staff soon became confident in the benefits of the automatic Evapo-irrigation system and transferred to the automatic program all the beds wired to the Heron, representing a total crop area of about 1,500 m$^2$.

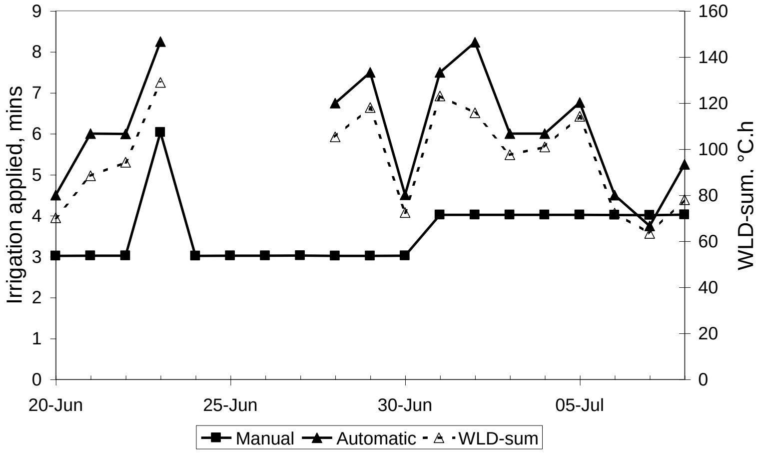


**Figure 2.12.** Daily irrigation times under automatic evaposensor-based scheduling of *Syringa* 'Red Pixie' compared with manual adjustment of irrigation times by experienced nursery staff for a bed of mixed crops including *Carex* 'Evergold' and *Weigela* 'Monet'. The automatic system tracked the variation in WLD-sum (and hence ET$_p$), for the preceding 24 hours much more closely than was achieved by manual adjustment (valid data are not available for WLD-sum and automatic irrigation for 24 to 27 June).

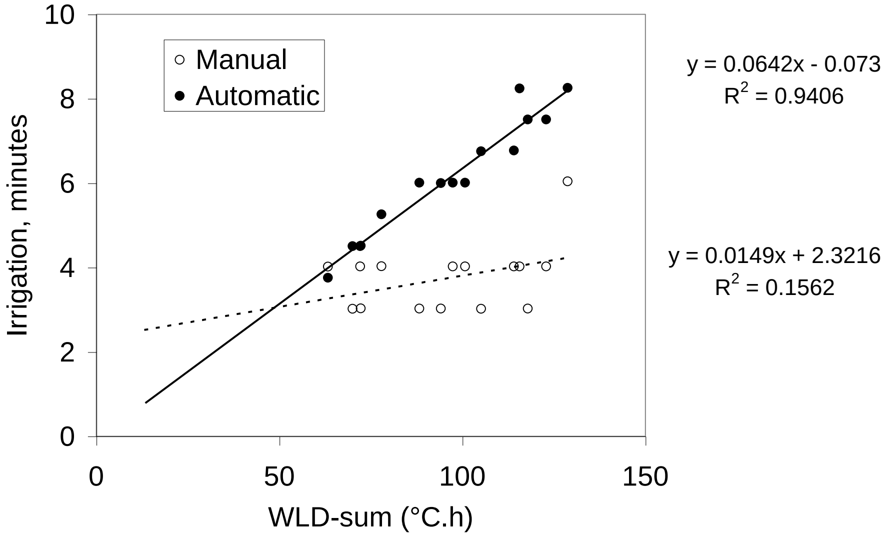


**Figure 2.13**. The data from Fig. 2.12 plotted to show the relationship between applied irrigation and potential evapotranspiration over the preceding 24 hours, as reflected in WLD-sum, under automatic evaposensor-based scheduling (solid line and filled circles) or under manual adjustment (dashed line, open circles).

*Adjusting set points*

Initially, the *Syringa* bed was set to receive 30 s of irrigation per 'start', based on previous experience. At this time, mean plant height was 30 cm and percentage canopy cover was estimated visually at 50%. Inserting these values into the model described above, estimates crop coefficient at 1.2 g (°C h)$^{-1}$, and applying an approximate estimate of water delivery of 50 g of water delivered to each plant per minute of irrigation gives a predicted irrigation requirement per 'start' (i.e. per 12.5 °C h) of 18 seconds. From this, we conclude that the model prediction was of the right order of magnitude and would, in the absence of any previous experience, have been a satisfactory starting point. Over the course of the season, irrigation per 'start' was altered 6 times, based on inspection of the crop at roughly weekly intervals, to a maximum of 55 seconds in mid-July, returning to 30 seconds by 2 September when growth had largely terminated.

When the other beds were added to the automatic program in July, initial settings based on experience ranged from 30 to 70 seconds, the longer times being for a bed with a mixture of taller plants (including *Magnolia grandifolia*, some *Phormium* species and stock plants). Slight adjustments to these settings were made 3 or 4 times over the course of July and August. Nursery staff rapidly became comfortable with this fine tuning process and it was much less time-consuming than the need to make daily decisions about time clock settings.

*Difficulties encountered*

The standard Heron software will apply accumulated 'starts' as soon as any other programs have finished running. To restrict irrigation to a specific part of the day (e.g. at night), whilst retaining the ability to manually switch on irrigation at any time, required a software modification, which the Heron company kindly undertook. Another important change from the standard software prevented the integrator from being reset every day at midnight.

Careful location and a rigorous maintenance schedule and / or an automatic refilling system are important for accurate WLD readings. Low WLD-sum readings (and hence insufficient irrigation) will occur if the reservoir is not topped up weekly, filled with the incorrect solution or its environment altered through accidental covering.

From 3 July, shade was applied to the part of the glasshouse where the Evaposensor was located, reducing evapotranspiration in that part of the house. Reducing the integrator threshold in proportion to the approximate reduction in light level (one third), provided a simple and effective way to compensate for the shade.

## Conclusions

Automating the use of an Evaposensor to schedule irrigation makes it a very attractive method of scheduling irrigation to a wide range of crops growing in a reasonably uniform aerial environment

Automation greatly reduces the difficulty of determining precise crop coefficients because the grower can easily arrive at an approximate settings of control parameters from his/her experience and then fine tune it based on crop inspection at approximately weekly intervals.

The system used in the trials worked well and is ready for uptake by the industry.

### ***Soil moisture sensor***

#### *Scale of variation in soil moisture across a bed*

Variation between pots in volumetric substrate moisture content across a crop of *Lonicera periclymenum* ‘Graham Thomas’ or *Cornus alba* ‘Elegantissima’ did not appear to be any greater under overhead irrigation than drip irrigation (Fig. 2.14). This was the case whether the crop was given full irrigation or RDI. These measurements were taken from the top of the pot, so the probes were about 6 cm deep in the compost. On different dates of measurement, there was little variation in substrate moisture under 200% overhead irrigation, but greater variation under RDI regimes, as would be expected. The extent of variation under RDI regimes varied however between dates of measurement and this was more noticeable when drip irrigation was used.

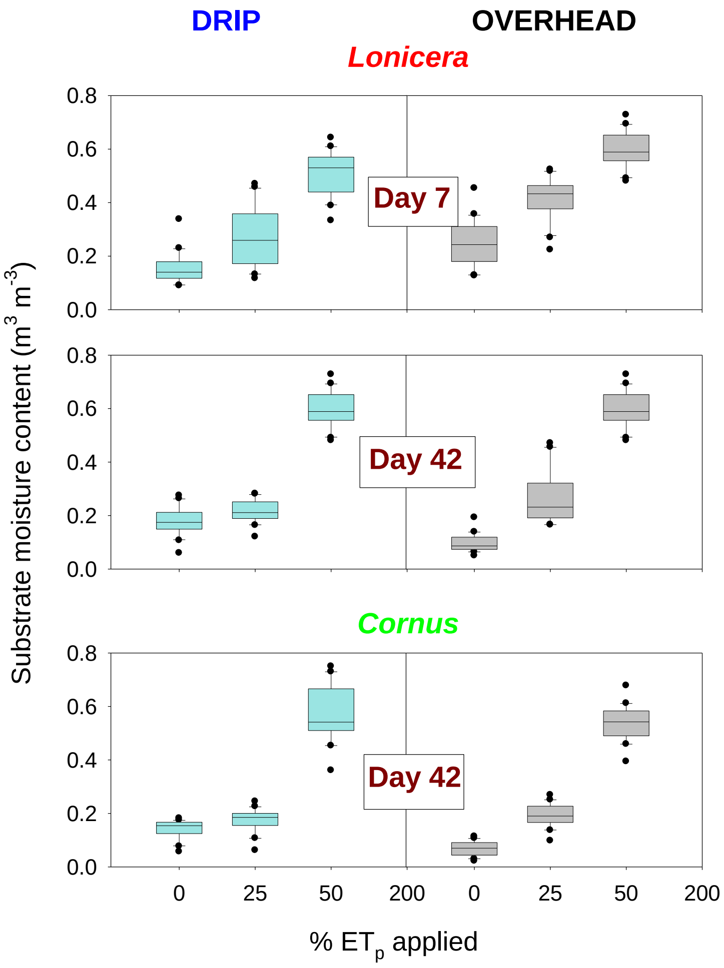


**Figure 2.14.** Variation in substrate moisture content in pots of *Lonicera periclymenum* ‘Graham Thomas’ and *Cornus alba* ‘Elegantissima’ under drip irrigation and overhead irrigation, measured on the 7th or 42nd day of full (200% $ET_p$) or RDI (25% or 50% $ET_p$). Boxes indicate the 25th to 75th percentile range, whiskers extend another 15% either way, and outliers are represented by dots.

At the end of the 2006 experiment, for *Lonicera* it was found for substrate moisture both at the top and at the bottom of the pot there was a significant interaction of irrigation system and % $ET_p$ ($P < 0.001$), with substrate moisture content being lower under overhead than drip irrigation for 25% and 50% $ET_p$ treatments, but higher under overhead than drip when $ET_p$ was set at 200% (Fig. 2.15a, c). In both upper and lower parts of the pot a significant interaction of irrigation system and % $ET_p$ also occurred in the case of *Cornus* ($P < 0.001$; Fig. 2.15b, d), showing the same pattern as seen in pots of *Lonicera*.

Our results for *Lonicera* in 2 L pots suggest that for the substrate used and with pots on Mypex under overhead irrigation, substrate moisture of around 28% corresponded to imposition of 50% RDI.

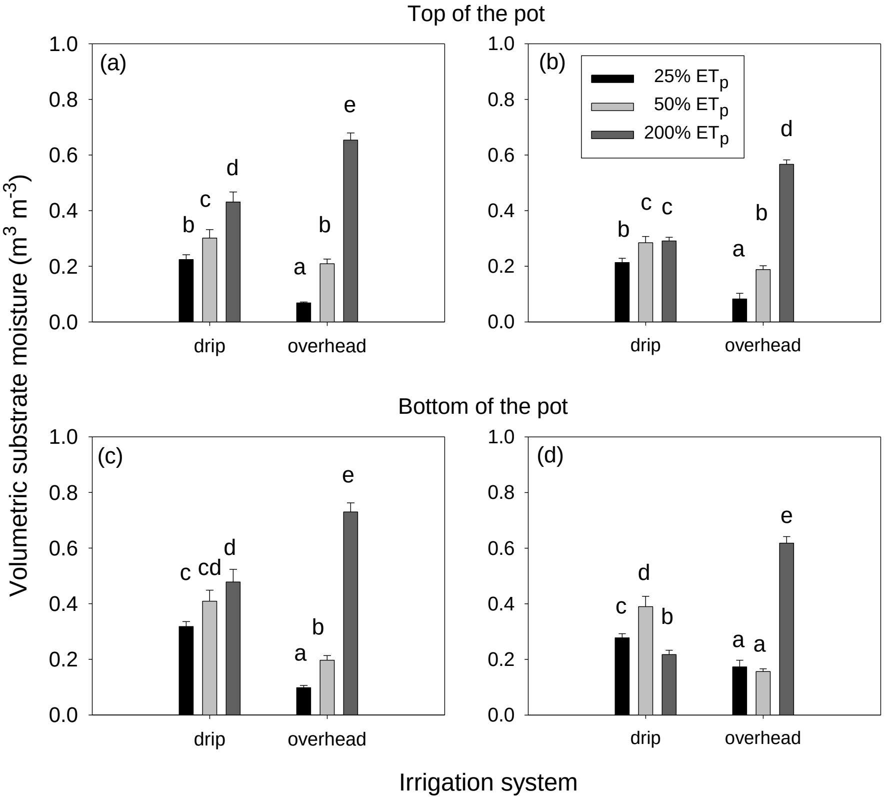


**Figure 2.15.** Substrate moisture at the top and 6 cm from the base of pots of *Lonicera* (a, c), and of *Cornus* (b, d) after 8 weeks of drip or overhead irrigation. Bars represent means ± s.e. Different letters represent significant differences between means (LSD) at $P < 0.05$, $n = 20$

In 2007, we were interested in whether variation across a bay was greater under the less uniform irrigation system (overhead) than under the more uniform system (drip). Taking two dates as examples, on 22 June similar variation in substrate moisture content within drip and overhead irrigation was seen at 50% $ET_p$, but greater variation within overhead irrigation than drip at 70 $ET_p$ (Fig. 2.16). However, there was no clear pattern under 150% $ET_p$. On 26 July, again there was limited variability within either drip or overhead at 50% $ET_p$, the pattern was different for peat + bark compared to peat only at 70% $ET_p$, and at 150% $ET_p$ there was greater variation under drip than under overhead irrigation. So there was no indication here that overhead irrigation leads to greater variability in substrate moisture content. Early in August plants and their substrate were taken out of the pots to determine substrate moisture content in different sections of the pot. The substrate was clearly drier at the top of the pot than lower down in both substrate types and under both irrigation systems, and independently of whether full irrigation or RDI was applied (Fig. 2.17). Looking at coefficients of variation (100 × standard deviation/mean), where a higher number indicates greater variation, between the four measurements taken per layer of the substrate, the greatest variation always occurred in the top layer (Table 2.2). This variation was far greater under drip than overhead. Variation was greatest in the more severe deficit irrigation treatment, 50% $ET_p$. Under 50 and 70% $ET_p$ with drip irrigation, variation between locations in a layer is quite high even in the middle and bottom layers. This reflects that fact that water from the dripper in one side of the pot will not always move to the other side of the pot, particularly where deficit irrigation is applied. The dripper is placed quite low down in the pot, so the effect is even greater in the upper layers. This variation is important to consider if substrate moisture content is to be used to schedule irrigation. The variation in substrate moisture content appeared to have an impact on root growth: roots were generally distributed in the lower section of the pot under deficit irrigation where drip irrigation was used (Fig. 2.18a), but were more evenly distributed through the pot were overhead irrigation was applied (Fig. 2.18b).

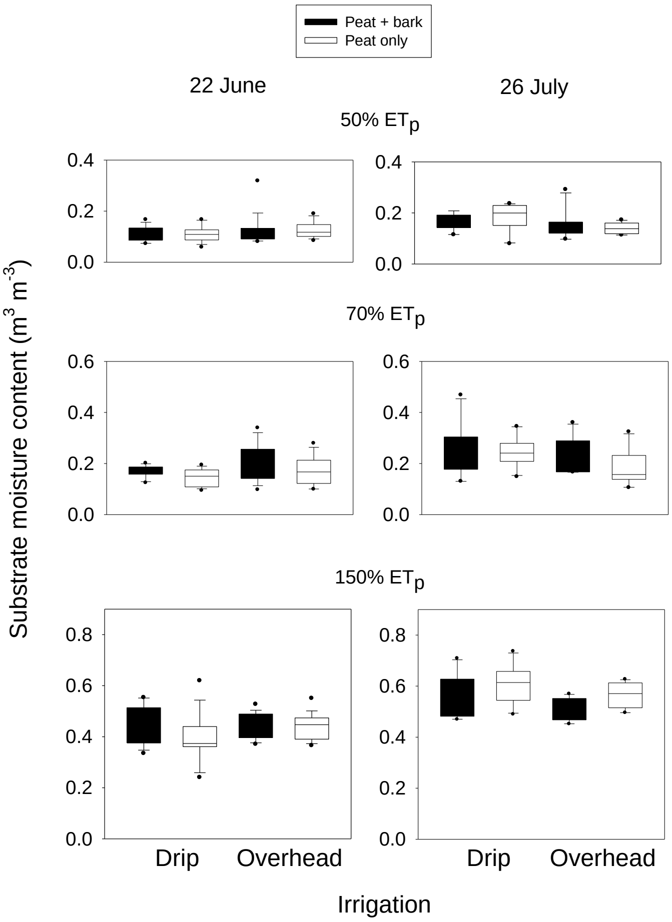


**Figure 2.16.** Box plots showing variation in substrate moisture content in pots of *Forsythia* under drip and overhead irrigation on two example dates: 22 June (left, before pruning) and 26 July (right, after pruning).

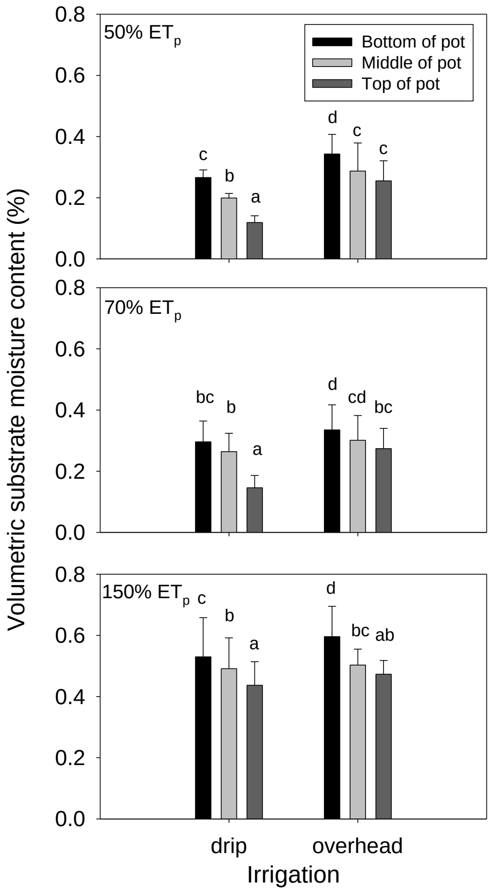


**Figure 2.17.** Substrate moisture in different layers, under drip and overhead irrigation and different % ET$_p$. Different letters indicate significant differences between treatments, $P < 0.05$.

**Table 2.2.** Coefficients of variation (%) of substrate moisture in different layers of substrate under two methods of applying irrigation and three different % ET$_{p.}$ Coefficients were calculated from four measurements per layer per pot

| **Irrigation** | **Layer of substrate** | | |
|---|---|---|---|
| | **Bottom** | **Middle** | **Top** |
| 50% drip | 16.9 | 33.3 | 73.7 |
| 70% drip | 9.3 | 16.7 | 56.9 |
| 150% drip | 11.0 | 10.5 | 14.2 |
| 50% overhead | 6.7 | 9.9 | 13.4 |
| 70% overhead | 5.2 | 10.2 | 13.0 |
| 150% overhead | 5.3 | 6.5 | 8.9 |

**Figure 2.18.** Examples of root distribution under drip (a) and overhead (b) irrigation

*Establishing protocols for use of soil moisture sensors*

Variability in soil moisture within and between pots could limit the potential of using a soil moisture sensor for scheduling RDI. When scheduling with a GP1 and scheduling with an Evaposensor was compared, differences in plant growth between treatments were less clear for the GP1-scheduled plants than for the Evaposensor-scheduled plants (Fig. 2.19a). Ultimately, however, both scheduling systems succeeded in controlling growth when used to schedule RDI (Fig. 2.19b). Moreover, with both systems, final plant height was reduced in the more severe RDI treatment (even though it was only imposed after pruning) than in the less severe RDI treatment. Neither shoot nor root dry mass was reduced in the 70% $ET_p$ treatment compared to FI when the GP1 was used to schedule irrigation (Fig. 2.19c, d). On the other hand, when the Evaposensor was used to schedule irrigation, there was no significant reduction in either shoot or root dry mass in the 50% $ET_p$ compared to the 70% $ET_p$ treatment. Precise scheduling of RDI is difficult with the Evaposensor because gravimetric calibration is not possible for RDI plants which have partially closed stomata. Imposing a precise % $ET_p$ is also complicated when scheduling is based on soil moisture. Imposition of a relatively severe (50% $ET_p$) treatment is therefore more certain to achieve results in growth control, and the results of three years of RDI experiments suggest that such a treatment does not impose risks to crop quality.

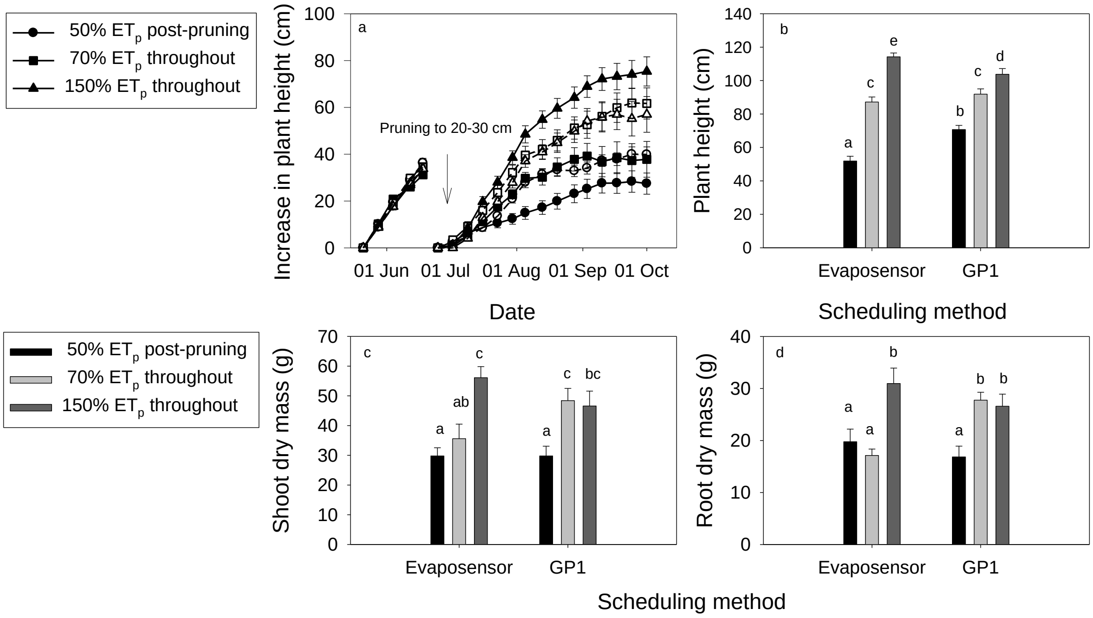


**Figure 2.19.** Impact of RDI applied only after pruning (50% $ET_p$ post-pruning) or throughout the season (70% $ET_p$) compared to FI (150% $ET_p$) on the growth (a) and final heights (b) of *F.* × *intermedia* 'Weekend', where irrigation was scheduled with an Evaposensor (closed symbols) or a GP1 (open symbols), and on shoot (c) and root (d) dry mass. Symbols/bars represent means ± s.e., *n* = 32

### Nursery application of soil moisture sensors for scheduling irrigation

The GP1 has a capacity to monitor soil moisture from two probes. On nurseries, the controlling moisture probe was located in a single representative pot within the crop, and a second probe was used simply to monitor a second pot nearby. Experience in this project has established that the sensor pins are best positioned within the central zone (horizontally and vertically) within the growing medium in the container. Initial settings for moisture levels at which irrigation was switched on were based on the measurement of a container judged to be at about the state when irrigation would be required. The 'off point' was usually set at 5% – 10% above this. The optional pulse irrigation control possible with the GP1 was used for the Hillier pinjet bay (2 mins On/2 mins Off), and at Johnson's (3 mins On/7 mins Off), but not for the trials at

John Woods Nursery. Irrigation settings were adjusted if necessary based on crop inspection together with the GP1 logged moisture graphs following one or two irrigation cycles from setting up. Usually little adjustment was required from then on. Choice of a representative pot in which to place the control probe was not critical where reasonable uniformity existed for both water uptake and water use across plants under that irrigation zone. Where different subjects were being grown in the same zone, it has been found best to adjust irrigation for the plants with greatest needs (but making sure these are maintained slightly dry rather than too wet). Other subjects would tend to 'run wetter', but provided the growing medium was sufficiently well drained, they would not be adversely affected.

GP1 scheduling worked very successfully at Hillier nurseries on the *Musa* trials with pinjet and gantry irrigation. The set points for the gantry program were 39% On/44% Off, and for the pinjet bay were 35% On/40% Off. The pinjet bay was pulsed for 2 mins On/2 mins Off, with irrigation available 24 hours/day. Even though both schedules were set to the same moisture band for lower and upper levels of irrigation, the pinjet bay received larger amounts less frequently than the gantry bay. Mean irrigation over an early July to mid September period was similar for the two treatments even though the frequency and doses varied. This averaged 1.5 mm $day^{-1}$ for the pinjet bay and 1.7 mm $day^{-1}$ for the gantry bay (Fig. 2.20). Closer examination of the wetting and drying patterns and relay activity from the GP1 data downloads reveals that wetting up of the pot continues for some time after the irrigation sprinklers or gantry stop (Fig. 2.21). Some of this was due to a time delay in water applied to the surface reaching the growing medium around the probes, and some from continued absorption and redistribution through the base of the pot. For both pinjet and gantry bays, the 'monitor' pots at the edge and bottom of the sloped bed by the centre path, tended to wet up more. These pots ran wetter and mainly parallel to the control pots in the middle of the bed. Typically, the pinjet bay would receive four pulses at each irrigation event, although this could vary from two to six pulses. There was no direct record of the number of irrigation passes made by the gantry, but from examination of the irrigation quantities, this was typically two return runs (at Speed 2).

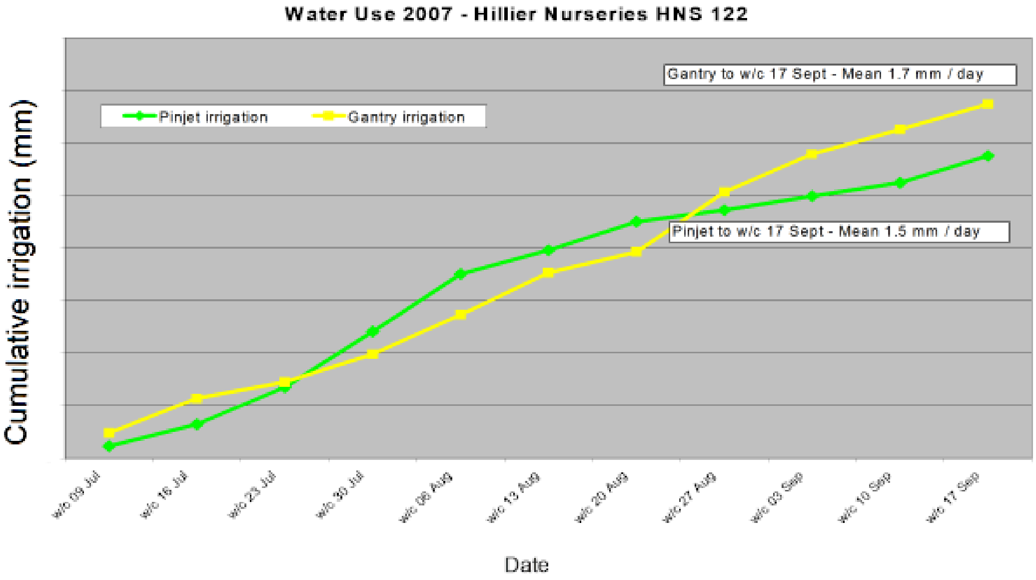


**Figure 2.20**. Cumulative irrigation for GP1-controlled pinjet and gantry irrigation of *Musa* at Hillier nurseries.

The experiment with *Ligustrum* at Wyevale in 2008 showed that irrigation control from monitoring a single representative pot can work well on large scale commercial production beds with overhead systems: substantial water saving were made using the GP1 in comparison with a bed on which irrigation was scheduled as the grower determined necessary (Fig. 2.22a). At the same site in 2009, with *Prunus*, the GP1 pot moisture set point for irrigation control was set at 35% On/37% Off from 15 May to 31 July 2009, and then reduced to 32% On/34% Off until the end of the trial. As found in other trials, setting a narrow control band of 1 – 2% moisture level gave good results, especially as probes needed to be partially buried to detect the optimal central zone of the container, and the pots continued to absorb and redistribute water for a while after the ‘Off’ point at the probe was reached (Fig 2.23). In both 2008 and 2009, the GP1/SM200 required little or no intervention to adjust set points, nor for top-up hand watering. These results confirmed that the system is capable of giving excellent automatic control of irrigation on large commercial area production beds using a probe in a single representative container, and that significant labour savings are possible. In both years the GP1 control treatment used much less water than the manually adjusted Timer treatment (45% and 64% as much respectively); Fig. 2.22). Apart from savings in direct water costs (which may only be moderate), energy costs for pumping, and treatment of recaptured water can be significant. Overall water consumption was greater in 2009 (2.1 mm day$^{-1}$ *c.f.* 1.1 mm day$^{-1}$ in 2008 for the GP1 treatment), and rainfall slightly less on average (2.3 mm day$^{-1}$ 2009 *c.f.* 2.7 mm day$^{-1}$ in 2008), compared to 2008 (Fig. 2.22). In both years, plant growth and quality was equally good within the two treatments.

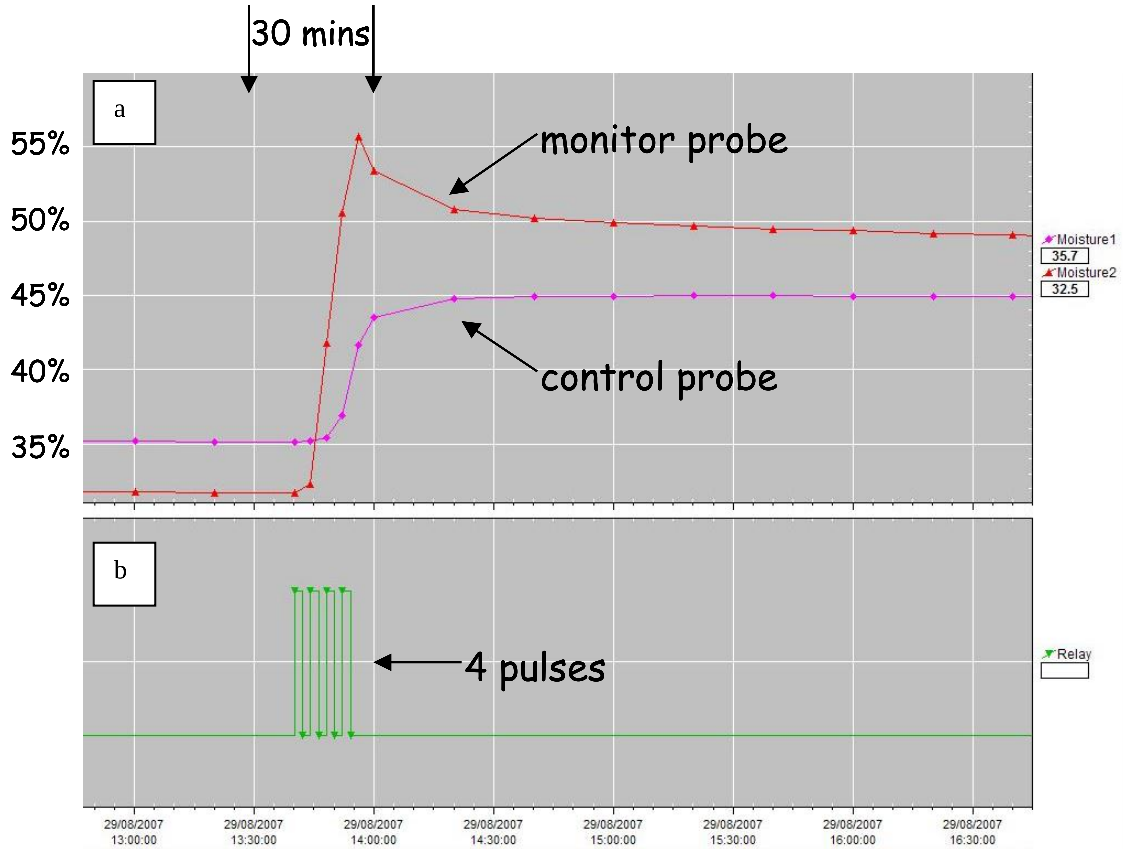
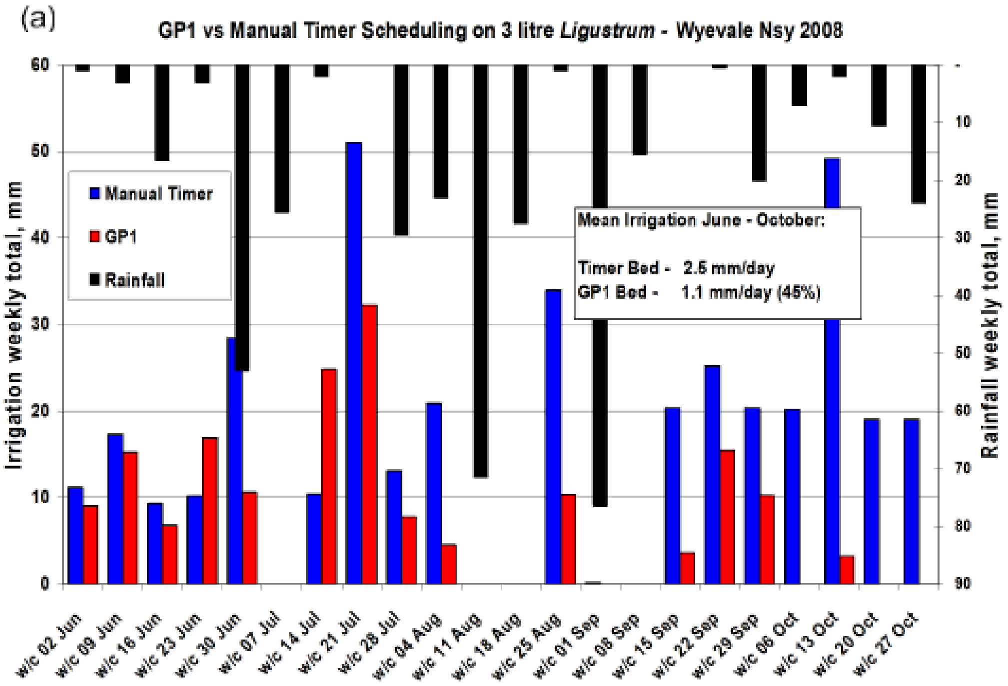


**Figure 2.21.** Detail of one irrigation event for the pinjet bay at Hillier nurseries, with the program set at 35% On/40% Off. Four × 2 min pulses were applied (b); the scheduling pot (centre of bed) and monitoring pot (edge of bed at bottom of slope) continue to wet up after the irrigation stops (a)

*GP1-scheduled imposition of RDI on a nursery*

Where a gantry was used to apply deficit and full irrigation to *Solanum* crops, 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 (Fig. 2.24a, b), but it was rather excessive in the less vigorous variety ‘Glasnevin’. At this nursery, 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 (Fig. 2.24c). These results reflect those found when scheduling irrigation of *Lonicera* and *Cornus* together on the one bed – with one solenoid and with the same rate of irrigation application, it is difficult to precisely schedule irrigation to different crops. However, the results with ‘Album’ (Fig. 2.24d) show that deficit irrigation can be applied successfully on the nursery, using gantry irrigation, to control plant growth. Use of the gantry and SM200 to apply deficit irrigation was also effective with *Tradescentia* (Fig. 2.25).



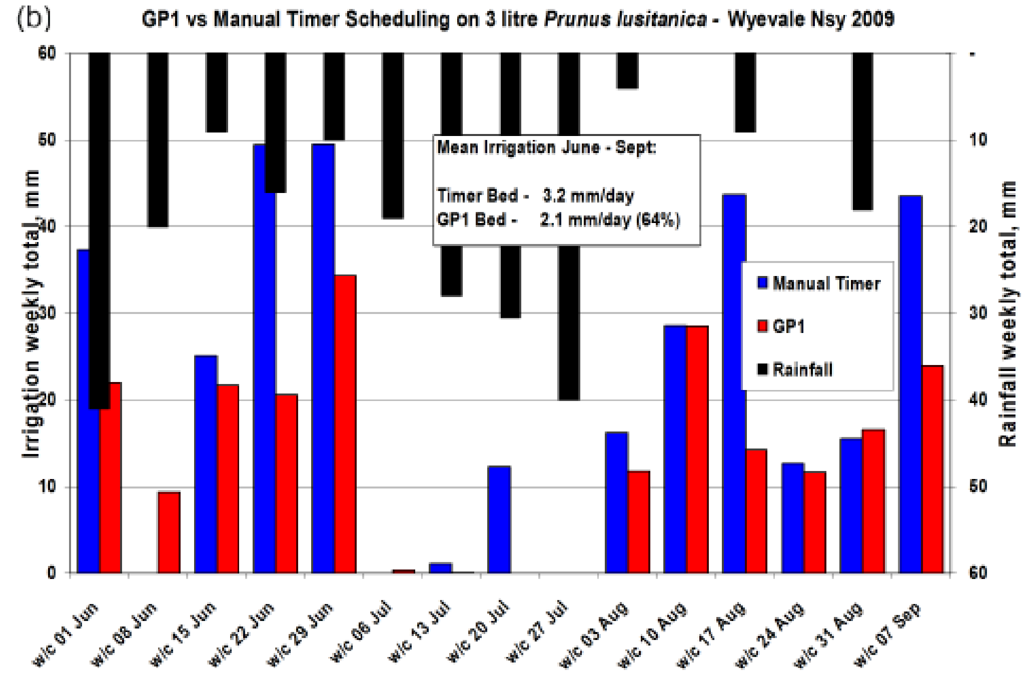


**Figure 2.22.** Weekly Evaposensor, rainfall and irrigation on GP1 *vs* timer-scheduled crops of *Ligustrum* in 2008 (a) and *Prunus* in 2009 (b) at Wyevale Nurseries.

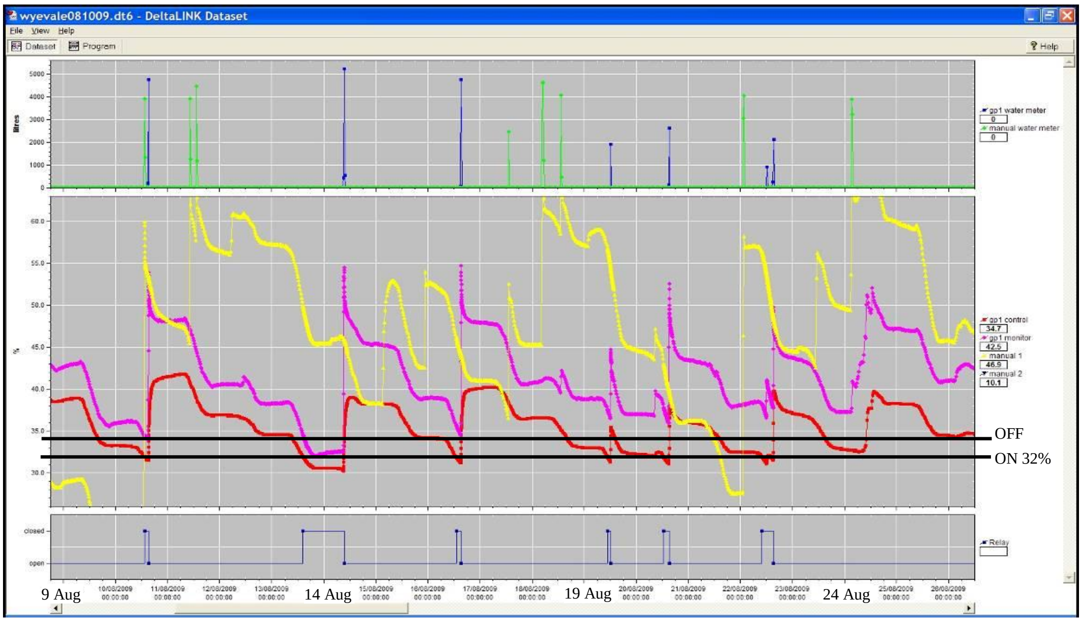


**Figure 2.23.** GP1 trace from the *Prunus* experiment at Wyevale in August 2009. Black lines show On/Off moisture set points for the GP1-controlled bed (red trace). The pink trace represents a separate monitored pot on GP1 bed, and yellow trace is a monitored pot on the timer-controlled bed. The GP1 relay activity (call for water) is shown on the bottom graph, and water applications (meter readings) on the top graph; for the GP1 bed (blue) and timer-scheduled bed (green).

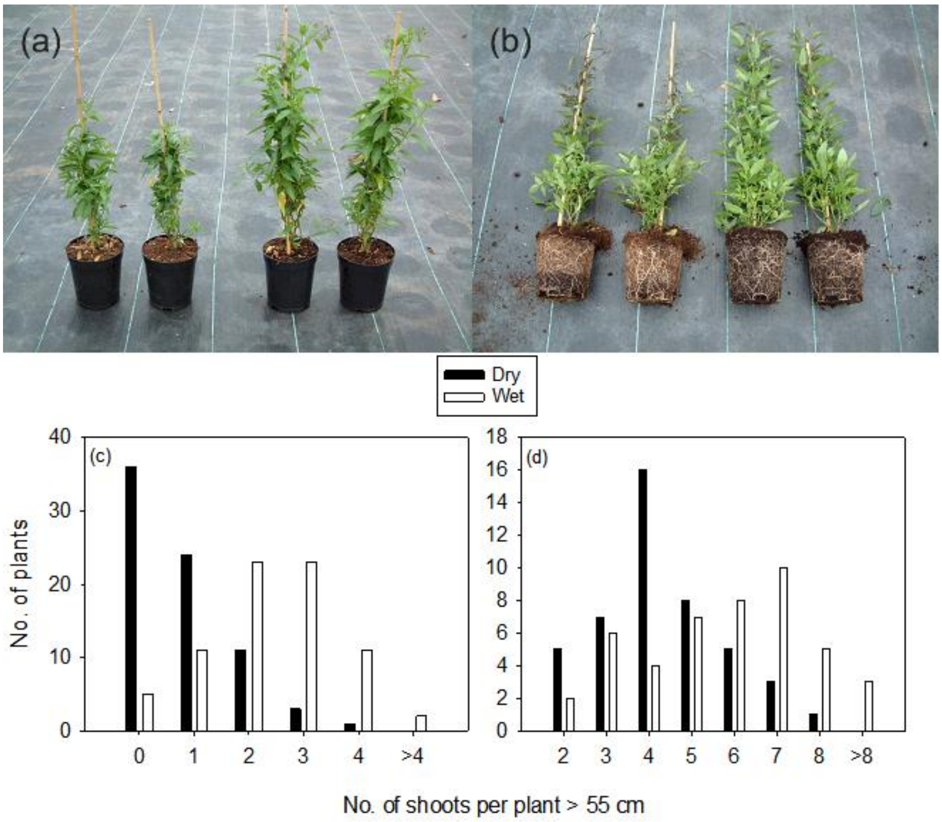


**Figure 2.24.** *Solanum* ‘Album’ (a) and ‘Glasnevin’ (b) plants that received deficit (left) and control (right) irrigation, and numbers of shoots per plant over ¾ cane height.

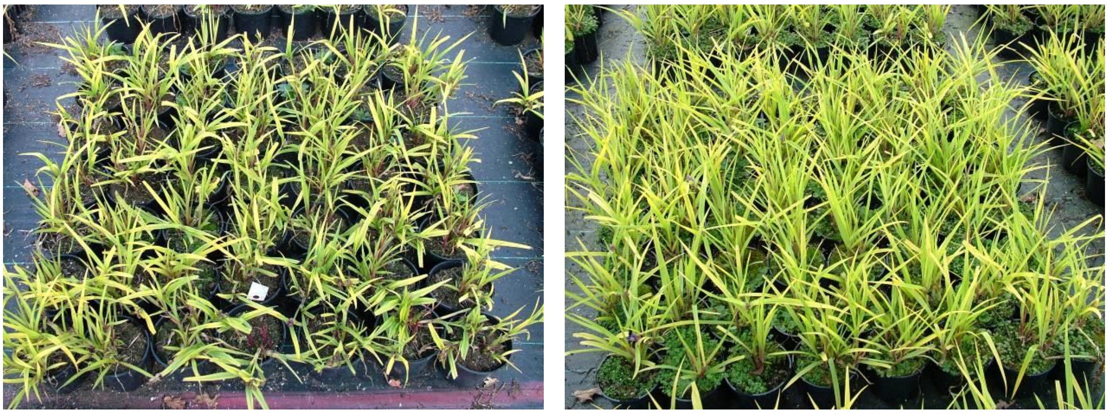


**Figure 2.25.** *Tradescantia* in 'Dry' treatment (left) and 'Wet' treatment (right) in March 2009, following scheduling using an SM200 in the Wet treatment, and applying half as much water to the Dry treatment.

## Conclusions

GP1-scheduled irrigation works best when the GP1 is linked directly to the solenoid, without the use of any irrigation timer. When a control panel is used, if the window during which irrigation is on is too short, this will mean irrigation will not be applied on some occasions when the substrate moisture content is in fact below the 'on' threshold.

The optimum position for SM200 probes is to ensure that the pins are in the central zone of the container. For a standard 3 L pot, an SM200 needs inserting to half way up the body of the probe.

As with any other scheduling method, grouping crops with similar water requirements on the same beds helps to ensure that those for which the irrigation is not being directly scheduled with the SM200s (i.e. the SM200s are in another crop) will not be severely under/over-watered at any point.

Soil moisture probes are sensitive to being disturbed in containers.

When using soil moisture probes to impose RDI, some careful monitoring and adjustment of set points is required.

## Objective 3

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

### Introduction

Under this objective we developed several lines of work. In the first year we further developed the basic leaf energy-balance model, to provide a tool to calculate expected canopy temperatures under any particular environmental conditions, and to derive the expected sensitivity to changes in stomatal conductance. In the second year we followed with a study of the theoretical sensitivity of thermal sensing under a range of environmental conditions, in order to determine the optimal conditions for use of thermal imaging in HNS irrigation scheduling; this included considering all possible sources of error and variability. We also investigated (years 1 and 2) the potential for using hand-held thermal imagers to monitor irrigation in a commercial HNS environment.

### Materials and Methods

*Estimation of boundary layer resistance*

We developed a simple heated leaf system to provide parameters for input into the model for estimation of leaf temperature, of which one of the most important is the boundary layer resistance. The energy input into the heated leaf is calculated from the voltage across the heating element and the resistance of the heating element. The temperature rise depends on the heat input and on heat loss through the boundary layer, with greater temperature rises reflecting larger boundary layer resistances.

Leaves were constructed in pairs, one heated and one unheated, with a thermocouple to measure the temperature difference between the leaves (figure 3.1). The leaves were made of silicone/polyamide heating pads, and covered in reflective material to minimise confounding effects of solar radiation.

Two pairs of leaves were attached to aluminium rods at different heights, to enable measurements to be taken above and within the plant canopy (figure 3.1). In total, six sets of such leaves, three small and three large (potentially representing different species) were used. The artificial leaves were set up outdoors, at the Johnson's of Wixley head office nursery site near York, from July to September 2006.

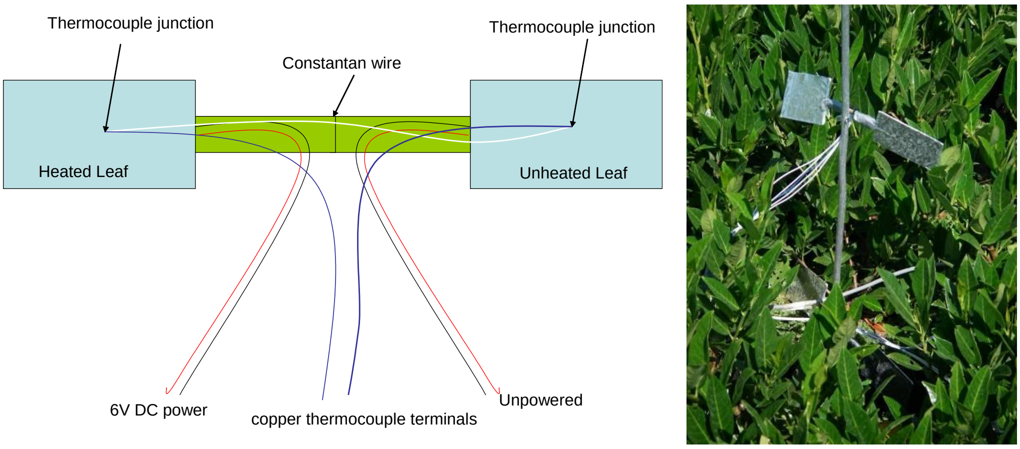


**Figure 3.1.** Heated leaf-pair sensor (left), and its installation in a canopy (right).

*Measurement and estimation of canopy temperature*

At the same time as the above experiment, environmental conditions (air temperature, relative humidity, incident solar radiation and wind speed) above and within the canopy were recorded at regular intervals. Individual spot canopy temperatures (cT) were continually recorded using Calex infra-red thermometers (IRT) positioned in the canopy. These readings varied considerably as the solar exposure/shading and cloud cover changed over the period of the experiment, but by averaging the results from four separate IRT sensors it was possible to derive reasonably robust estimates of canopy temperature at any time.

*Use of hand-held thermal imagers for rapid monitoring of plant stress*

Tests were performed at Johnson's of Wixley near York during June 2007. Plants of twelve common HNS species were taken from open-air beds and placed in an unheated greenhouse and left un-watered for up to five days, while the plants left in the beds were irrigated as normal. Visible and thermal images were taken of the water-restricted and control plants, and volumetric moisture content of the pots was also measured.

## Results and Discussion

*Energy balance model for leaf temperature*

The idea behind the use of thermography for scheduling irrigation involves the detection of plants that are hotter than they would be expected to be if they were transpiring normally in the given environmental conditions. However there are several factors that affect the temperature of a plant other than evapotranspiration, two of the main ones being the incident solar radiation and the wind speed. We undertook to devise a model that could be used to predict the expected temperature for a normally- transpiring well-watered plant, from a relatively few environmental measurements. This model could then be used to detect ‘hot’ plants by comparing the measured plant temperature with the expected plant temperature.

The approach was to reformulate the basic energy balance model in such a way as to minimise the requirements for environmental information, for example by using wet and/or dry reference surfaces (see Leinonen *et al.* 2006). The following equation (equation 3.1) gives the expected difference between a leaf temperature $T_l$ and the surrounding air temperature $T_a$ in terms of the total radiation absorbed by the leaf ($Rn$, which is dependent on the leaf position and orientation to the sun and its reflectance of solar radiation), the air humidity $\delta e$, stomatal resistance to water loss $r_{sW}$ and boundary layer resistance to heat loss $r_{aH}$ and water loss $r_{aW}$ and various physical constants ($\gamma$, $s$, and $\rho\, c_a$).

$$T_l - T_a = \frac{[r_{aH}(r_{aW} + r_{sW})\gamma R_n] - \rho c_a r_{aH} \delta e}{\rho c_a [\gamma(r_{aW} + r_{zW}) + s r_{aH}]} \qquad (3.1)$$

Given good estimates for the boundary layer resistances, equation 3.1 then permits us either to calculate the expected temperature difference between a leaf and the air for a well watered plant, or to calculate the stomatal resistance given a measured temperature difference.  So the next step was to develop ways of measuring boundary layer resistance to incorporate into the model.

*Leaf boundary layer estimation*

To investigate the effect of wind speed on the boundary layer resistance, data were collected for a variety of crops in both exposed and sheltered locations. Figure 3.2

shows the relationship between the temperature difference between the two sensors (dT; a measure of boundary layer resistance), and wind speed (u), for two pairs of leaves placed above and within the canopy. (The relationship has been linearised using an exponential transformation.) As expected the correlation is lower for a sensor placed within the canopy than for one placed at the top of the canopy, and the values of dT for any given external wind speed are larger, reflecting the fact that wind is slowed within the canopy leading to a less effective cooling effect (i.e. higher boundary layer resistance).

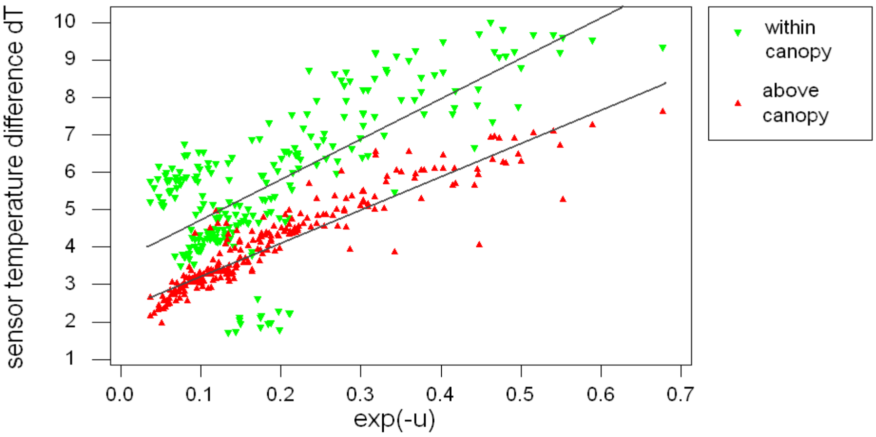


**Figure 3.2.** Regressions for within- and above-canopy temperature differences against external wind speed (measured at 2 m height).

*Estimation of canopy temperature*

The temperature of the leaf canopy depends not only on the transpiration rate of the leaves but on many other environmental factors. The relationship between these environmental factors and canopy temperature (cT) was investigated using a multiple regression approach, with extra factors added to the model in a stepwise manner.

In practice, the single most important factor affecting canopy temperature was found to be incident radiation, which explained 39% of the variation in recorded canopy temperature. The best model, which included leaf-pair temperature difference, air temperature and air humidity as well as radiation, explained 84% of the variation (table 3.1). The use of heated leaf sensor temperature as a measure of boundary layer resistance gave consistently better fits than raw wind speed figures.

**Table 3.1**. Comparison of models of canopy temperature (cT) as functions of radiation (r), wind speed (u), leaf-pair temperature difference (dT), ambient air temperature above the canopy (aT) and air humidity above the canopy (aH). The value of $R^2$(adj) is a measure of how much of the variation in the data is explained by the given model.

| **Fitted model** | **S** | **$R^2$** | **$R^2$(adj)** |
|---|---|---|---|
| $\mathrm{cT} = 12.2 + 0.674\mathrm{r}$ | 1.994 | 39.3% | 39.0% |
| $\mathrm{cT} = 14.4 + 6.73\mathrm{e}^{-\mathrm{u}}$ | 2.411 | 11.3% | 10.9% |
| $\mathrm{cT} = 12.4 + 0.811\mathrm{dT}$ | 2.360 | 15.0% | 14.7% |
| $\mathrm{cT} = 9.77 + 0.781\mathrm{r} + 9.72\mathrm{e}^{-\mathrm{u}}$ | 1.585 | 61.8% | 61.5% |
| $\mathrm{cT} = 6.88 + 0.797\mathrm{r} + 1.14\mathrm{dT}$ | 1.460 | 67.6% | 67.3% |
| $\mathrm{cT} = -5.45 + 0.271\mathrm{r} + 0.755\mathrm{e}^{-\mathrm{u}} + 0.324\mathrm{aT}$ | 1.136 | 80.5% | 80.2% |
| $\mathrm{cT} = 4.30 + 0.312\mathrm{r} + 0.597\mathrm{dT} + 0.304\mathrm{aT}$ | 1.084 | 82.2% | 82.0% |
| $\mathrm{cT} = -7.34 + 0.285\mathrm{r} + 1.14\mathrm{e}^{-\mathrm{u}} + 0.254\mathrm{aT} - 0.00423\mathrm{aH}$ | 1.088 | 82.2% | 81.9% |
| $\mathrm{cT} = 7.76 + 0.325\mathrm{r} + 0.853\mathrm{dT} + 0.228\mathrm{aT} - 0.00460\mathrm{aH}$ | 0.917 | 84.0% | 84.0% |

*Theoretical sensitivity of thermal sensing*

In this exercise we concentrated on the key linkage between stomatal conductance and the thermal measurements obtained with a thermal camera or other infrared sensor. Figures 3.3 and 3.4 show the calculated sensitivity of thermal sensing to variation in wind speed and humidity for the detection of a 20% reduction in stomatal conductance from a typical well-watered conductance of 200 mmol $m^{-2}$ $s^{-1}$.

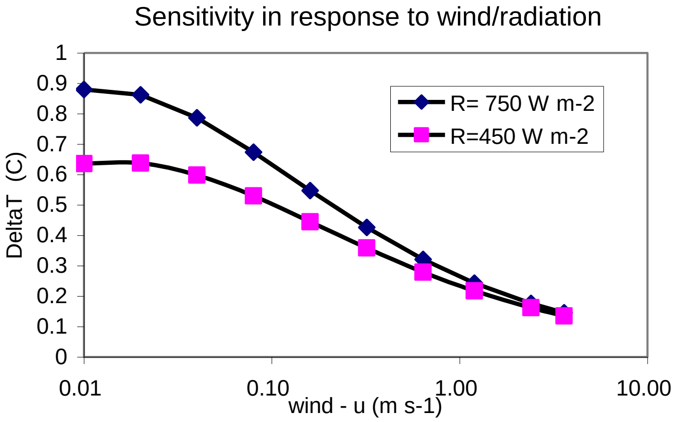


**Figure 3.3**. The leaf temperature change expected for a 20% decrease in stomatal conductance from a typical well-watered value of 200 mmol $m^{-2}$ $s^{-1}$ (= 5 mm $s^{-1}$): response to varying wind-speed. Calculations shown for broad leaves (10 cm across) under bright sun conditions or dull conditions and at a temperature of 20 °C.

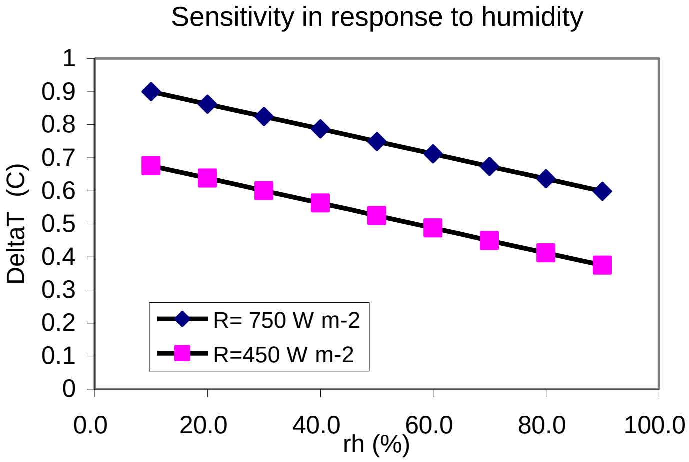


**Figure 3.4.** The leaf temperature change expected for a 20% decrease in stomatal conductance from a typical well-watered value of 200 mmol $m^{-2}$ $s^{-1}$ (= 5 mm $s^{-1}$): response to varying air humidity. Other conditions as for Figure 3.4.

It is apparent from these figures that thermal approaches are most sensitive at low wind speeds, low humidities and with high irradiance. This favours the potential application of the technique in the protected environments that are common within the HNS industry, though the advantage of the low wind speed can be partly offset by the higher humidities often encountered. Still, figure 3.5 shows that a 20% reduction in conductance is almost equally detectable for conductances above about 100 mmol $m^{-2}$ $s^{-1}$ at two different humidities.

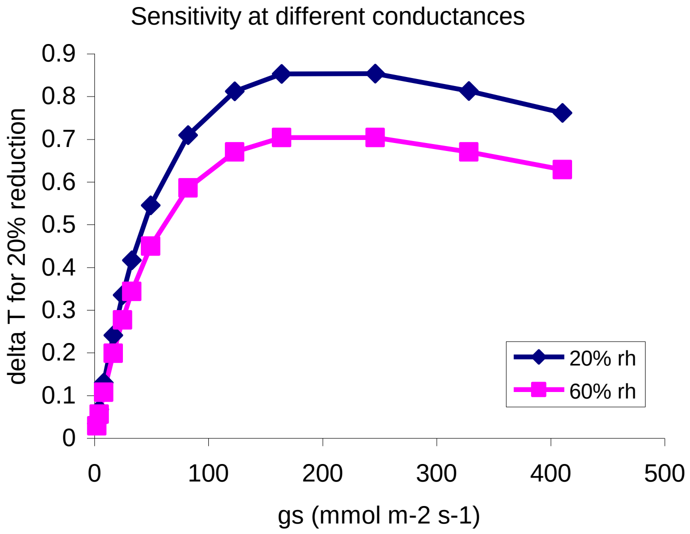


**Figure 3.5.** This illustrates, for two different humidities, how the sensitivity of temperature to a 20% reduction in conductance depends on the initial value (given on the x-axis).

*Potential sources of variability and error in the use of thermography*

Canopy variability

Leaves in any canopy will be receiving different amounts of incoming radiation and therefore will heat up differently. This problem is less severe under low irradiance conditions than in full sunlight, but there is a trade-off between the advantage of doing measurements in lower light and the advantage of getting greater sensitivity at higher light. Also, because stomata show a diurnal trend in opening, with partial closure in the afternoon and complete closure at night, thermal imaging cannot be used effectively for scheduling irrigation at night, and application in the late afternoon is likely to be of lowered sensitivity.

Image resolution

Thermal cameras produce a grid of data points or pixels that cover the field of view. In general, the more expensive the instrument, the more individual sensors it will have, so the proportion of the total image recorded by each sensor will be smaller. In a camera such as the IRISYS 1002, where there are only 16 x 16 sensors, the individual sensors cover relatively large areas, which means they may be recording temperatures not only from leaves but also background compost or pots. This can lead to errors in leaf temperature measurements. Figure 3.6 shows the temperatures obtained with a thermal imager plotted against spot measurements of leaf temperature. The background was warmer than the plant, leading to the higher temperatures recorded by the camera, particularly with sparse canopies and small leaved species.

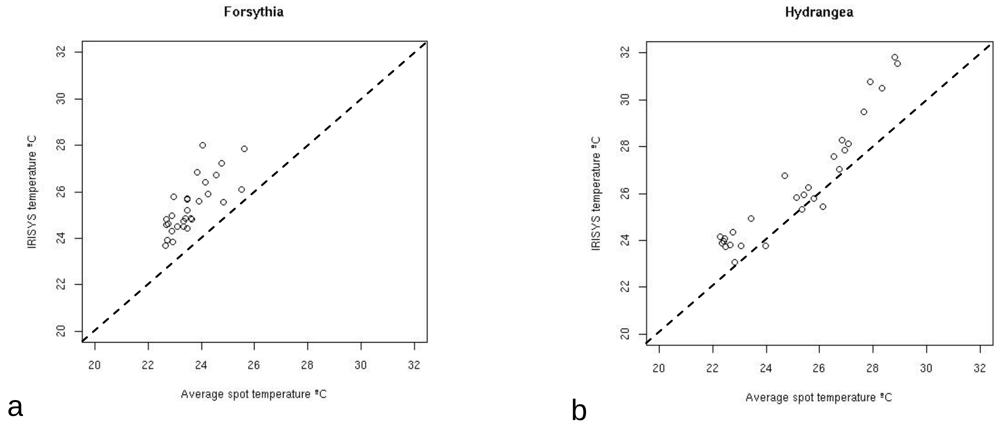


**Figure 3.6** IRISYS 1002 temperature measurements for (a) *Forsythia* and (b) *Hydrangea* against average spot leaf temperature measurements. The dashed line indicates the 1:1 relationship.

Sensor thermal resolution

(i.e. the ability to discriminate different temperatures): Even under quite unfavourable conditions, the effect on leaf temperature of only a 20% reduction in conductance should be readily detectable with a thermometer with a resolution of 0.1 °C; and a sensor such as the IRISYS multipoint radiometer, which can detect differences of 0.3 °C, should be able to detect reductions in conductance of 20% from typical well-watered values under most conditions.

Sensor thermal accuracy

(i.e. the precision with which the temperatures are measured): Most thermal sensors have a substantially lower *accuracy* than they have *resolution*, with accuracies often only being of the order of 2 °C. Therefore, a method for incorporation of the temperature data that only requires *relative* values is preferable. This can be achieved by ensuring that all the relevant calculations are based on temperature differences from reference surfaces, in which case the absolute accuracy of the sensor becomes of much lesser importance. This is the recommended strategy for any development of this approach, so the next step was to investigate the use of reference surfaces. Further details of these analyses may be found in Leinonen *et al.* 2006.

*Reference surfaces*

An advantage of the use of reference surfaces is that this approach accounts for most of the effects of fluctuating environmental conditions (e.g. varying wind speed or radiation). Reference surface temperatures can be used in two ways: to directly calculate the stomatal conductance, or to calculate an index that is indicative of the degree of stomatal closure. Calculation of stomatal conductance requires some supplementary environmental information; therefore, we used a simple index based on Idso's Crop Water Stress Index, which calculates a temperature index ($T_i$) as:

$$T_i = \frac{(T_l - T_w)}{(T_d - T_w)} \qquad (3.2)$$

where $T_l$ is the measured plant temperature, $T_d$ is the dry (upper) reference temperature and $T_w$ is the wet (lower) reference temperature.

Two ways of generating reference temperatures were investigated: the first using 9 cm discs of wetted and dry filter paper, and the second using the temperatures of the dry and wet arms of a Skye EvapoSensor. Figure 3.7 shows that the wet/dry filter paper references gave a better resolution of temperature stress index (calculated from equation 3.2) than the EvapoSensor method when applied to *Hydrangea* plants.

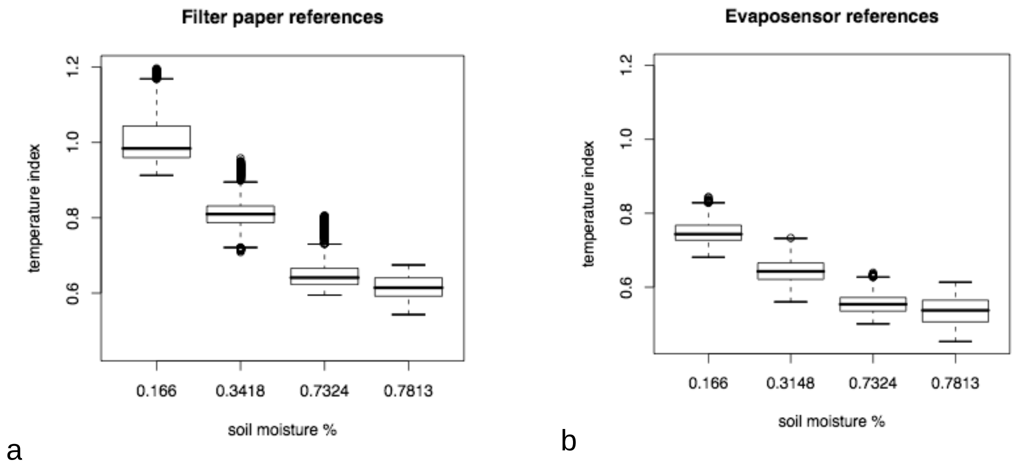


**Figure 3.7.** Box-whisker plots of the temperature index ($T_i$) for *Hydrangea* plants with different substrate moisture contents.

The use of a simplified model to predict expected canopy temperature from a single dry reference was investigated by monitoring plant temperature of two well-watered

*Choisya* plants over a 24 hour period. A linear regression of canopy temperature ($T_l$) against dry reference temperature ($T_d$) was fitted to the data, and this model was then used to predict expected temperatures for pairs of well-watered and droughted *Choisya* plants over a 24 hour period. Figure 3.8a shows a plot of the predicted and recorded leaf temperatures, while Figure 3.8b shows a clear distinction between the two treatments during the daylight period when the stomata should be open. These results confirm that droughted plants are warmer than both well-watered plants and the predicted temperature for unstressed plants.

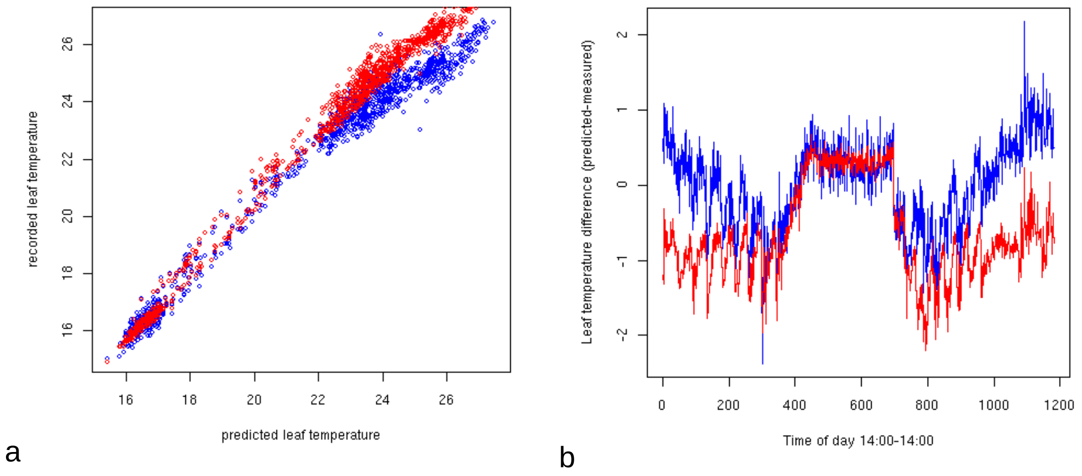


**Figure 3.8.** (a) Recorded leaf temperature against predicted values for a pair of droughted (red, 16% soil moisture) and well-watered (blue, 45% soil moisture) Choisya plants. (b) Difference between predicted and measured temperatures over a 24 hour period.

### *Use of hand-held thermal imagers for rapid monitoring of plant stress*

#### Detecting stressed plants

Analyses of the visible and thermal images of well-watered and droughted *Hydrangea* and *Hebe* plants are shown in figures 3.9 and 3.10 respectively. While in *Hydrangea* the droughted leaves had wilted and differences were clearly visible to the naked eye, this was not the case with *Hebe*. Analyses of the visible images (RGB histograms and hue colour wheel at the right of the pictures) show a clear colour shift between droughted and non-droughted plants for *Hydrangea*, but much smaller for *Hebe*. However, the thermal images (inset top left) clearly show that the droughted plants are warmer than the non-droughted ones in both species; this is confirmed by the graphs of temperature distribution for droughted and non-droughted plants (inset bottom left).

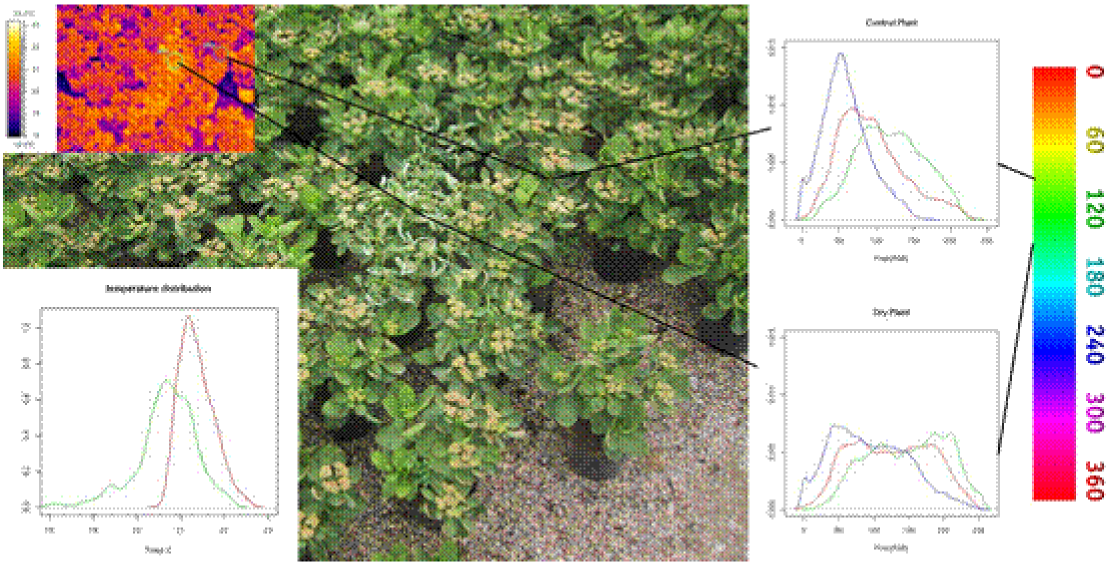


**Figure 3.9.** Analysis of images of *Hydrangea* lacecap white. Inset top left: thermal image. Graph bottom left: temperature distribution of droughted area (red circle) and non-droughted area (green circle). Graph top right: RGB pixel intensity for non-droughted area. Graph bottom right: pixel intensity for droughted area. Extreme right: average hue value for droughted and non-droughted areas shown on hue wheel.

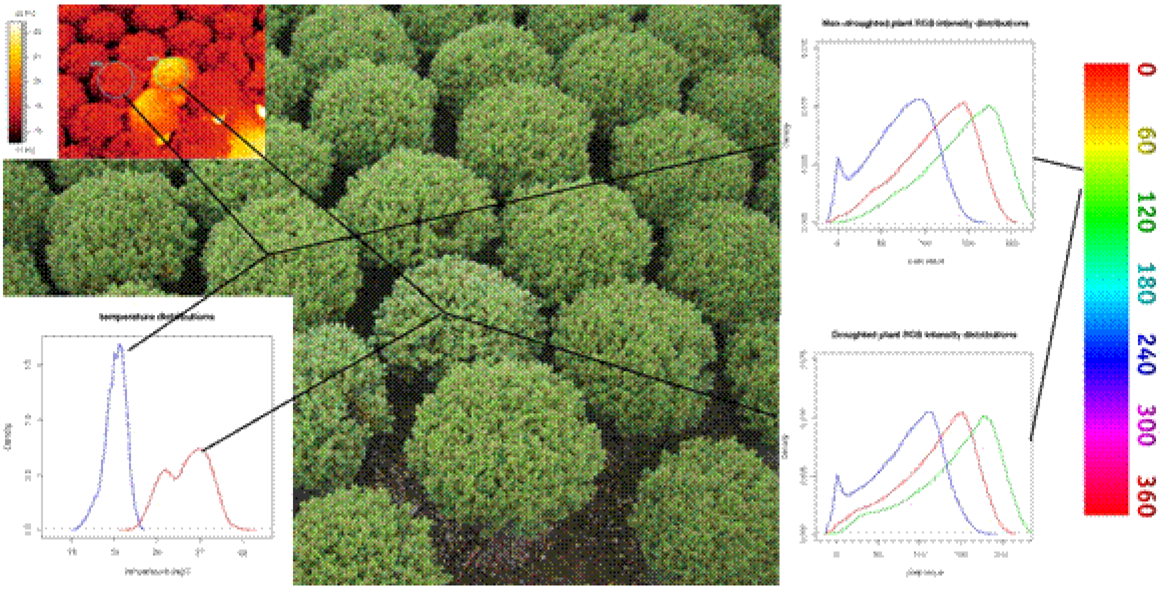


**Figure 3.10**. Analysis of images of *Hebe ping* var. ‘Sutherlandii’. Inset top left: thermal image. Graph bottom left: temperature distribution of droughted area and non-droughted area. Graph top right: RGB pixel intensity for non-droughted area. Graph bottom right: pixel intensity for droughted area. Extreme right: average hue value for droughted and non-droughted areas shown on hue wheel.

## Monitoring irrigation coverage

This was investigated in some more general surveys of the growing beds. One example is shown in figure 3.11. The thermal image (right) detected some hotter plants (yellow region) with an average temperature of 20.2 °C, whilst the average temperature of the green region was 19.5 °C. Closer examination showed that the average soil moisture content of the pots in the yellow region was 28.3%, whereas those in the green region had an average of 44.9% soil moisture. However, there was no distinguishable visible difference between the two types of plants (left image).

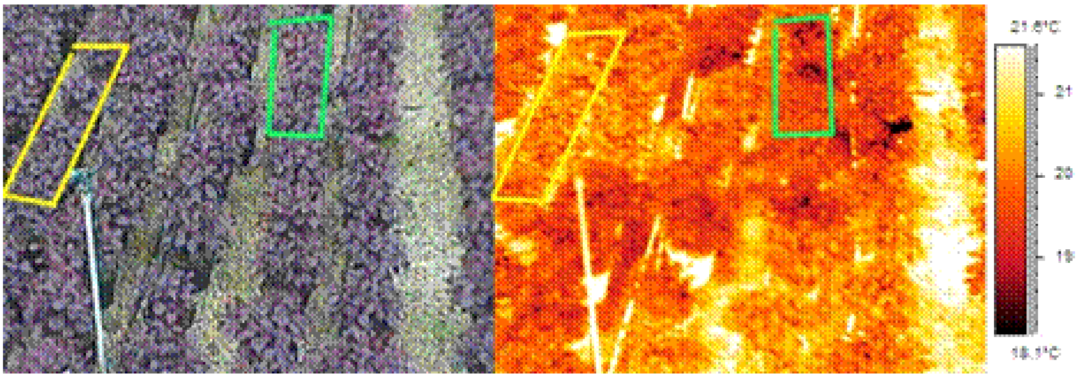


**Figure 3.11.** Variation of temperature and soil moisture content amongst *Cotinus* royal purple.

## Cross-species comparison

When the average leaf temperature is plotted against the average soil moisture content for all the plants in the trial (figure 3.12a), there is substantial variability, because the effect of soil moisture on leaf temperature is overshadowed by other environmental variation, particularly solar radiation. Still, when pairs of droughted and non-droughted plants of the same species are compared (represented in figure 3.12a by matching symbols), it is apparent that all the droughted plants are warmer than their non-droughted counterparts. However, the influence of radiation is important, as non-droughted plants in full sun are warmer than droughted plants in overcast conditions (represented by blue and red points respectively in figure 3.12a).

Figure 3.12b shows the same data but plotted as temperature difference (droughted *minus* non-droughted) against percentage soil moisture reduction (from non-droughted). Now the relationship becomes clearer, with differences in temperature increasing with increasing moisture stress. The fact that temperature differences are less than 1°C when moisture loss is less than about 50% indicates that the non-droughted plants are possibly receiving more water than necessary, and that the standard irrigation practice could be modified to save water.

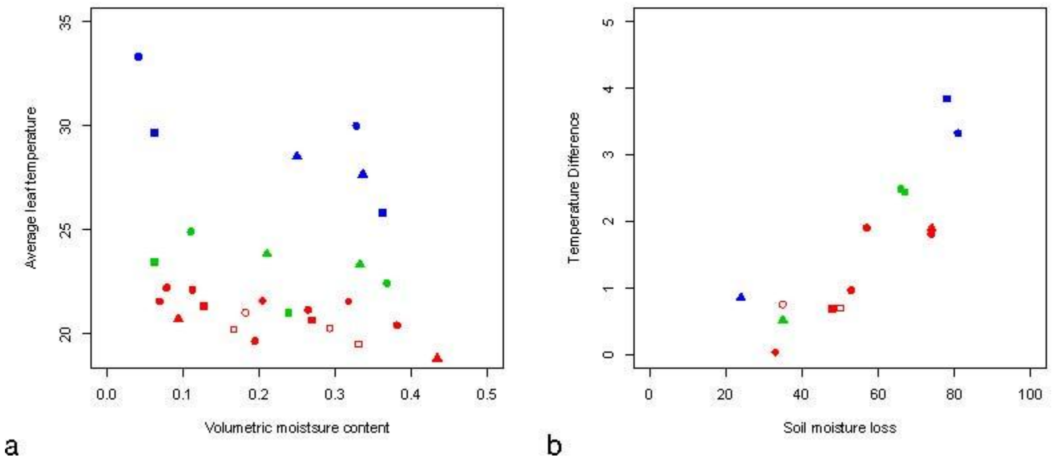


**Figure 3.12.** (a) a plot of leaf temperature (°C) against soil moisture (%); matching symbols and colours represent dry and wet data for the same species. (b) leaf temperature difference (°C) against percentage moisture loss; blue: full sun; green: patchy sun; red: overcast.

Effects of palette and temperature scaling

Many thermal imagers have the ability to adjust the colour palette and temperature range of the live image in the view finder, and also come with software that enables the manipulation of these properties in the saved image files. There is usually an automatic setting for the temperature range, set to be from the minimum to the maximum temperatures in the field of view. While this permits good visible resolution of objects in the view finder, it is not necessarily a good option for spotting dry plants. This is illustrated in figure 3.13 which shows examples of colour palettes and temperature scales on the sensitivity of visualisation of temperature differences. Selecting a narrow temperature range around that of the canopy (in this case around 23.5 °C) improves the visibility of ‘hot spots’; use of the rainbow palette also appears to be beneficial. However, too narrow a temperature range may eliminate some of the detail in areas of extreme temperature.

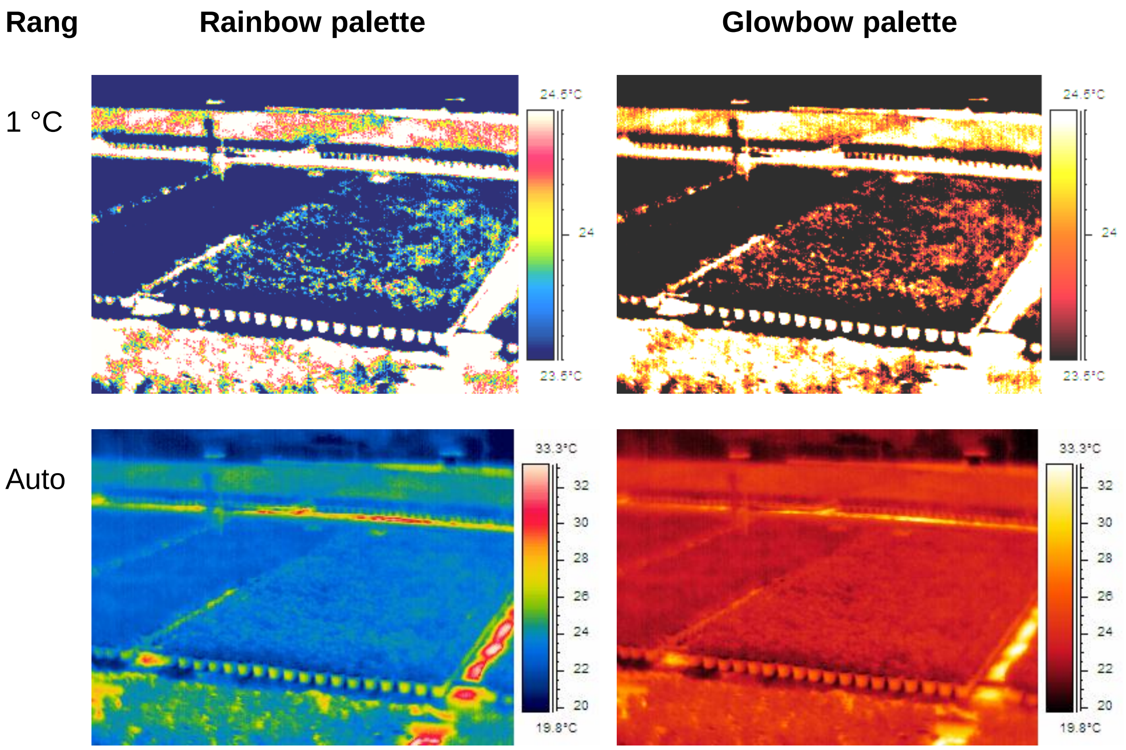


**Figure 3.13.** Visual effects of selecting different temperature ranges for thermal images using the rainbow and glowbow palettes. The Auto-range is the range selected by the camera**.**

## Conclusions

The energy balance model has been re-expressed in a convenient form for estimation of stomatal conductance from leaf temperature data. These results have been published (Leinonen et al 2006).

It is clear that even low precision thermal cameras have adequate sensitivity in relation to the expected variation in leaf temperature. Success in using thermography for monitoring HNS irrigation is likely to be more related to biological and irradiance heterogeneity.

Our studies have confirmed that sensitivity to stress is greatest at low humidity, high irradiance and low wind speeds. Development of practical sampling protocols will need to take these factors into account.

The use of suitable wet and dry reference surfaces enables the environmental conditions to be accounted for in the calculation of the plant stress index and minimises errors due to limited accuracy of thermal cameras.

Monitoring tests demonstrated the power of thermography for monitoring of irrigation in an HNS production environment. Using a handheld thermal imager it was possible to identify not only individual plants in the early stages of water stress, but also uneven irrigation and specific irrigation failures, even when no variation in foliage was apparent to the naked eye.

There is scope for optimising the presentation of images for detection of uneven irrigation by the appropriate choice of colour palette and scale that would maximise the ability to discriminate. The best results are obtained with high resolution cameras.

## 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.*

## Introduction

### *Regulated Deficit irrigation (RDI)*

Regulated Deficit irrigation (RDI) has been shown to be an effective means of saving water without deleterious consequences to the crop for a wide range of species (Fereres & Soriano 2007). HNS 97 showed that with HNS, RDI could be applied to produce more compact and saleable plants. This would be particular useful with species that require frequent pruning, as it could result in substantial savings on labour costs. However, while RDI was shown to be successful in controlled experiments with high precision irrigation, it was unclear as to how effective it would be commercially, with less precise delivery of water. With overhead irrigation, the uniformity of water delivery would normally be poorer than with drip irrigation. Variation across a bed in water capture, on account of different amounts and structure of foliage on different plants, would also be expected to lead to non-uniform water delivery to plants. Finally, variation in uptake from the standing surface across a bed would accentuate non-uniformity of water uptake. Such non-uniformity could make it impossible to accurately schedule irrigation to match a specific percentage of evapotranspiration ($ET_p$), making RDI difficult and risky. In this project, therefore, the possibility of using overhead irrigation to impose RDI was investigated. We also investigated whether the response to RDI is influenced by the growing medium.

## Materials and Methods

### *RDI*

*Impact of irrigation system, substrate, and stage at which deficit irrigation is imposed*

In years 1, 2, and 3, responses of HNS crops to full irrigation and RDI were compared at EMR. In years 1 and 2, a high precision drip irrigation system was compared with an overhead irrigation system. The sprinklers in the overhead system were arranged to maximise the uniformity of irrigation. As a result the coefficient of uniformity of deposition of irrigation was approximately 97%. The deficit treatments applied in year 1 were 50% and 25% $ET_p$, for a crop of *Lonicera periclymenum*

Graham Thomas. *Cornus alba* Elegantissima were irrigated on the same beds, but as scheduling was applied to match the requirements of *Lonicera*, the deficit treatments applied to *Cornus*, which used more water, were more severe. The treatments were applied over seven weeks in the first year experiment.

In the second year experiment, the deficit treatments applied were 70% and 50% $ET_p$, for a crop of *Forsythia* × *intermedia* ‘Lynwood’. The crop was pruned at the end of June, following standard nursery practice, but then not pruned again. Treatments were applied from May until October, and then the plants were kept until the following spring to determine whether the RDI treatments had any impact on flowering. In this experiment, the impact of RDI on plants grown in a 100% peat substrate was compared to that on plants grown in a reduced peat substrate i.e. 60% peat, 40% bark.

Irrigation was scheduled in years 1 and 2 with an Evaposensor, whereas in year 3 scheduling using the Evaposensor was compared to scheduling using a GP1 (see Objective 2). In year 3 a *Forsythia* × *intermedia* ‘Weekend’ crop was used, and all plants were overhead irrigated. In this experiment the two RDI treatments were: 70% $ET_p$ throughout, from May to October, and a treatment whereby the crop was given full irrigation until pruning, and after that we attempted to ‘hold’ it using 50% $ET_p$ RDI. This relatively severe RDI for a shorter period of time was investigated because, if successful, such a strategy may be useful for avoiding damage to the crop as a result of imposing an early RDI treatment.

Physiological responses to RDI were assessed by measuring stomatal conductance (EGM-1, PP Systems, UK), photosynthesis (Ciras-1, PP Systems), and carbon isotope composition (analysis was undertaken by Mylnefield Research Services) of fully-developed, exposed leaves. Carbon isotope composition provides a measure of photosynthetic water use efficiency integrated over time (Farquhar and Richards 1984).

## Results and Discussion

*Impact of irrigation system*

As expected, RDI led to reduced substrate moisture content (e.g. Fig. 4.1a). In terms of how this affected the crop, in year 1 there was only a very slight increase in the height of plants given the more severe RDI treatment over the course of seven weeks (Fig. 4.1b, c). The milder RDI treatment allowed growth, but it was reduced compared to full irrigation. The result was quite compact *Lonicera* in the 50% $ET_p$ treatment, whereas growth in the full irrigation treatment was excessive (Fig. 4.1c). Within any % $ET_p$ treatment, there were no differences in the final plant heights whether drip or overhead irrigation was used, but clear differences between RDI and full irrigation under either system (Fig. 4.2). This means that despite variation in delivery of water under overhead irrigation, RDI can be applied successfully to control plant growth when a relatively uniform overhead irrigation system is used. This is very encouraging because it means that growers can start using RDI without having to change their irrigation system. In the example with *Lonicera*, however, irrigation was being scheduled specifically to match the requirements of that crop. In reality, most nurseries have a range of crops on the one bed, irrigated from the one solenoid. The *Cornus* on the same beds was found to use more water than the *Lonicera*, so for *Cornus* 25%, 50%, and 200% $ET_p$ corresponded to approximately 17%, 34% and 136% $ET_p$ respectively. In addition, *Cornus* under overhead irrigation took up less water than *Lonicera* (Fig. 4.3). This is partly due to water hitting and rolling off *Cornus* leaves rather than going directly into the pots, and partly due to the bamboo canes that supported the *Lonicera* funneling water into the pots. With drip irrigation the *Cornus* given the more severe deficit treatment survived, but not very well (Fig. 4.4a). With overhead irrigation the substrate probably became too dry to take up any water from the Mypex, and there was too little foliage to capture much water, so both RDI treatments were too severe (Fig. 4.4b). This highlights the problem of placing different species on one bed, which is even more problematic where RDI is applied. So if applying RDI with overhead irrigation, care needs to be taken that only crops with very similar water requirements are placed together.

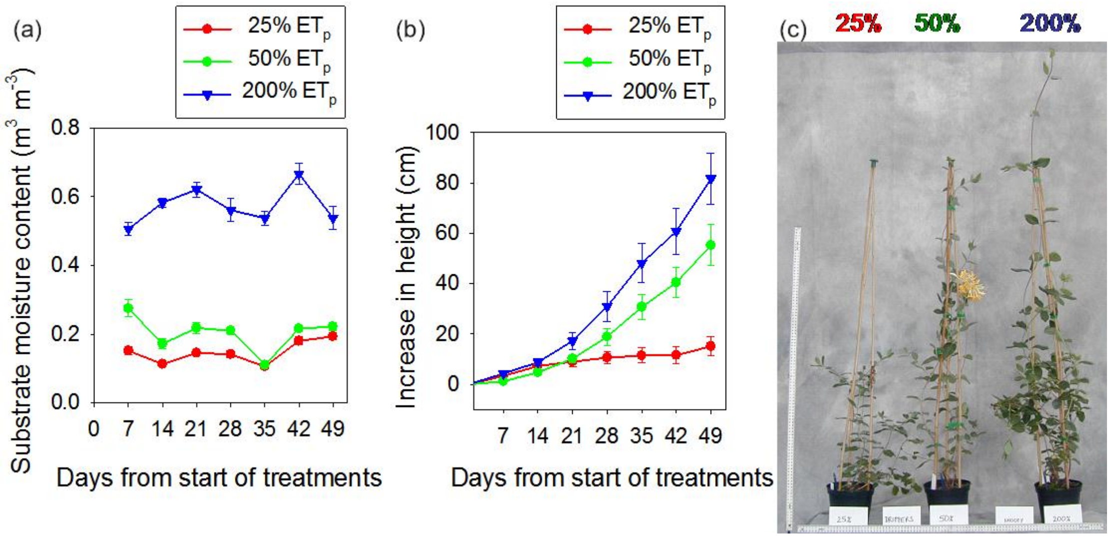


**Figure 4.1.** Substrate moisture content (a), and the increase in plant height (b) over the course of seven weeks of irrigating *Lonicera periclymenum* Graham Thomas with either RDI (25 or 50% $ET_p$) or full irrigation (200% $ET_p$), and some examples of the final plant size under each treatment (c). Symbols represent means ± s.e., *n* = 20. Irrigation was applied via drippers.

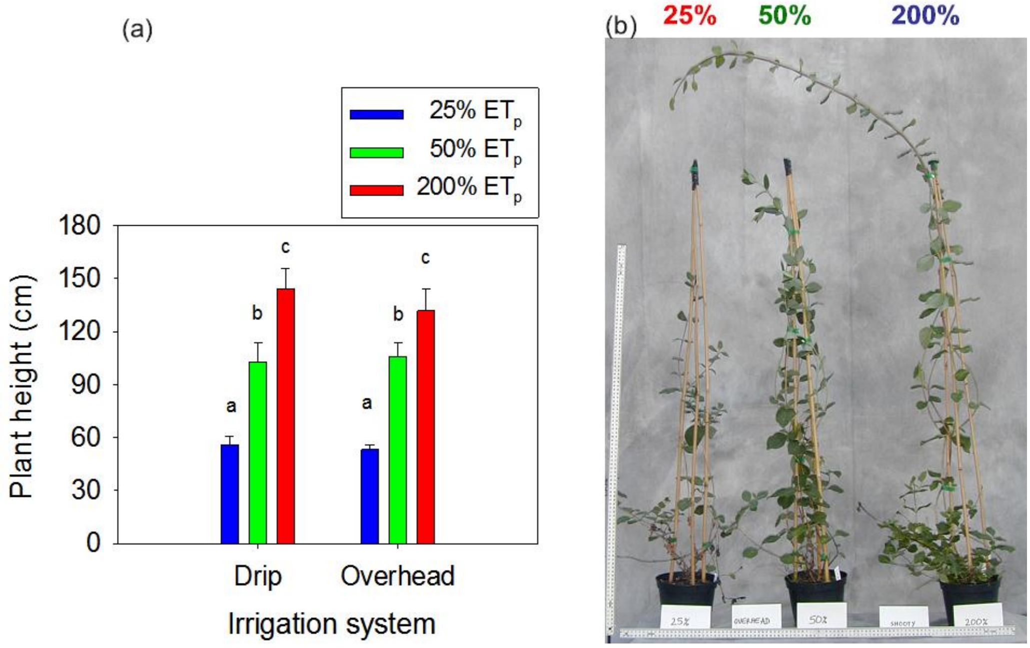


**Figure 4.2.** Final plant heights of *Lonicera periclymenum* ‘Graham Thomas’ after seven weeks of drip or overhead irrigation and deficit (25 or 50% $ET_p$) or full irrigation (200% $ET_p$) (a), and some examples of the final appearance of overhead irrigated plants (b) Symbols represent means ± s.e., *n* = 20

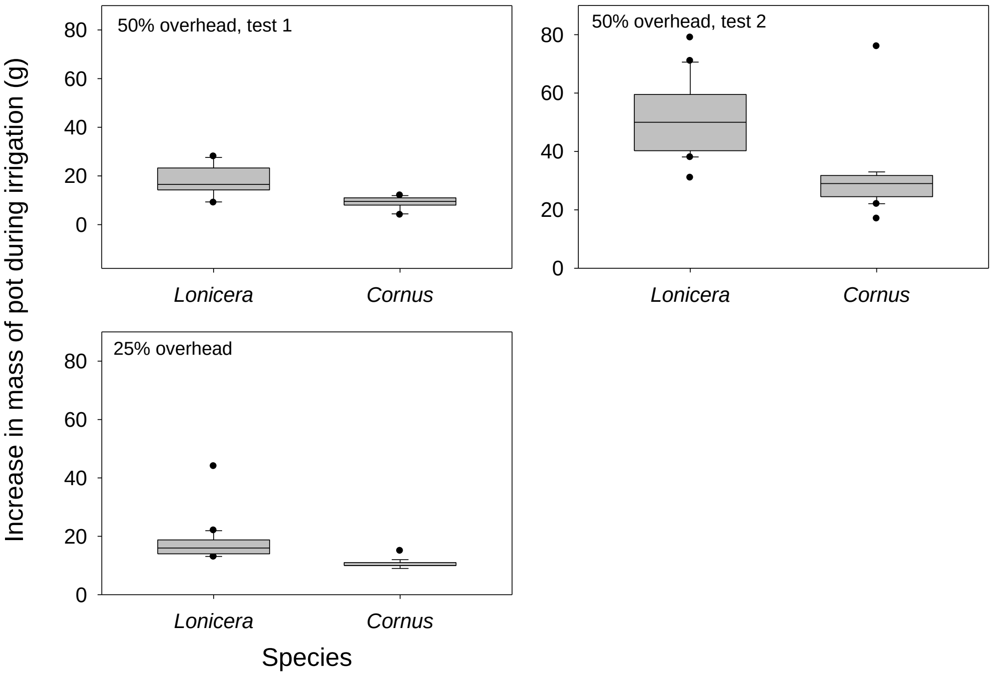


**Figure 4.3.** Uptake of water during irrigation, as measured by the increase in mass of pots of *Lonicera* and *Cornus* in the 2006 RDI experiment. Boxes indicate the 25th to 75th percentile range, whiskers extend another 15% either way, and outliers are represented by circles. $n$ = 20 except in "test 2", where $n$ = 10.

**Figure 4.4.** The appearance of *Cornus alba* 'Elegantissima' after seven weeks of drip (a) or overhead (b) irrigation and deficit (25 or 50% $ET_p$) or full irrigation (200% $ET_p$), where $ET_p$ refers to that of *Lonicera periclymenum* 'Graham Thomas' on the same beds.

*Impact of substrate*

When we investigated whether the response to RDI is dependent on growing medium, it was found that there was a faster growth rate in the peat/ bark mix than in peat only, after pruning in June (Fig. 4.5). In either substrate, however, there were clear effects of RDI in terms of controlling plant growth, so it would seem that RDI can be applied effectively where substrates that are less water retentive than peat are used.

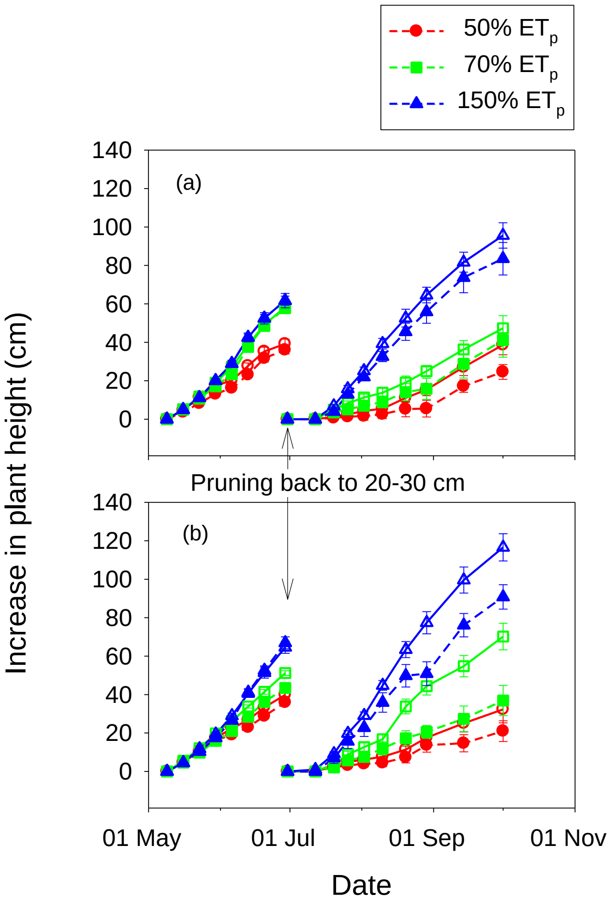


**Figure 4.5.** Impact of RDI (50% or 70% ET$_p$) compared to full irrigation (150% ET$_p$) on the growth of *Forsythia* × *intermedia* 'Lynwood' grown in 100% peat (closed symbols) or a peat/bark mix (open symbols) and under overhead irrigation (a) or with drip irrigation (b). Symbols represent means ± s.e., $n$ = 16.

*Impact of stage at which RDI is imposed*

Where we attempted to 'hold' the crop by imposing relatively severe RDI (50% ET$_p$) only after pruning (year 3), this treatment showed greater control of crop growth than a relatively mild (70% $ET_p$) RDI treatment throughout the growing season (Figure 4.6).

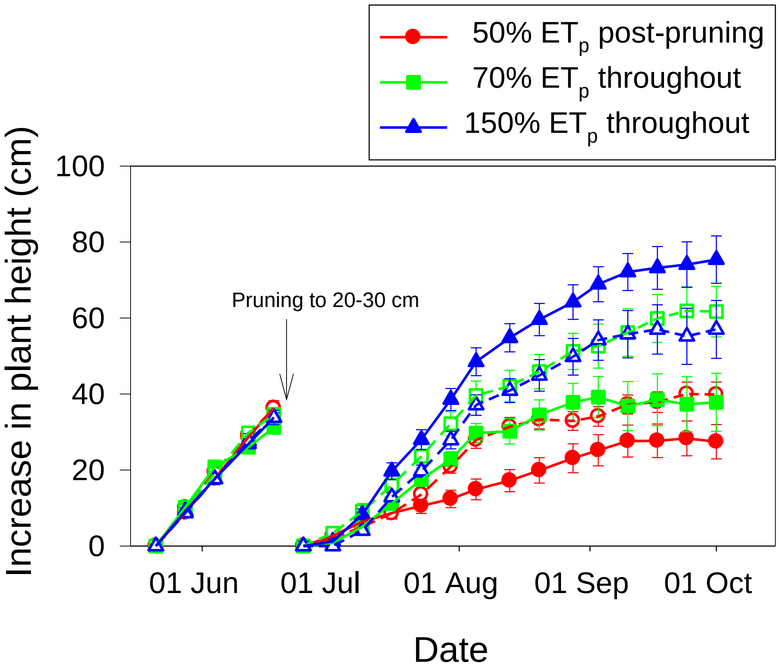


**Figure 4.6**. Impact of RDI applied only after pruning (50% $ET_p$ post-pruning) as opposed to more moderate RDI throughout the season (70% $ET_p$) compared to full irrigation (150% $ET_p$) on the growth of *Forsythia* × *intermedia* ‘Weekend’, where irrigation was scheduled with an Evaposensor (closed symbols) or a GP1 (open symbols). Symbols represent means ± s.e., *n* = 32.

*Impact of RDI on plant physiology*

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 treatment where 50% $ET_p$ was applied after pruning a more substantial reduction in photosynthetic rate meant that there was no increase in photosynthetic water use efficiency compared to the control (Fig. 4.7a, b); later in the season however the pattern was not so clear. This is reflected in carbon isotope composition ($\delta^{13}C$): Prior to pruning, leaves of *Forsythia* receiving 70% $ET_p$ had higher $\delta^{13}C$ than fully irrigated plants (Fig. 4.7c), suggesting that RDI improved photosynthetic water use efficiency. At the end of the experiment, the data were more variable and only those plants receiving 50% $ET_p$ showed significant elevation of $\delta^{13}C$.

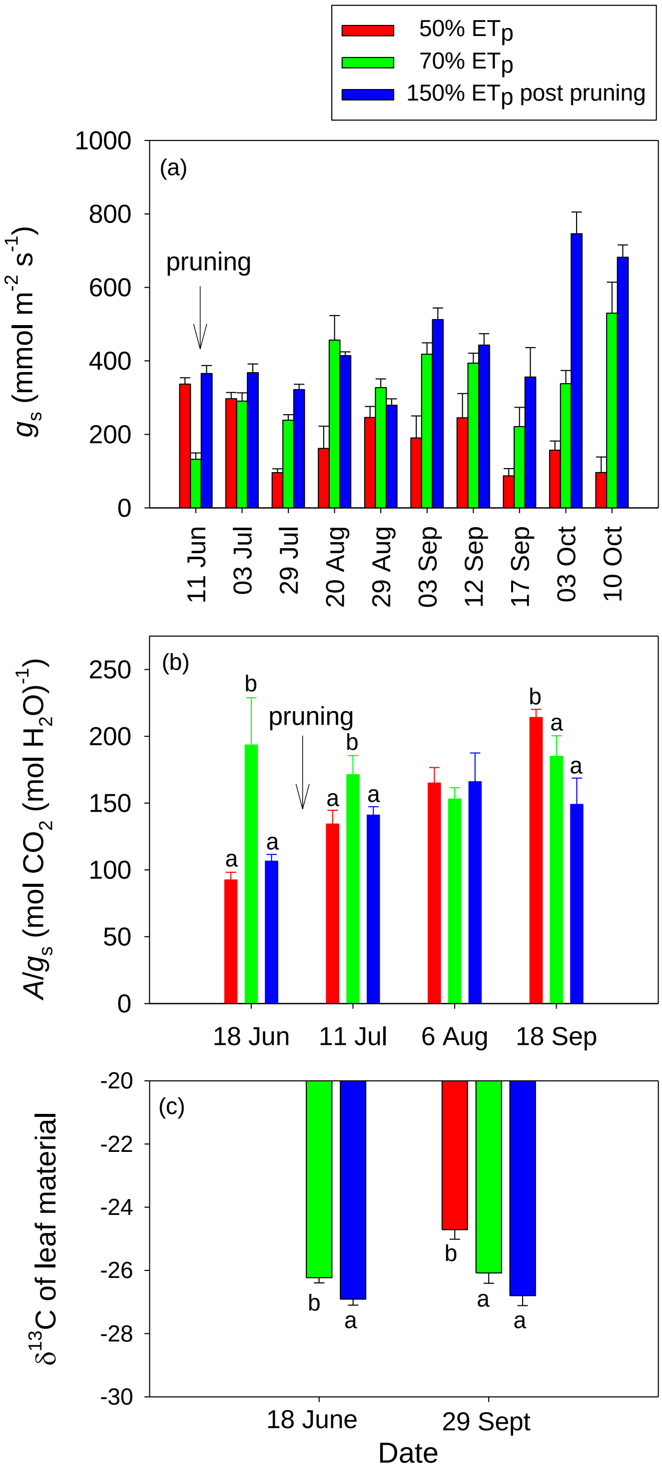


**Figure 4.7.** Stomatal conductance (a), photosynthetic water use efficiency (the ratio of assimilation to stomatal conductance) (b), and carbon isotope composition ($\delta^{13}$C) (c) of *Forsythia* leaves under three different irrigation treatments, *n* = 8-18 in (a), *n* = 24 in (b), except on 18 June when *n* = 14, and n = 16 in (c). Different letters indicate significant differences between treatments within each date.

On days on which there were no rapid fluctuations in air temperature, the difference in evapotranspiration between fully irrigated and deficit irrigated plants could be very clearly visualised using a thermal imaging camera (Fig. 4.8). This was the case whether either a relatively high resolution camera (P25, Flir, US) or a lower resolution camera designed for the building industry (IRI 4010, IRISYS, Northampton, UK) was used.

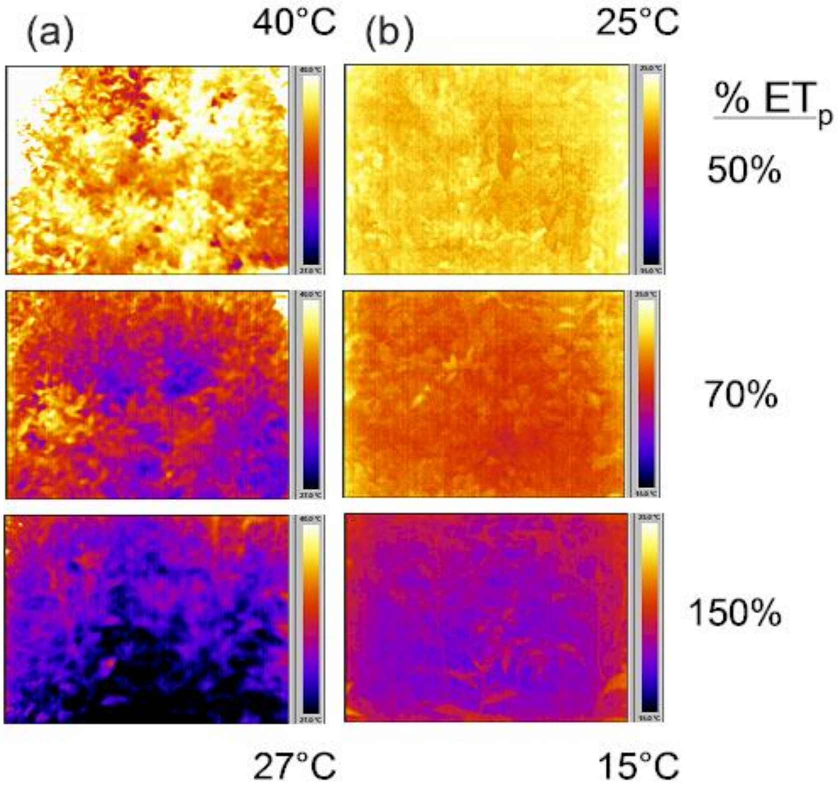


**Figure 4.8.** Thermal images of canopies of *Forsythia* × *intermedia* ‘Weekend’ given RDI (50% or 70% $ET_p$) or full irrigation (150% $ET_p$) on a relatively hot day (a) and a more moderate day (b). All images taken on one day were set to the same temperature scale [27 - 40°C in (a) and 15 - 25°C in (b)]. As shown in the scale bars to the right of each image, white/yellow indicates relatively high temperatures, orange/red represents intermediate temperatures, and purple/blue/black represents the coolest temperatures detected in the canopies on that day. Images were taken with an IRI 4010 (IRISYS) thermal imaging camera.

*Impact on flowering*

In both experiments with *Forsythia*, when approximately 80% of flower buds on a given plant were open, the extent of flowering was estimated, since it was important to ensure that the RDI treatments had no deleterious effects on flowering the following spring. RDI was found to not significantly affect the percentage of nodes on a plant at which there were flowers the following spring (Year 2 data shown in Fig. 4.9a). 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 (Fig 4.9b). 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 RDI treatments can be seen in Fig 4.7d. 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 4.9c). 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. RDI, whether imposed through the season (70% ET$_p$), or after pruning (50% ET$_p$) had a similarly positive impact on flowering of *Forsythia* in the Year 3 experiment (Fig. 4.10). In conclusion, flowering of *Forsythia* was not deleteriously affected by the application of RDI. Indeed, the density of flowering was increased under deficit as opposed to control irrigation.

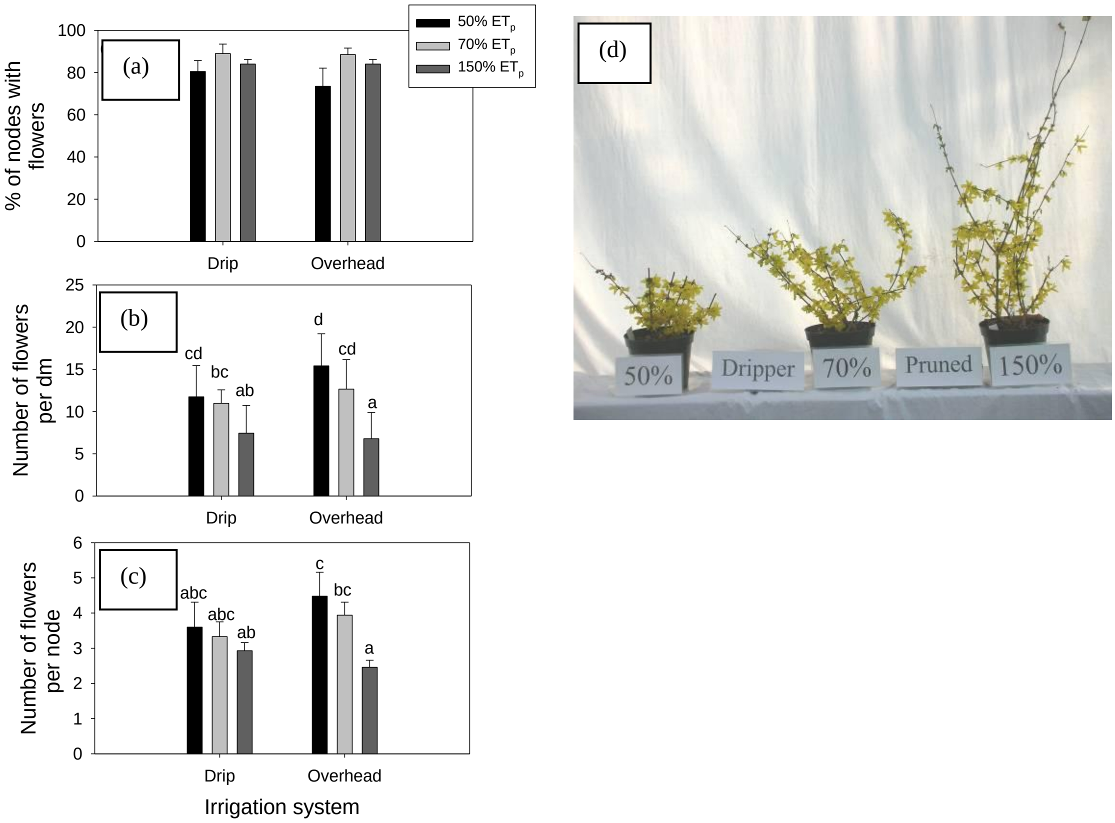


**Figure 4.9.** Percentage of *Forsythia* × *intermedia* 'Lynwood' covered in flowers (a), numbers of flowers per dm (b), and number of flower nodes per dm (c) during flowering in the spring following different % ET$_p$ treatments, and with irrigation applied either overhead or by drippers, and examples 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.

**Figure 4.10.** *Forsythia* × *intermedia* 'Weekend' in flower the spring following either RDI after pruning (50% $ET_p$, left), more moderate RDI through the whole growing season (70% $ET_p$, centre), or full irrigation (150% $ET_p$, right)

## Conclusions

RDI successfully controlled growth without deteriorating crop quality, whether overhead or drip irrigation was used, and whether plants were grown in 100% peat or a peat/bark mix.

Delaying the application of relatively severe (50% $ET_p$) RDI until after pruning of *Forsythia* in June was effective in maintaining them as compact plants.

A more moderate RDI treatment (70% $ET_p$) throughout the growing season resulted in high quality crops in two separate experiments run from May until October. Such a treatment entails less risk of damaging individual plants that receive less water than average (as a result of non-uniformity of uptake).

## Objective 5

*Identify physiological mechanisms underlying plant responses to deficit irrigation (drought) and novel fertiliser treatments (nutrient excess or deficiency) in order to optimise practical exploitation of plant signalling*

### *Variability among HNS species in the apoplastic pH signalling response to drying soils*

### Introduction

After the imposition of soil drying treatments, an elevation of xylem sap pH is one of the earliest observable responses in many herbaceous model plant species. It is theorized that alkalization of sap results in a concurrent elevation in abscisic acid (ABA) concentration delivered to transpiring tissues by preventing Henderson–Hasselbalch-regulated partitioning between the apoplast and symplast. However, here it is demonstrated that the sap alkalzation response to soil drying is far from universal in higher plant species.

### Methods

Tests were conducted to determine how universal the pH response to drying soil was in a range of perennial HNS species from a diverse range of plant families. Eighteen rooted cuttings of 22 species were potted into 0.9 $dm^3$ pots using a medium consisting of 100% sphagnum peat with 6.0 kg $m^{-3}$ Osmocote Plus 12–14 month controlled-release fertilizer (The Scotts Co., Surrey, UK) and 1.5 g $m^{-3}$ $MgCO_3$ (excluded for *Rhododendron obtusum* and *Hydrangea serrata*). Plants were then left to acclimate in the growing environment for 2 weeks. Plants were grouped by species, with treatments randomized in an indoor growing environment [photoperiod 16 h, daytime temperature 20 °C, night-time temperature 18 °C, relative humidity 35–45%, mean photosynthetically active radiation (PAR) 500 µmol $m^{-2}$ $s^{-1}$]. Regulated deficit irrigation (RDI) was used to apply soil water deficits, as it allows water deficits to be generated in a controlled and gradual manner. Daily irrigation was applied in proportions of the estimated potential evapo-transpiration (ETp) of the plants over a 24 h period. Fifteen plants received a well-watered treatment, where containers were filled to capacity by replacing 100% of the daily evapo-transpiration (1.0 ETp). Two sets of 15 plants were supplied with 0.8 ETp and 0.5 ETp of the control plants and deemed to be receiving mild and severe soil water deficits, respectively.

Thermal imaging of leaf temperature was used as a surrogate for stomatal conductance. Leaf temperature is known to be a sensitive indicator parameter of leaf conductance to water vapour and thus an acceptable method for approximating leaf $g_{s.}$ Leaf temperatures taken from thermal images were the most practical method of assessing the high numbers of leaves within this study in a representative time frame, and exhibited a very high resolution. Porometers were used to confirm that leaf temperatures were indicative of stomatal closure, but the requirement for porometer calibration for each species, the small needle leaves of certain species, and the high sampling number precluded the use of porometry. The maximum adaxial temperatures of two leaves per plant were recorded using a FLIR SC200 thermal imaging camera (FLIR Systems, Wilsonsville, USA). The atmospheric environment and incident radiation were kept unchanged, and relative humidity was kept low (35–45%) in order to reduce the errors in estimating $g_s$ from leaf temperatures. Once the soil drying regime generated a significant increase in leaf temperature, further analysis began.

In order to measure stem water potential ($\Psi_{stem}$) and extract xylem sap, the two largest stems per plant were then cut 50 mm from the apex and placed in a Scholander pressure bomb (Plant Moisture Systems, Santa Barbara, CA, USA) with the chamber lined with damp blotting paper. Compressed air was progressively added to the chamber until sap began to appear at the site of excision (viewed with a x10 hand lens), and the pressure when sap emerged was noted and this was taken be equal to the negative value of $\Psi_{stem}$. The cut stem was then blotted dry and the pressure increased by 0.2 MPa over the balance pressure in order to extract xylem sap. The subsequent sap exuded was collected in 100 $mm^3$ tubes (Eppendorf, Hamburg, Germany) and kept on ice before the pH of the sap was measured using a micro PHR-146 pH probe (Lazer Research Labs, Los Angeles, CA, USA). Three species were found to be unsuited to the measurement of $\Psi_{stem}$ in pressure chambers. *Forsythia x intermedia* possesses hollow stems, which causes air to leak from the chamber, *Elaeagnus augustifolia* only exudes very low xylem sap contents, and *Trachelospermum jasminoides* produces latex at the sight of excision that obscures observations and sap analysis.

## Results

Plants that closed stomata (indicated by significant increases in leaf temperature) under water deficits while exhibiting no change in water potential were considered to be regulating water relations in an isohydric manner. Those species that had increased leaf temperatures under water deficits at the same time as significant reductions in stem water potentials were considered to be behaving anisohydrically.

The response was not found in the majority of the 22 species tested (Table 5.1). Four species exhibited significant increases in pH, but the majority showed no significant change in xylem sap pH. There was no evolutionary relationship between the species that showed alkalization under drought stress. However, the species that alkalized sap also exhibited good control over internal water status and were the most isohydric species of those tested. None of the species exhibiting anisohydric responses alkalized xylem sap under drought stress. Regardless of alkalization response, plants still retain the ability to respond to changes in xylem sap pH when manipulated by alkaline buffer foliar sprays. This finding indicates that plants have conserved the ability to respond to changes in xylem pH and redistribute ABA, even if they do not currently utilize the mechanism when exposed to drought stress. It was found in *Buddleja davidii*, *Euonymus fortunei*, and *Hydrangea serrata* that the xylem sap pH response to water deficits mirrored the natural pH changes that occur as sap is transported to the leaves, indicating that plants need to be able to have naturally occurring alkalization processes in place for them to be up-regulated under drought stress.

**Table 5.1** The response of leaf temperature, stem water potential, and xylem sap pH in 22 perennial plant species to being well watered (1.0 ETp), a mild soil water deficit (0.8 ETp RDI), and a severe soil water deficit (0.5 ETp RDI)

| **Species** | **Leaf temperature (°C)** | | | | **Water potential (MPa)** | | | | **Xylem pH** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***1.0 ETp*** | ***0.8 ETp*** | ***0.5 ETp*** | ***LSD*** | ***1.0 ETp*** | ***0.8 ETp*** | ***0.5 ETp*** | ***LSD*** | ***1.0 ETp*** | ***0.8 ETp*** | ***0.5 ETp*** | ***LSD*** | |
| *Abeliaxgrandiflora* | 27.03 | 27.38 | **27.82** | 0.37 | –0.43 | –0.35 | –0.34 | –0.22 | 5.85 | 5.67 | 5.70 | 0.19 | |
| *Abies koreana* | 28.59 | **29.62** | **30.40** | 0.55 | –1.27 | –1.17 | **–1.77** | –0.35 | 5.31 | 5.34 | 5.16 | 0.22 | |
| *Buddleja davidii* | 26.70 | 27.14 | **29.09** | 0.85 | –0.28 | –0.30 | –0.38 | –0.12 | 7.84 | 8.17 | **9.25** | 1.19 | ↑ |
| *Cortaderia selloana* | 26.11 | 26.04 | **27.22** | 0.49 | –0.29 | –0.45 | **–1.48** | –0.22 | 5.84 | 5.82 | 5.81 | 0.07 | |
| *Dicksonia antarctica* | 30.46 | **32.13** | **33.05** | 1.36 | –0.30 | –0.34 | –0.49 | –0.23 | 5.90 | 6.37 | **6.86** | 0.83 | ↑ |
| *Elaeagnus angustifolia* | 32.72 | 32.71 | **34.45** | 1.18 | – | – | – | – | – | – | – | – | |
| *Escallonia rubra* | 25.86 | **26.63** | **27.20** | 0.50 | –0.81 | **–1.23** | **–2.05** | –0.35 | 5.51 | 5.41 | 5.40 | 0.15 | |
| *Euonymus fortunei* | 29.06 | **29.87** | **29.67** | 0.54 | –0.41 | –0.52 | **–0.60** | –0.17 | 6.20 | 6.05 | 6.09 | 1.61 | |
| *Forsythiaxintermedia* | 29.73 | **32.93** | **32.79** | 2.21 | –0.74 | **–1.24** | **–1.96** | –0.16 | – | – | – | – | |
| *Hydrangea serrata* | 32.81 | 34.24 | 34.11 | 1.59 | –0.40 | –0.36 | –0.41 | –0.06 | 6.00 | 5.95 | **5.92** | 0.06 | ↓ |
| *Hypericum calycinum* | 24.72 | **25.43** | **26.43** | 0.54 | –0.22 | –0.31 | **–0.35** | –0.15 | 5.08 | 4.90 | 4.89 | 0.28 | |
| *Incarvillea delavayi* | 26.63 | **27.55** | **27.56** | 0.45 | –0.37 | **–0.96** | –0.50 | –0.46 | 5.68 | 5.56 | 5.78 | 0.16 | |
| *Laurus nobilis* | 31.46 | **33.78** | **33.83** | 1.33 | –1.70 | –1.88 | –2.07 | –0.54 | 5.84 | 5.87 | 5.76 | 0.10 | |
| *Lonicera periclymenum* | 24.65 | **25.80** | **26.00** | 0.34 | –0.21 | **–0.41** | **–0.52** | –0.20 | 5.67 | 6.08 | 5.67 | 0.54 | |
| *Penstemon heterophyllus* | 24.82 | **25.93** | **26.39** | 0.61 | –0.20 | –0.19 | –0.19 | –0.08 | 7.53 | 7.53 | **8.90** | 1.32 | ↑ |
| *Perovskia atriplicifolia* | 25.66 | **27.23** | **27.08** | 0.99 | –0.29 | –0.39 | **–0.66** | –0.19 | 7.15 | 7.35 | 6.32 | 1.50 | |
| *Philadelphus coronarius* | 24.67 | **25.29** | **25.69** | 0.54 | –0.49 | –0.60 | **–2.15** | –0.56 | 6.26 | 6.18 | 6.12 | 0.17 | |
| *Physocarpus opulifolius* | 26.80 | **28.27** | **28.91** | 0.86 | –0.42 | –0.52 | **–1.43** | –0.18 | 8.25 | 7.30 | **6.32** | 1.23 | ↓ |
| *Rhododendron obtusum* | 22.03 | **24.81** | **24.89** | 1.70 | –0.74 | **–1.28** | **–1.66** | –0.91 | 5.935 | **6.22** | **6.17** | 0.12 | ↑ |
| *Spiraea japonica* | 24.11 | **26.18** | **25.98** | 0.81 | –0.57 | –0.72 | **–1.21** | –0.22 | 6.11 | 6.04 | **5.94** | 0.16 | ↓ |
| *Trachelospermum jasminoides* | 35.20 | 34.98 | 35.78 | 0.72 | – | – | – | – | – | – | – | – | |
| *Yucca filamentosa* | 28.70 | **30.43** | **30.84** | 0.59 | –0.33 | –0.38 | **–0.54** | –0.10 | 5.57 | 5.48 | 5.50 | 0.26 | |

Measurements were taken once plants exhibited a significant increase in leaf temperature in a deficit treatment. All plants were pot grown and contained in a climate-controlled glasshouse with supplementary lighting. Treatments consisted of 15 plants with values equalling means from 30 stems. LSD values calculated at $P < 0.05$, df=29. Treatments that produced significant differences in a parameter compared with the control (1.0 ETp) treatment are highlighted in **bold**. Arrows illustrate if a species exhibited significant raising or lowering of xylem sap pH in response to soil drying to RDI.

### ***Response of species with differing apoplastic pH response to soil drying to apoplastic pH manipulation***

## Methods

Potassium phosphate ($KH_2PO_4$:$K_2HPO_4$) buffer was sprayed on to the foliage of species that exhibited divergent responses in xylem sap pH to soil drying; *Buddleja davidii* significantly increased xylem sap pH, *Physocarpus opulifolius* decreased xylem sap pH, and *Lonicera periclymenum* exhibited no significant change in xylem sap pH. These species were also chosen because they possessed high stomatal conductance under well-watered conditions. Eight plants of each species were treated with 20 mol $m^{-3}$ potassium phosphate buffer spray iso-osmotically adjusted to either pH 6.0, 7.0, or 8.0. After 2 h, adaxial leaf temperatures were measured on two leaves per plant.

## Results

Foliar sprays of pH 8.0 phosphate buffer (20 mol $m^{-3}$ $KH_2PO_4$:$K_2HPO_4$) significantly increased adaxial leaf temperatures above those measured on plants sprayed with water controls (Table 5.2). Increases in leaf temperature were observed in *B. davidii*, *P. opulifolius* and *L. periclymenum* (Table 5.2). Foliar sprays of phosphate buffers adjusted to pH 6.0 and pH 7.0 had no significant effect on leaf temperature compared with water control sprays in all three species.

**Table 5.2.** The change in leaf temperature 2 h after a single treatment with phosphate buffer (20 mol m$^{-3}$ $KH_2PO_4$:$K_2HPO_4$) iso-osmotically adjusted to pH 6.0, 7.0, and 8.0 in intact pot-grown *Buddleja davidii, Lonicera periclymenum,* and *Physocarpus opulifolius* plants

| **Buffer pH** | ***Buddleja*** | ***Lonicera*** | ***Physocarpus*** |
|---|---|---|---|
| 6 | –0.2 | 0.025 | –0.21 |
| 7 | 0.25 | 0.375 | –0.03 |
| 8 | **0.83** | **0.658** | **0.291** |
| LSD | 0.525 | 0.484 | 0.4947 |

All plants were acclimatized in a climate-controlled glasshouse with supplementary lighting for 14 d before treatment imposition. Treatments consisted of 15 plants; values are means from 30 leaves. LSD values calculated at *P* <0.05, df=29. Treatments that produced significant differences in a parameter compared with the water control spray treatment are highlighted in bold.

## Conclusions

The findings that plant species with differing apoplastic pH responses to soil drying retain the ability to respond to artificial modifications in sap pH could have potential for use in the horticulture industry. Alkaline buffers could be applied to crops to limit excessive transpiration and thereby cut down the need for irrigation when water supplies are limited. In ornamental and fruit crops alkaline buffers could be used to stimulate a spike in xylem ABA concentration to control excessive vegetative growth, and reduce the need for pruning.

The pH response to drying soil is far from universal in perennial species and there is no evolutionary relationship between the species that alkalize sap under drought stress. However, the species that do alkalize sap have good control over internal water status and were the most isohydric species. It was found that plants retain the ability to respond to changes in xylem sap pH regardless of the alkalization response. The xylem sap pH response to water deficits mirrored the natural pH changes that occur as sap is transported to the leaves, indicating that there is a necessity for a plant species to have a naturally occurring alkalization processes in place for it to be up-regulated under drought stress.

### *The effects of alkaline buffers on plant water use*

## Introduction

Alkaline buffers can control plant growth and development and stomatal behaviour but we were keen to determine whether stomatal closure on the nursery leads to a significant effect on plant/crop water use.

## Methods

Applications of pH8 buffer where made as a foliar spray twice weekly to *Euonymus* in 2 L containers at Garden Centre Plants in Preston, Lancs. Twelve plants received a complete covering spray of buffer while 12 plants received a spray of water as a control. The buffer was changed from a potassium-phosphate solution to one containing potassium hydrogen carbonate due to a lack of activity on other species tested. Water use was monitored every other day and plants were kept at an optimum container capacity.

## Results

The degree of saving of irrigation water depended on the prevailing evaporative demand in the growing environment. An average saving of 11% was achieved, but this rose to ~20% (Table 5.3) during hot and dry periods.

**Table 5.3.** The percentage of the total irrigation supplied to control *Euonymus* plants that was not required to be applied to the plants treated with a pH8 buffer foliar spray twice weekly.

| Day | % irrigation water saved |
|---|---|
| 0 | 15 |
| 2 | 19 |
| 4 | 0 |
| 6 | 5 |
| 8 | 21 |
| 10 | 11 |
| 12 | 22 |
| 14 | 0 |
| **Mean** | **11.6** |

### ***Manipulating plant stress signalling via inoculation of growing media with the rhizobacterium Variovorax paradoxus***

## Introduction

Inoculation of growing media with plant growth promoting rhizobacteria (PGPR) has a number of potential benefits for the production of ornamental plants (Belimov et al. 2009). Certain rhizobacteria synthesise the enzyme ACC deaminase, which cleaves ACC, the precursor of the plant hormone ethylene. Bacterial metabolism is now known to lead to a reduction in [ACC] in the plant transpiration stream and bacteria are hypothesised to act on ACC exuded from roots. This in turn reduces the ethylene generated in plants growing in growing media inoculated with these bacteria. Here we tested applications of the ACC deaminase containing rhizobacteria *Variovorax paradoxus* 5C-2 to determine whether reducing ethylene generation in stressed plants could be benefit to ornamental growers. Ethylene is produced at levels that are inhibitory to growth and development under a number of abiotic stresses. The propagation and production of hardy ornamentals is deleteriously affected by abiotic stresses that involve ethylene signalling, including drought and physical wounding.

A number of processes involved in water availability and propagation are hypothesised to be due to stress and potentially involve ethylene signalling. Many of the previous studies with PGPRs have applied bacteria via inoculation of the seeds, while in hardy ornamental production we foresee root drench as being the optimal method of obtaining inoculated roots compatible with the methods of propagation and production of the plants currently grown on nurseries. We addressed three stress situations known to occur with ornamentals:

1. *Cytisus* x *praecox* possesses a summer deciduous response to drought and high light intensity; as is common in shrubs from Mediterranean habitats. When a sufficiently severe soil water deficit is imposed the leaves senesce and eventually abscise. While this response allows the plant to reduce water loss and prevent death *via* dehydration in its native habitat, it presents a problem to commercial propagation if the crop is allowed to dry out periodically. The entire foliage can be lost for a whole growing season, and thus unsalable until at least the following year. Drought has been found to increase ethylene emission (Kalantari et al., 2000; Mayak et al., 2004)

http://www3.interscience.wiley.com/cgi-bin/fulltext/121488855/main.html,ftx_abs - b38 (Sobeih et al., 2004) and increased ethylene production is known to be involved in the promotion of senescence and abscission (Gomez-Cadenas et al., 1996; Lim et al., 2007). Therefore we chose to apply ACC deaminase containing bacteria on *Cytisus* x *praecox* to determine if inoculation could prevent or minimise the summer deciduous response in plants experiencing soil drying.

2. Divisional propagation of hardy ornamentals results in large amount of damage to roots as they are separated. This results in reductions in the health of the foliage and reduction in subsequent growth, as the plant directs assimilates towards repairing damaged tissue and rebalancing the root:shoot ratio. Therefore we assessed if ACC deaminase containing rhizobacteria could reduce the effects of excessive ethylene generation caused by the physical damage by lowering soil [ACC]. This study was conducted on the bamboo *Fargesia murielae,* which is commonly propagated by division.

3. Late season senescence is a problem in a number of ornamental herbaceous perennial species when grown under protection. As ethylene is key regulatory hormone in activating senescence, we investigated if ACC deaminase containing rhizobacteria can reduce senescence in crops of *Aquilegia* x *hybrida*, which is prone to exhibiting this stress response in the autumn in the UK.

**Methods**

All plants were potted in a medium of 100% sphagnum peat with 6.0 g $dm^{-3}$ Osmocote Plus 12–14 month controlled-release fertilizer (The Scotts Co, Surrey, UK) and 1.5 g $dm^{-3}$ $MgCO_3$. The growing media was not sterilised, in order to produce conditions comparable to those found on commercial nurseries. All experiments were conducted in a temperature controlled glasshouse (Temp day 20 °C / Night = 18 °C, RH 35-45%, mean PAR = 500 µmol $m^{-2}$ $s^{-1}$). All plants were positioned in accordance with a randomised plot design.

Culturing of V. paradoxus 5C-2 and Alcaligenes xylosoxidans CM4 *V. paradoxus* 5C-2 and *Alcaligenes xylosoxidans CM4* were kindly provided by Dr AA Belimov, All-Russia Research Institute for Agricultural Microbiology, St Petersburg University. Isolated colonies from stock agar plates were incubated in a sterile media of 10 g $L^{-1}$

peptone, 10 g $L^{-1}$ triptone, 9 mmol $K_2HPO_4$ and 6 mmol $MgSO_4$, for 24 h at 28 °C and stirred permanently at 180 RPM. The bacteria were concentrated by centrifuging at 4000 x *g* for 10 min, the pelleted bacteria were then resuspended washed with deionised water, recentrifuged, and the pellet resuspended and diluted with deionised water so that the optical density OD540= 1.0. Then 35 mL of the bacterial suspension was applied as a root drench to the plants designated for bacterial inoculation. The growing media was lightly irrigated to allow the bacteria to flow throughout the growing media and left un-irrigated for a further 48 hours to allow colonisation of the root surface.

22 days after the imposition of treatments the colonisation levels of *Cytisus* x *praecox* roots by *V. paradoxus* 5C-2 was assessed. Roots were teased apart and 1 g of tissue from different depths of the growing media was removed and lightly dusted to remove particulate matter. The roots were macerated in 5 mL deionised water and the liquid removed. 100 μL of this solution was diluted 10:1, 100:1 and 1000:1 in sterilised deionised water, 50 μL from each dilution was placed on an agar plate containing the media described above plus agar (8 g $L^{-1}$) and antibiotics (Kanamycin, Rifampicin, Nystatin). Plates were then left for 5 days at 25 °C to allow colony growth, after which the number of *V. paradoxus* colonies on each plate was counted and the colony forming units (CFU) were calculated. In the WW+5C-2 treatment roots had a final mean colony count of 40,000 *V. paradoxus* CFU per gram FW and in the RDI+5C-2 treatment roots there were 180,000 CFU per gram FW.

### *The imposition of drought and V. paradoxus on Cytisus x praecox*

A regulated deficit irrigation (RDI) regime was utilised in order to impose drought using a controlled and gradual method. The control treatment consisted of a well watered regime delivered to the 13 plants per treatment. These plants were adjusted to container capacity daily by reapplying the volume of water lost through evapotranspiration (ETa). The second treatment was a well watered irrigation regime plus *V. paradoxus* 5C-2 (WW+5C-2). The third treatment was a RDI regime where 50% of the water that was lost through ETa in the previous 24 h was applied back to the plants. The final treatment combined the 0.5 ETa RDI irrigation regime plus *V. paradoxus* 5C-2 (RDI+5C-2) root inoculation. All treatments and measurements were repeated 30 days after the first experiment using the same methods, growing conditions and freshly cultured bacteria.

*Measurement of ethylene emission by gas chromatography*

The emission of ethylene in *Cytisus* x *praecox* was measured seven days after imposition of drought and bacterial inoculation. Each plant was measured twice, with the first measurement taken from 10 shoot tips and later from 10 leaves produced in the previous year's growth, which were termed 'mature' leaves. Samples were taken from plants, weighed, then immediately placed in a 2.0 mL clear glass vial (Suba-Seal, SLS, Nottingham, UK) with a water reservoir in the bottom and capped with rubber septum lid. Samples were incubated for 50 min under comparable illumination to the growing environment before 1 mL of the gas from the vial headspace was manually injected into a gas chromatograph (6890N, Agilent Technologies UK Ltd, Wokingham, UK) fitted with a J&W HP-AL/S (50 m ¥ 0.537 mm ¥ 15.0 mm) column (HiChrom Ltd, Reading, UK). The temperature was maintained at 100 °C for 5 min to resolve ethylene and then increased at 15 °C min$^{-1}$ to 150 °C and held for 1.5 min to remove the water vapour introduced into the column by sample injection. The helium carrier gas was set at a flow rate of 5.7 mL min$^{-1}$ and detection was by flame ionization. Ethylene concentration was calculated with reference to peak areas of known ethylene standards (BOC Special Gases, Manchester, UK) and corrected for tissue fresh weight and time in incubation to determine the plant emission rate.

*Measurement of vegetative growth and flowering*

21 days after the imposition of treatments, plants were divided at the root-shoot junction and the canopy cut into individual branches and scanned on area meter (Li-300A + Li-3050A/4, Li-Cor, Lincoln, Nebraska, USA) to measure total stem length and total tissue area. Leaf density was calculated by dividing the total tissue area by the total plant stem lengths. Assessment of the presence of drought-induced leaf necrosis was undertaken by an independent judge with no knowledge of which plants were experiencing each treatment. Flowering was assessed by counting the percentage of plants with ≥1 anthesed flower or floral bud, and calculating the mean number of flowers per plant.

*Determining the level of late season senescence in Aquilegia x hybrida*

*Aquilegia* x *hybrida* plants were obtained in mid-summer and grown in a glasshouse until 1st October 2008. Then treatments were imposed to 10 plants each. The control treatment consisted of well watered plants where ETa was applied back to the plant daily. An interrupted drought treatment was imposed by supplying irrigation every 5 days, which returned plants to container capacity. The last two treatments combined the interrupted drought treatment with inoculation of either *V. paradoxus* 5C-2 or *Alcaligenes xylosoxidans* CM4. Late season senescence was visually assessed by an independent judge who determined the number of plants in a senescent state. The leaf chlorophyll content was determined as described below.

## Results

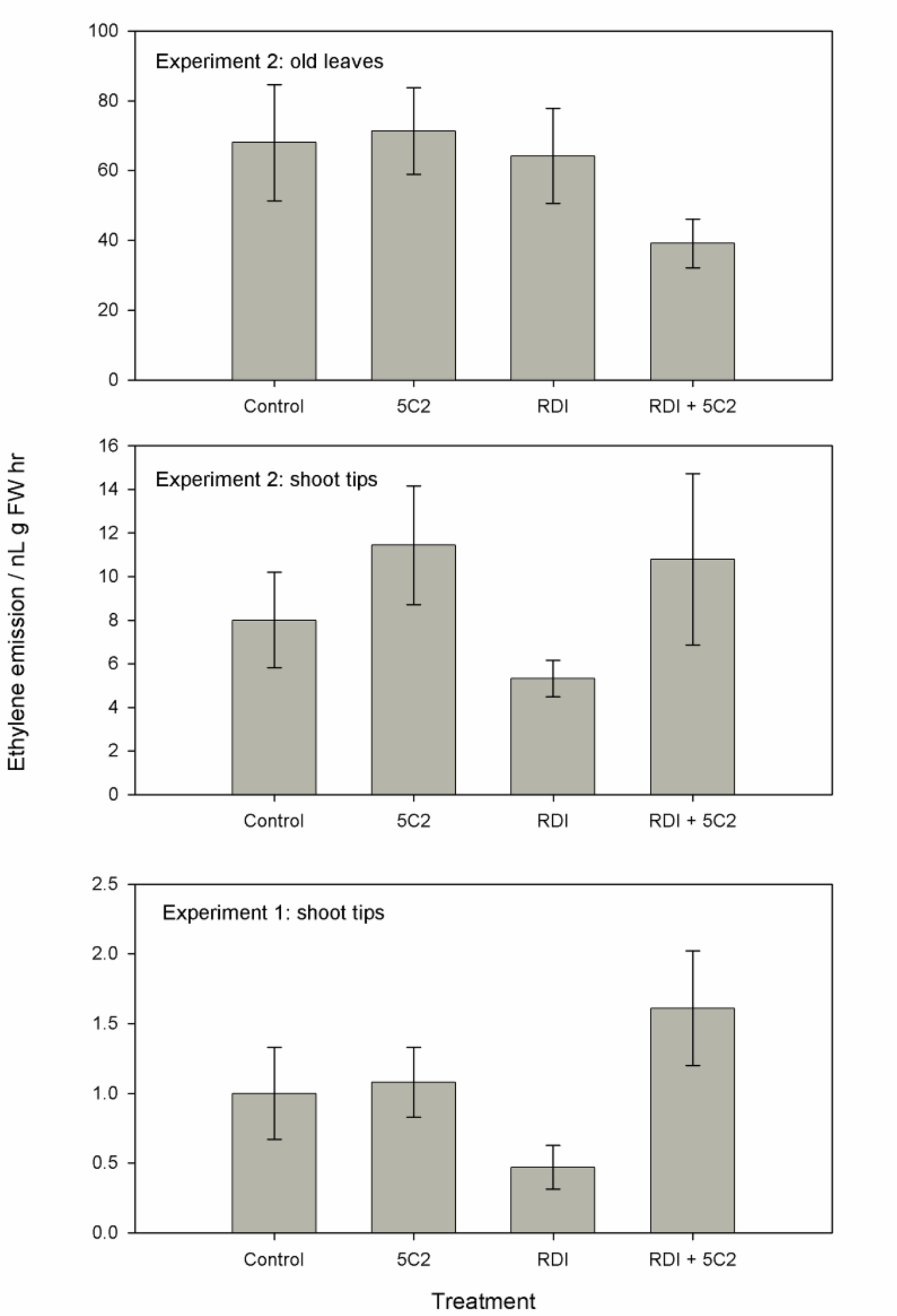


**Figure 5.4.** Effects of rhizobacteria and drought on ethylene production

Inoculation of growing media with *Variovorax paradoxus* 5C-2 lowered ethylene emission from mature leaves of *Cytisus* x *praecox* experiencing drought stress. In addition, bacterial inoculation of the growing media resulted in significantly reduced abscission of the mature leaves under drought treatment. Beneficial effects of inoculation where also found in the wounding response of *Fargesia murielae* following divisional propagation and late season senescence in *Aquilegia* x *hybrid* in response to drought stress. Together these results demonstrate that ACC deaminase containing rhizobacteria are of real potential for use on ornamental nurseries in situations where plant stresses are unavoidable. Flowering of *Cytisus* was also increased by bacterial inoculation

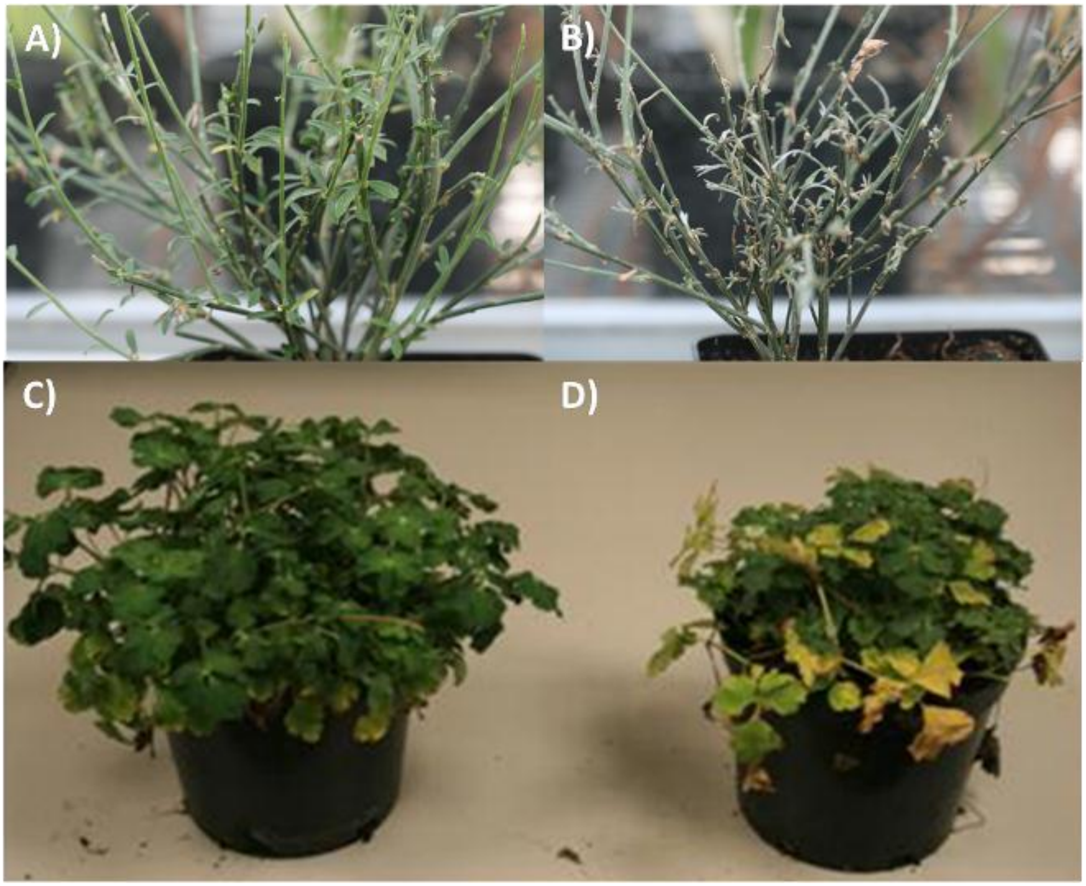


**Figure 5.5.** Effects of rhizobacteria and drought on plant senescence

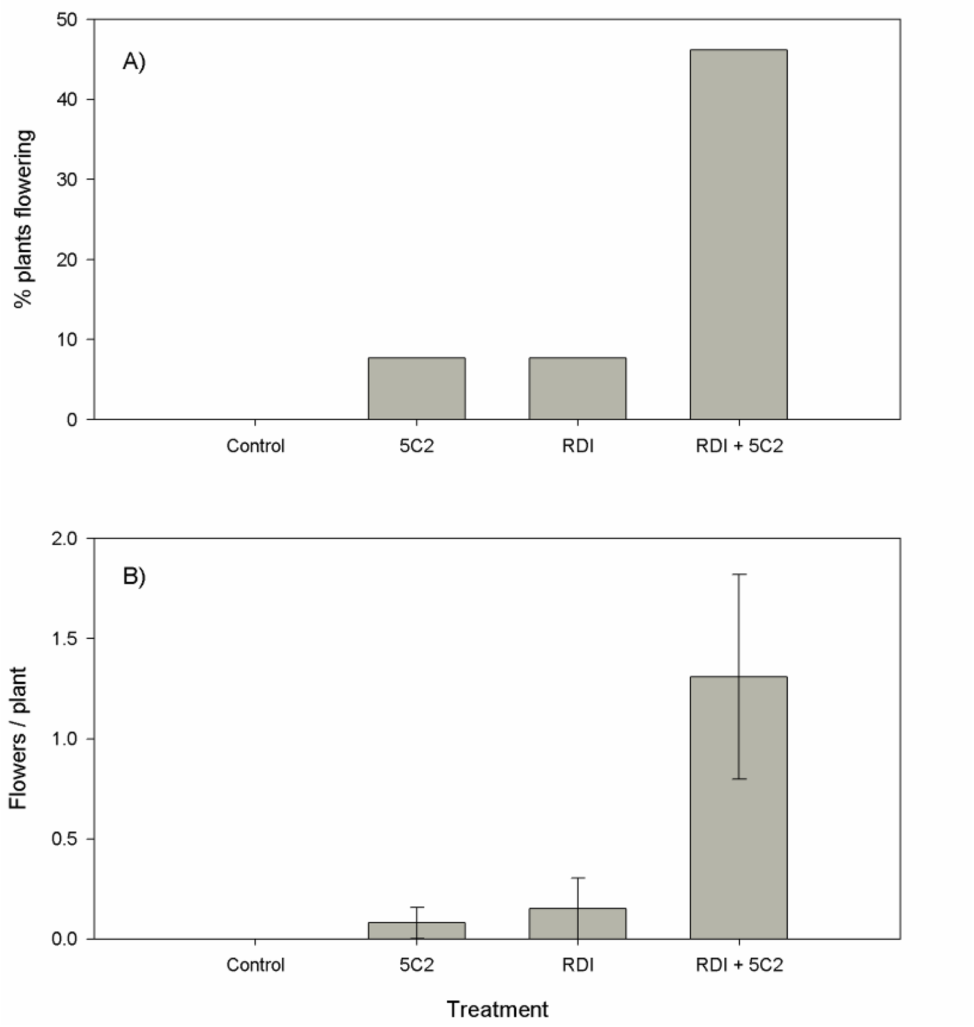


**Figure 5.6.** Effects of rhizobacteria and drought on flowering

The use of bacteria that modify plant responses to abiotic stresses has been given less attention than using them as biocontrol of pests and pathogens. Therefore there is no current use of purified bacterial isolates that modify plant stress on hardy ornamental nurseries. However, the beneficial effects of compost teas and commercially available pro-biotic plant growth stimulators/enhancers may be due, at least in part, to the effect of bacteria that affect plant stress signalling by metabolising ACC and ACC deaminase activity.

## Conclusions

In conclusion, ACC deaminase containing bacteria exhibit clear beneficial effects when applied to hardy ornamental plants experiencing abiotic stress. This feature could be used on nurseries to mitigate the effects of drought resulting from inadequate watering regimes as well as the stress of certain propagation methods. Bacterial inoculation allows the user to control of plant 'stress' ethylene levels, without the disadvantages found with the use of some synthetic regulators of plant ethylene emission.

Future research should establish the life expectancy of bacteria in standard growing media, the optimal inoculation concentration and how persistent the effects on plant growth are. This in turn will establish if the use of ACC deaminase-containing bacteria in ornamental horticulture is financially and thus commercially viable.

### ***Using rhizobacterial soil additives to restore stomatal responses to drought stress under ozonated conditions***

## Introduction

Increased tropospheric ozone concentrations are among the most damaging of stresses that are imposed on plants in the northern hemisphere. Concentrations are continuing to increase and levels higher than 100 ppb are routinely recorded in the summer months in UK. Genotypic sensitivity to ozone is well established. Links have been made between stomatal aperture and ozone sensitivity (see Wilkinson & Davies 2010), however our research is the first to link ozone sensitivity to a change in the sensitivity of the stomatal / growth response to the ubiquitous plant stress hormone abscisic acid (ABA), and thus to drought stress (Mills et al. 2009, Wilkinson & Davies 2009, Wilkinson & Davies 2010).

## Methods

### *Plant material*

*Trifolium repens* plants of two genotypes showing differential stomatal response to ozone were raised in 10-cm-tall pots in John Innes No. 2 compost from plugs until the rosette contained at least five leaves of over 5.0 cm in length. This was carried out in a greenhouse under supplemental lighting (provided by 600 W sodium Plantastar lamps, Osram, Germany), giving a photoperiod of 16 h, with a variable day/night temperature. They were watered daily with tap water to the drip point, and every 2 weeks with nutrient solution. At the appropriate stage (see above), plants were transferred to one of four 1.0 $m^3$ growth cabinets in a second greenhouse for ozone exposure (or to one of four identical cabinets without supplemental ozone – controls) for up to 5 weeks, at the end of which time plants comprised up to approximately 30 leaves. Growth cabinets were glass-topped, such that plants were exposed to supplemental lighting as described above, and air-conditioned to temperatures of 21 ± 2.0 °C. Plants were watered as described above. After 2–3 weeks with or without ozone in the growth cabinets, plants were transferred to larger 1.0 L pots.

### *Ozone exposure*

Ozone was generated (TOGB1 generator, Ozonia Triogen, Glasgow, UK) from compressed air which had first been dried (air dryer model TPD50A, Ozonia Triogen). The gas was bubbled through distilled water to remove impurities. A manifold system was used from which four manually controlled flow meters could be manipulated to adjust the flow of gas directly into each of the four growth chambers. Excess ozone and exhaust ozone from the chambers was vented to the exterior of the building. Ozone concentrations in each chamber were measured using an ozone analyser (model 49c, Thermo Environmental Instruments Inc., MA, USA), and the flow of gas to each chamber was adjusted two to three times daily to achieve a concentration of 70 ± 15 ppb (nL $L^{-1}$) ozone. Unadjusted ozone concentrations in the four control chambers (which were also air-conditioned) were measured daily and varied from 10–35 ppb (nL $L^{-1}$). These concentrations are lower than those that would have been present in the air outside the greenhouse.

### *Stomatal conductance measurements*

Abaxial stomatal conductance (gs) was measured with a porometer (AP-4, Delta-T Devices Ltd, UK) in five to eight plants per treatment, in two to three of the most recently fully expanded leaves per plant.

### *Soil-drying experiments*

Plants (30-leaf-stage) in 1.0 L pots were watered to field capacity and weighed. The following day, the pots and plants were re-weighed. Half from each treatment combination were re-supplied with water to field capacity (well-watered), and the other half were only re-supplied with 50% of the water that would have been required to re-establish field capacity (droughted). This procedure was followed for the five weeks of the experimental period. Gs was re-measured at 14.30 h on some days. Soil moisture potentials were measured with a theta probe (Delta-T Devices Ltd, UK) and expressed gravimetrically

*Bacterial treatments*

Plants were transplanted into 4 l pots containing a peat: loam (1 : 1 v : v) with the following characteristics (mg kg$^{-1}$): total C, 62 000; total N, 5400; nitrate N, 15; available P, 45; available K, 260; pH 6.7. Pots were maintained in a glasshouse during summer under natural illumination and temperature Two watering regimes, 40% WHC (soil drying) and 80% WHC (well watered) were imposed 10 d after transplanting with evapotranspirational losses replenished every second day. Before transplanting seedlings, each pot was moistened to 80% WHC with tap water (control) or with a bacterial suspension. Bacteria (Variovorax parodoxus 5C-2) were grown on agar BPF medium for 3 d at 28°C; cells were collected from agar surface (to minimize transfer of nutrient-rich agar to the pots) and suspended in tap water with a final concentration of $10^8$ cells ml$^{-1}$. Bacterial suspension was added to the pots to a final concentration of $10^6$ cells g$^{-1}$ soil.

## Results

Figure 5.7 shows that an ozone-sensitive plant has more open stomata in polluted air than an ozone-tolerant genotype under droughted conditions, the implication being that this genotype will lose too much water to sustain growth, and that this is the reason for the differences in sensitivity between the two.

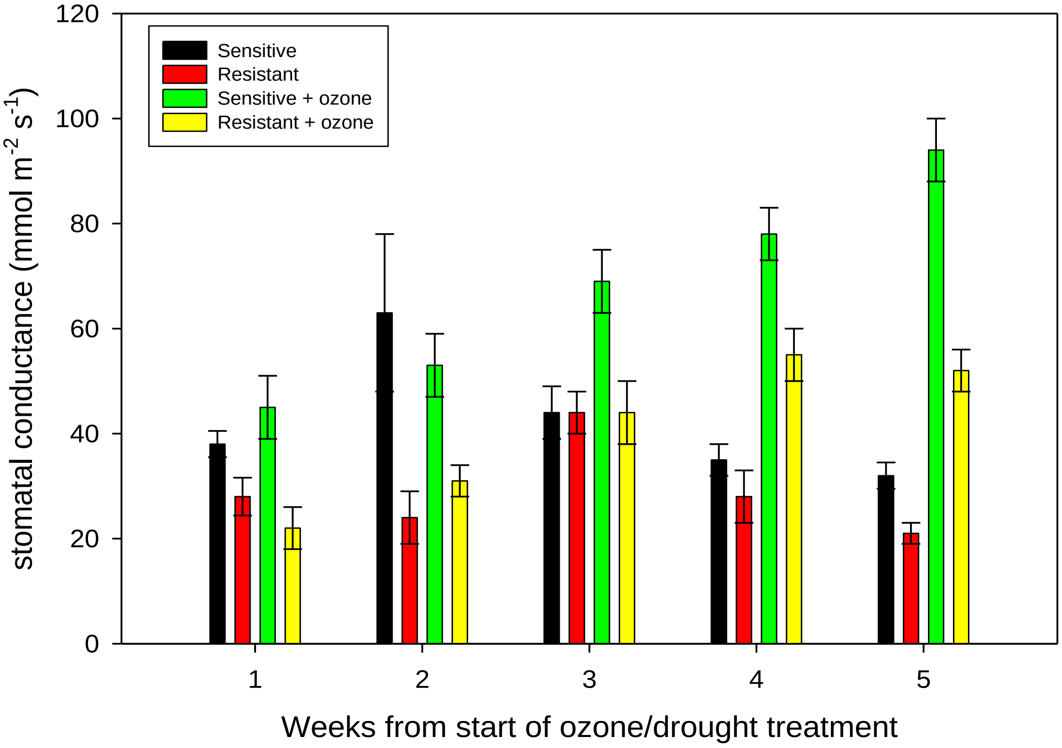


**Figure 5.7.** Effect of ozone plus drought on stomatal conductance.

Our research has shown that ozone-induced loss of stomatal sensitivity to the drought stress hormone ABA (which normally closes stomata) in sensitive species (causing stomata to remain more open under drought/high VPD), is caused by increased ethylene emission. More open stomata will detrimentally affect plant water balance and biomass growth. Ethylene antagonises the stomatal response to ABA, and early indications have been that the same is true of shoot growth (see Wilkinson & Davies 2010). Rhizobacteria containing high levels of ACC deaminase (e.g. Belimov et al. 2009) added to the soil can reverse the effects of ozone on the drought response of stomata

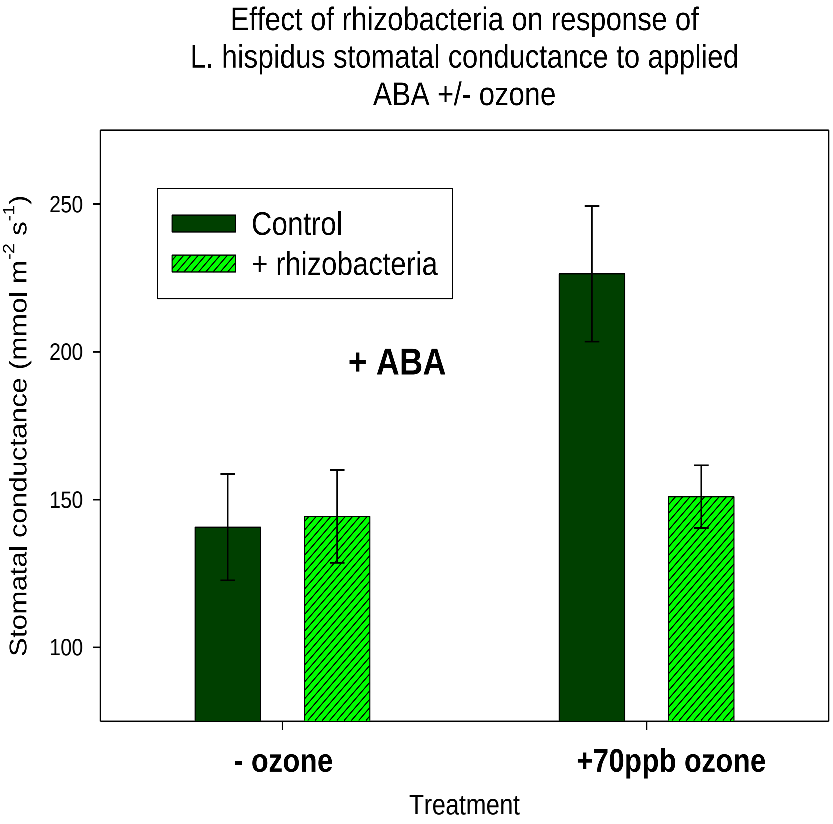


**Figure 5.8.** Rhizobacteria restore the effect of drought/ABA on stomatal behaviour in ozonated plants

## Conclusion

This rhizobacteria result suggests that improvements in the drought stress tolerance of a particular species to ozone could be implemented using field-viable treatments that reduce ethylene production, such as soil seeding with ACC-deaminase-producing rhizobacteria (Fig. 5,8) (see also Wilkinson & Hartung 2009).

## Objective 6

*Identify the relationship between stomatal closure and plant performance for representative HNS species and relate these to their temperature behaviour*

## Introduction

Much of the work to obtain basic information on the relationship between plant water status, growth and leaf temperature was done in the first three years. During the last year of the project we extended the study to include some more species. The work was done by establishing controlled irrigation trials and monitoring soil water status, stomatal conductance and plant temperature.

## Methods

In year 2, the experiment included three species (*Hydrangea macrophylla*, *Choisya ternata* and *Forsythia intermedia*) grown under three irrigation treatments (low, medium and high) for six weeks. Plant size (height and width) was measured at the start of the treatments, and then at regular intervals. Average pot moisture, leaf temperature (with a low-resolution IRISYS imager) and stomatal conductance were also monitored during the six weeks of the experiment, and the environmental conditions (air temperature, incident radiation, relative humidity and temperature of wet and dry filter papers) were recorded.

In the final year we have studied six species, *Viburnum tinus*, *Hebe ping*, *Berberis darwinii*, *Choisya ternata*, *Hydrangea macrophylla* and *Forsythia intermedia*, with up to 25 plants of each. Plants were grown in pots in an unheated greenhouse at the Scottish Crop Research Institute, Invergowrie, Dundee. Pots were initially divided into groups and given different amounts of irrigation to establish a range of soil moistures (irrigation treatments). This range was later maintained by adding the required amount of water to each pot depending on their soil moisture. Treatments lasted from end of June to early September, depending on species.

Soil moisture (2-3 readings per pot) was measured every other day with a Delta-T ML2 Theta Probe. Stomatal conductance (4 leaves per plant) was measured with a Delta-T AP4 porometer, and leaf temperature was extracted from 4 sub-samples of a single plant picture taken with a FLIR Systems thermal camera. Environmental conditions in the greenhouse (relative humidity, air temperature and incident light) were recorded with a Skye Minimet weather station. Wet and dry reference temperatures were obtained from thermal images of wet and dry green filter paper, taken at the same time as the plant image. Wet ($T_{wet}$) and dry ($T_{dry}$) references were used to calculate a Crop Water Stress Index (CWSI) thus:

$$\mathrm{CWSI} = \frac{T_{leaf} - T_{wet}}{T_{dry} - T_{wet}}$$

where $T_{leaf}$ is the recorded leaf temperature. Although some measurements of growth were made, the main objective of these experiments were primarily to investigate the relationships between thermal and porometric estimates of stomatal conductance (and hence ‘stress’).

Due to the quantitative nature of the main treatment factor (continuous variation in soil moisture), statistical analysis of the data was done in terms of correlation and regression.

## Results and Discussion

*Year 2*

The three irrigation treatments resulted in three significantly different levels of soil moisture in the pots for the three species, although there was considerable variation within any treatment. Measurements of stomatal conductance were also different according to irrigation treatment, with values ranging from around 300 mmol $m^{-2}$ $s^{-1}$ for the controls to less than 50 mmol $m^{-2}$ $s^{-1}$ in the most severe drought system, for both *Hydrangea* and *Forsythia*; conductances in *Choisya* were generally lower. Linear correlation between soil moisture and stomatal conductance was significant, but with a lot of dispersion in the data (Figure 6.1)

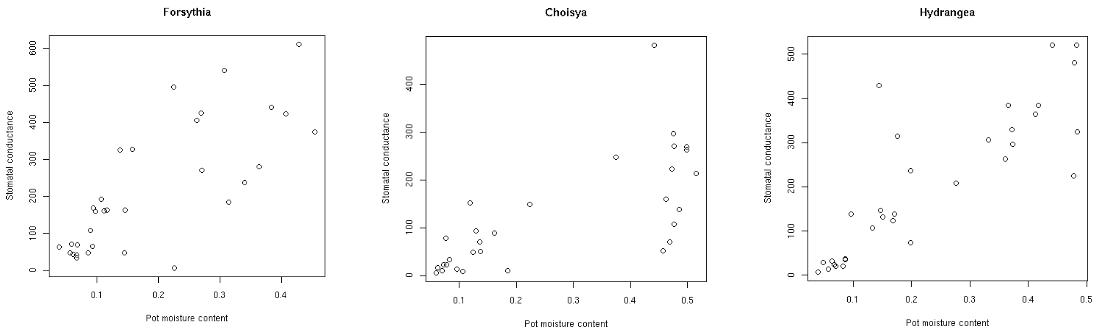


**Figure 6.1.** Relationship between stomatal conductance (mmol $m^{-2}$ $s^{-1}$) and pot volumetric moisture content (ml $ml^{-1}$) in the three species used in Year 2 experiment.

A temperature index ($T_i$) was calculated as:

$$T_i = \frac{T_{dry} - T_{leaf}}{T_{leaf} - T_{wet}} ;$$

This index is linearly related to stomatal conductance (Jones 1999). Linear correlations of $T_i$ with soil moisture or stomatal conductance were significant, but not very high (Table 6.1). The weakest relationships were found for *Forsythia* but this was probably a consequence of the way leaf temperatures were recorded: the plants were placed under a fixed camera, and with *Forsythia* having long shoots, the most actively transpiring leaves might have been out of the field of view of the camera.

**Table 6.1.** Linear correlation (adjusted $R^2$) between temperature index and either soil moisture or stomatal conductance.

| **Plant species** | **$T_i$ *vs.* soil moisture – $R^2$** | **$T_i$ *vs.* conductance – $R^2$** |
|---|---|---|
| *Forsythia intermedia* | 0.2553 | 0.3261 |
| *Choisya ternata* | 0.3805 | 0.5987 |
| *Hydrangea macrophylla* | 0.4944 | 0.5150 |

Plant growth was measured as an increase in cylindrical volume (estimated from maximum diameter and height) in *Hydrangea* and *Choisya*, and as approximate total length of shoots in *Forsythia*, due to the tendency of the latter to grow a few long shoots. Differences between treatments were significant, with the most severe drought treatment stunting growth in all species. However, the growth of some plants in the control treatment seems to have been affected by too much water, particularly in *Choisya* (Figure 6.2). This probably explains the lower readings seen for stomatal conductance in *Choisya* compared to the other species.

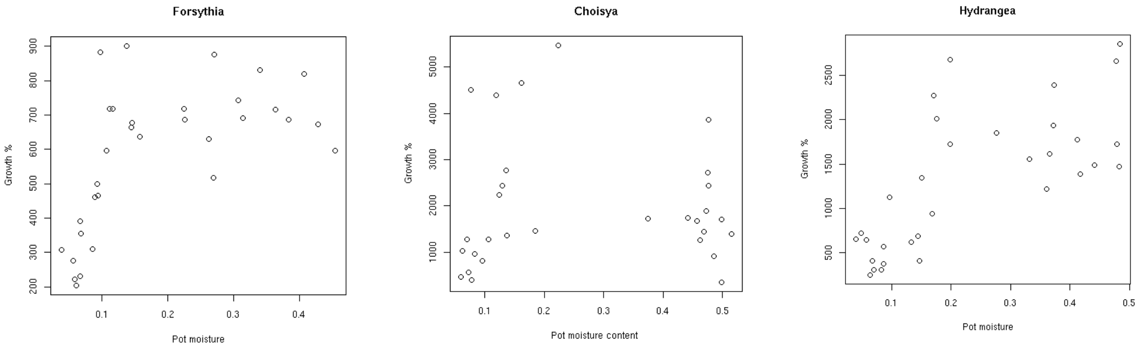
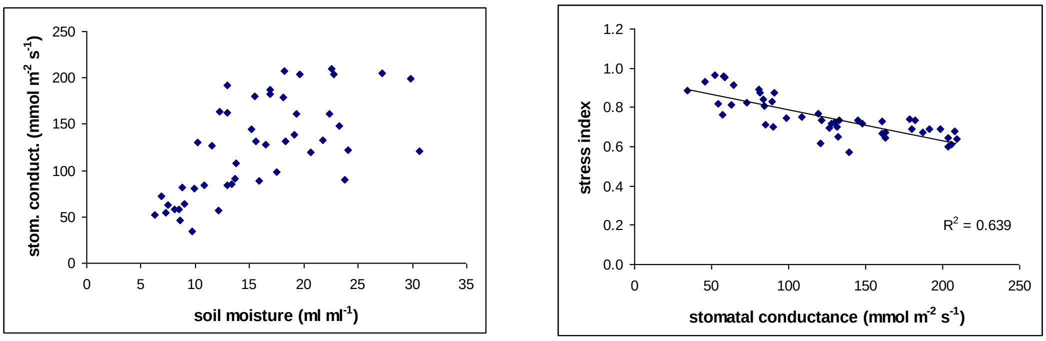


**Figure 6.2.** Percentage growth against pot volumetric water content (ml ml$^{-1}$).

*Year 4*

*Viburnum tinus*

Volumetric water content in the pots ranged from 5 to 35 ml ml$^{-1}$, with stomatal conductance increasing with increasing soil moisture, at least up to 20% moisture (figure 6.3a). Leaf temperature increased at lower soil moistures, particularly below 25%, but the correlation was not very high (data not shown). The stress index (calculated as described in the Materials and Methods section) gave a better linear correlation with stomatal conductance than the raw leaf temperatures (figure 6.3b).



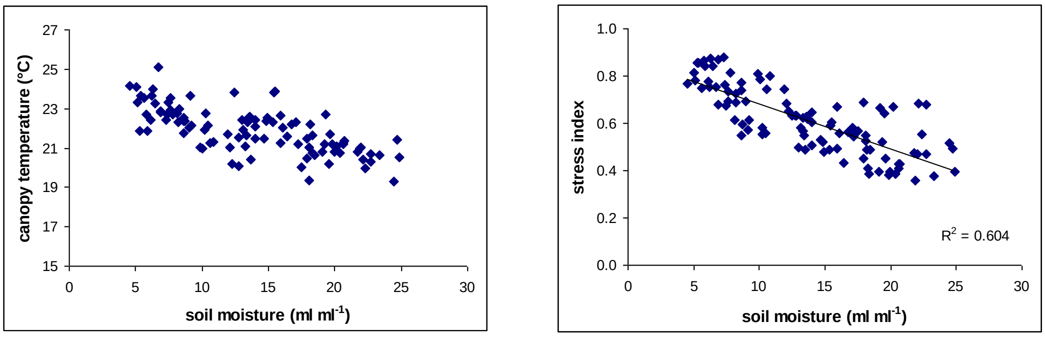
a) b)

**Figure 6.3.** Relationship between a) stomatal conductance and soil moisture, and b) stress index and stomatal conductance in *Viburnum*; based on data collected over two days (08, 15 July).

*Hebe ping* var. 'Sutherlandii'

Due to the small size of the leaves in this species, it was very difficult to measure stomatal conductance in a consistent and meaningful way, and after several attempts it was decided not to record these data.

Volumetric water content in the pots ranged from 5 to 25 ml ml$^{-1}$, and a good linear correlation was found between canopy temperature / stress index and soil moisture (figure 6.4), even though there was considerable variation from day to day.



a) b)

**Figure 6.4** Relationship between a) plant temperature and soil moisture, and b) stress index and soil moisture in *Hebe*; based on four days (06, 07, 08, 16 July) data.

Hebe was particularly suited to thermal imaging, with differences in temperature being easily detected (figure 6.5).

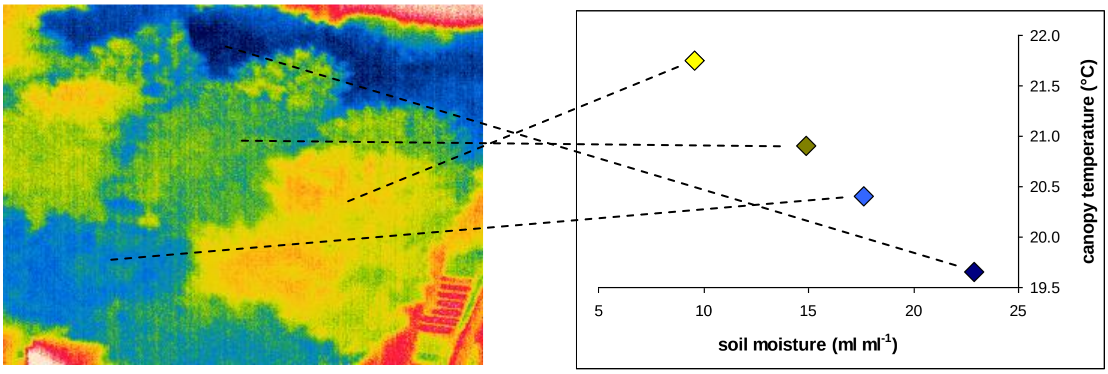


**Figure 6.5.** Thermal image, temperature and soil moisture in some *Hebe* plants (02 September).

*Berberis darwinii*

The range of soil moistures in the pots was similar to the previous two species (from 5 to 30 ml ml$^{-1}$). Stomatal conductances were only measured in the first few days, and were found to be always below 100 mmol m$^{-2}$ s$^{-1}$, with averages around 45 mmol m$^{-2}$ s$^{-1}$. This range was considered to be too small to detect differences in leaf temperature. Indeed, on many days the relationships between conductance, temperature / stress index and soil moisture were not significant (data not shown).

The plants were hot, with high values of the stress index at all levels of soil moisture (CWSI usually above 0.75). This agrees with the low conductances measured, even though the plants did not look stressed and seemed to be growing well. Probably the thick coriaceous leaves with thorns of this species are an adaptation to drought. Figure 6.6 shows the relationship between stress index and soil moisture for two different days. Compared to the top line, the bottom line corresponds to a day with more light, higher air temperature and lower relative humidity, i.e. higher evaporative demand. The plants were probably transpiring more on that day, resulting in cooler leaves and lower stress indices.

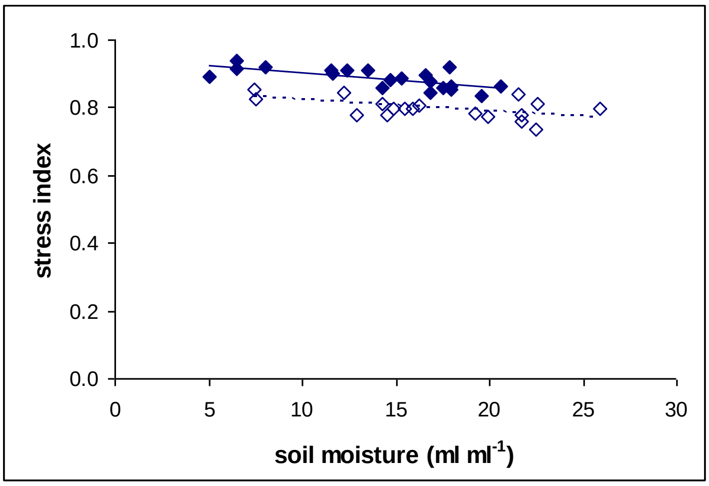


**Figure 6.6.** Relationship between stress index and soil moisture in *Berberis*; data for two different days (14, 16 July).

*Forsythia intermedia*

The range of soil moisture in these plants was larger than in the other species (from 6 to 38 ml ml$^{-1}$), but only a few plants were below 12 ml ml$^{-1}$; (with bigger pots it was more difficult to control the water levels). Stomatal conductance showed a good response to soil moisture, and high values of conductance (almost 600 mmol m$^{-2}$ s$^{-1}$) were recorded. However, there was considerable variation within plant: between main branches and side branches, and between older and newer leaves. Only the plants with the lowest soil moistures (below 12 ml ml$^{-1}$) had stomatal conductances below 150 mmol m$^{-2}$ s$^{-1}$ and stress index values higher than 0.63 (figure 6.7).

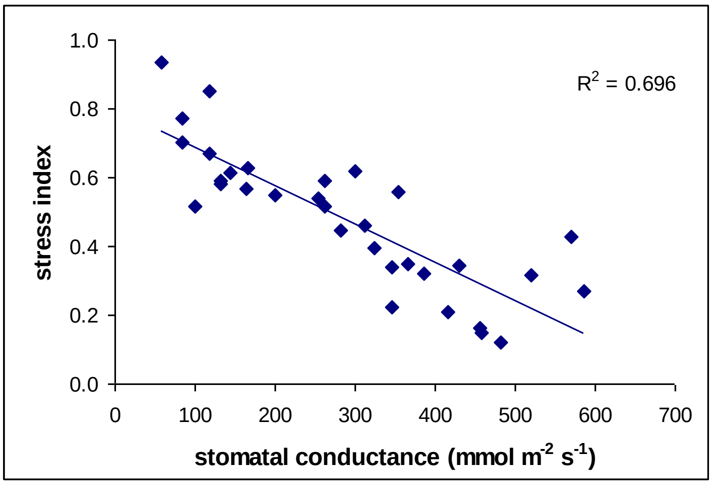


**Figure 6.7.** Relationship between stress index and stomatal conductance in Forsythia; based on three days (02, 03, 04 September) data.

### *Choisya ternata*

Soil moistures in these plants were again in the range of 7 to 35 ml ml$^{-1}$, but stomatal conductances were always very low (under 80 mmol m$^{-2}$ s$^{-1}$, with averages around 35 mmol m$^{-2}$ s$^{-1}$). No clear trends were found between soil moisture and stomatal conductance, but plants in pots with higher water contents (over 25 ml ml$^{-1}$) tended to have lower conductances. The highest values of stomatal conductance were found at around 15 ml ml$^{-1}$. A few plants might have been suffering from over-watering (they looked wilted and yellow), and this could have resulted in stomatal closure. However, even the healthy-looking plants did not seem to be actively growing. This might be a feature of this species, which grows in phases, particularly after having been in the greenhouse for some time.

### *Hydrangea macrophylla*

These plants grew very fast in the greenhouse, and by the time the measurements were taken they seemed to have reached a more mature, non-growing state. Stomatal conductances were found to be quite low (mostly below 100 mmol m$^{-2}$ s$^{-1}$), regardless of soil water content. No reliable data were obtained.

## Conclusions

Whilst severe drought treatments reduced growth in all species, it was difficult to define a threshold level where this might be of economic importance, mostly due to the large variation in the data. This was in part related with the difficulty of measuring growth in a non-destructive manner.

In general there were clear differences between irrigation treatments in both stomatal conductance and plant temperature, The response of thermal (CWSI) or stomatal conductance measurements to varying soil water was smaller in some species (e.g. Berberis) than in others (e.g. Forsythia).

In those trials where soil moisture content resulted in a wide range of stomatal conductances, differences in plant temperature were successfully detected by both the low-resolution IRISYS imager and the higher-resolution FLIR camera.

The two variants of the stress index used in these experiments were better related to both soil moisture and to stomatal conductance than were the raw measurements of temperature (because of environmental variation). However, even though the stress index is supposed to account for variations in environmental conditions, considerable day-to-day differences were still found.

*Hebe ping* var. 'Sutherlandii' was found to be particularly suited to the use of thermal imaging to monitor plant water status and automate irrigation. Other promising species are *Viburnum tinus*, *Hydrangea macrophylla* and *Forsythia intermedia*.

No responses to water levels in terms of stomatal conductance or canopy temperature were found in *Berberis darwinii*. It might be that this species adapts to water stress by other means, in which case it would not be suited to thermal monitoring.

All the experiments were somewhat confounded by the fact that plants responded to any irrigation mismanagement (e.g. over irrigation) by showing stomatal closure, so that even the well-watered plants sometimes had conductances less than 100 mmol $m^{-2}$ $s^{-1}$. *Choisya ternata* seemed to be particularly sensitive to over-watering, which may lead to stomatal closure. If automated irrigation based on thermal imaging was to be applied to this species, a more detailed understanding of the adequate water levels (upper and lower limits) would be required.

The growth stage of the plants seems to be quite important in terms of their stomatal response to water stress, with differences in conductance (and hence leaf temperature) best detected with smaller, more actively growing plants.

## 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

Work at Dundee University has focussed on developing software and algorithms to extract plant temperature from thermal images or from point thermal sensors (as adopted in preference to imagers) later in the project. After a review of previous work on the use of thermal imaging for scheduling irrigation, a two-camera system was developed in the first two years, designed to acquire three images (visible, NIR, and thermal) necessary to distinguish plant material from background. This two camera system was particularly useful for calibration purposes, but was considered likely to be too expensive for a production system. Therefore we later switched our approach to using point sensors, to make the system more portable and affordable.

### Materials and Methods

*Two-camera system*

In a thermal image, it is difficult to distinguish plant material from the background. We have borrowed a technique from remote sensing which uses Vegetation Indices (VIs), and in particular the Normalised Difference Vegetation Index (NDVI), to estimate plant cover. This is based on the fact that green vegetation has a much higher reflectance in the near infrared (NIR) than in the red (R) wavelength bands.

We devised, constructed and tested a test-bed that allowed us to overlay images from a thermal camera and a visible/NIR camera using a moveable mirror as a beam splitter. The system is illustrated in figure 7.1. The standard digital camera image was enhanced by obtaining an image in the red wavebands and one in the NIR using a movable IR filter. The system was tested using two different thermal imagers: an IRISYS 1002 multipoint radiometer (16x16 pixel resolution), and a FLIR P25 Thermacam (resolution 320x240 pixel). The visible light camera used was a 640x480 resolution Fire-I webcam from Unibrain. Because of the different resolutions, to match information from the two cameras it was necessary to resample the thermal images to the same resolution as the visible/NIR image.

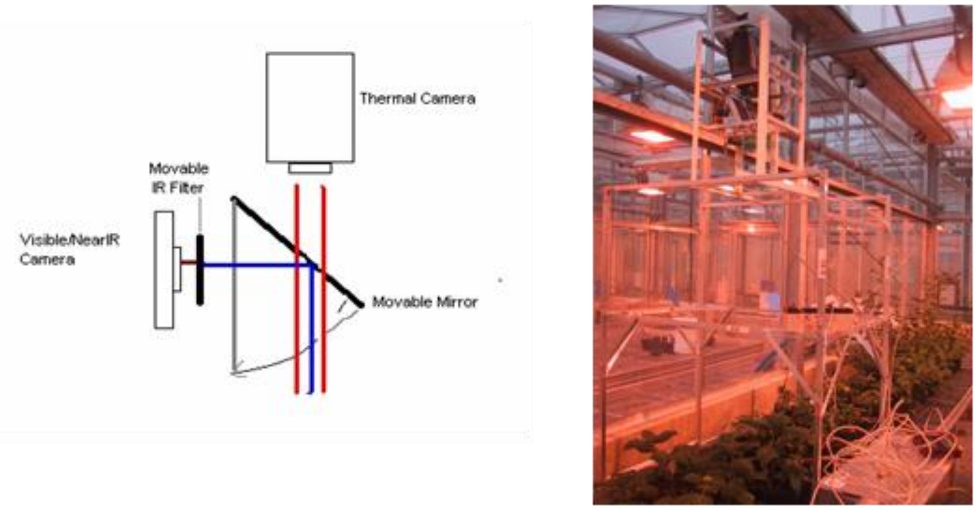


**Figure 7.1**. Diagrammatic and actual image of the beam splitting device trialled in the first year.

We also devised a simple, easy to use computer control interface that allows one to collect the necessary visible, near-IR and thermal images semi-automatically and to automate the necessary image manipulation. Some improvements were made to the system at a later stage, by incorporating environmental sensors to record reference surface temperatures.

*Linear array of thermal sensors*

To complement the approach adopted by PERA of using a mobile array of point thermal sensors instead of a thermal camera, we produced a test system to evaluate the concept. This mobile scanner uses an array of simple thermal sensors (spot sensors - sometimes called infrared thermocouples) for generating an image through movement. It consists of a set of five Calex thermal sensors arranged to generate a swath of 30°×6° (figure 7.2).

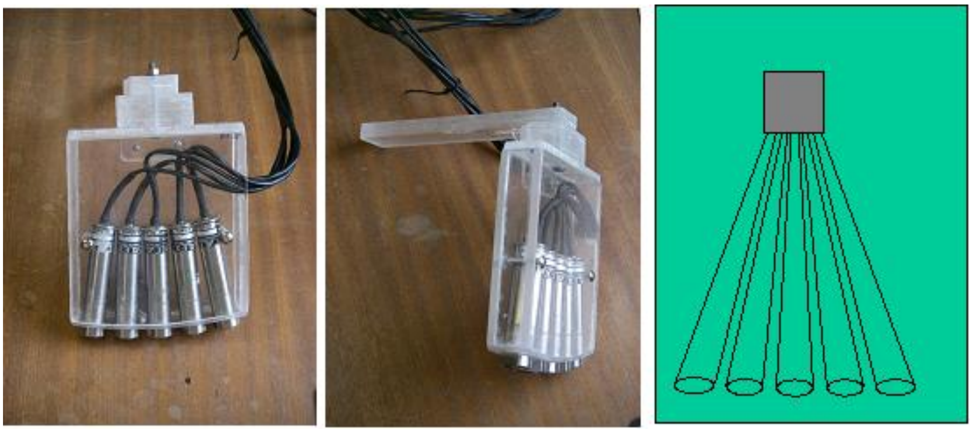


**Figure 7.2.** Arrangement of the mobile thermal scanner for generation of a 30°×6° ‘image’ which can then be used to generate a full temperature image as it moves over the crop.

We tested the approach by wheeling the thermal scanner at a steady rate over an area of grass and soil and thereby generating a thermal 'image' of the whole canopy. The images were then compared with a 'stitched' series of thermal images and a 'stitched' series of visible images of the same view.

*Plant / No-plant sensors*

Although the original two-camera system was successful at identifying plant and non-plant pixels, it was not felt to be suitable for handheld monitoring or for mounting on a gantry. Therefore, we looked at alternative approaches.

The first approach was to use a commercial NDVI sensor to match the array of five Calex thermal sensors. The Crop Circle™ (Holland Scientific, Soil Essentials, Brechin, UK) is an 'active' green leaf area sensor that covers an area of 30°×6°. This gives a single NDVI value for all the five thermal readings of our temperature scanner.

To obtain canopy density data at a higher resolution than the Crop Circle™, the next step was to use two low-cost web-cams. This two-camera NDVI sensor uses the same principle as described before, but the moving mirror is now replaced by a fixed half-silvered acrylic mirror. One camera is fitted with a filter to block NIR radiation (>700 nm), and the other with a filter to block visible radiation. Combined with the thermal scanner, this provides an NDVI pixel map over the viewing area of the Calex sensors. Figure 7.3 shows the construction of the NDVI sensor and the combined handheld temperature / NDVI sensor being used.

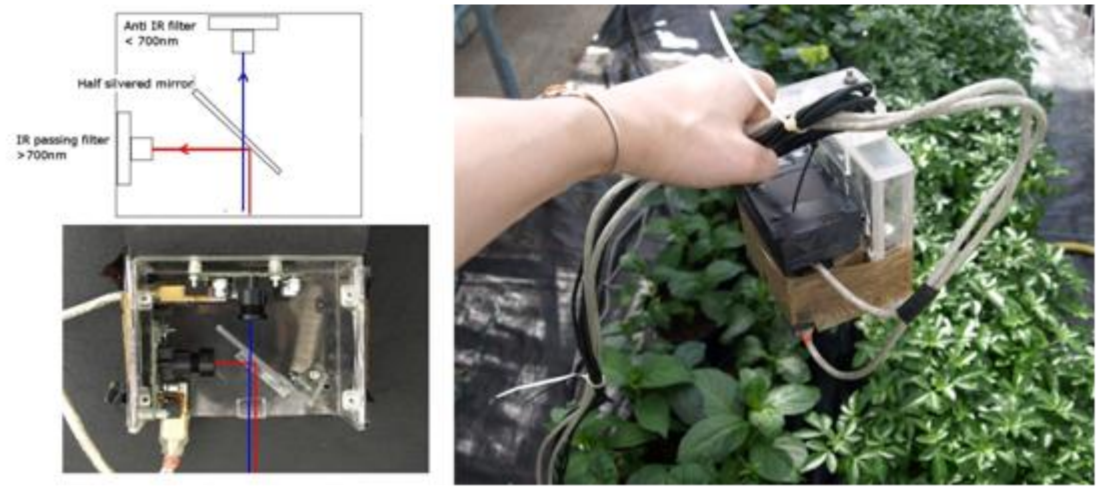


**Figure 7.3.** Left - Twin webcam NDVI sensor construction. Right - Handheld scanner NDVI sensor combined with Calex temperature sensor.

The final approach, which we propose should be used in a production system (gantry), is to use a pair of Red and NIR sensors associated with each thermal sensor. This would provide NDVI data at the same resolution as the thermal data. We investigated the sensitivity of this method using a single set of three sensors: a Calex Convir IRT, and two single channel light sensors (red: 650 nm, and NIR: 800 nm) supplied by Skye Instruments (figure 7.4). Most of the work with these sensors was done in the final two years, and the work of the final year is described in more detail below.

**Figure 7.4.** Left - Three sensor cluster with thermal sensor (8-14 μm), red (650 nm) and NIR (800 nm) sensors. Right - Experimental setup**.**

*Year 4*

Work at Dundee University concentrated during this last year on developing and refining methods for quantification of plant cover in the sensor field of view. The principle remains that of using vegetation indices (VIs), which are based on the fact that green vegetation has a much higher reflectance in the near infrared (NIR) than in the red (R) wavelength bands. We evaluated the suitability of different vegetation indices to estimate percentage of plant cover.

Previously we had developed a system of two cameras (red and infrared) to estimate canopy cover using this principle, and later we investigated the use of two collimated light sensors to do the same job (i.e. the three-sensor system comprising Skye sensors -650 nm and 800 nm- and a Calex infrared sensor). In addition we also did some tests on a cheaper alternative system developed by PERA that might be more suitable for a production system. To this end, PERA provided a prototype three-sensor unit for potential incorporation on the gantry, and we spent some time developing a method to calibrate this sensor.

### Comparison of different vegetation indices

We used the high-resolution two-camera system, which directly estimates the fraction of plant in the defined focal area, to calibrate the results from the Skye R/NIR sensors. To that end, it was important to align the sensors with the camera, so that the two systems were pointing at exactly the same area.

We investigated the relationship between different VIs and the percentage of plant visible by taking simultaneous readings from the two systems when looking at different proportions of plant and background. In general we tested the systems using the end-point conditions 0% (no plant – i.e. all background) to 100% plant cover. Several backgrounds commonly found in glasshouses were studied: black plastic matting, concrete, dry compost and wet compost.

Following some initial analyses, were selected the following VIs for further work:

$$\text{NDVI} = \frac{R_{NIR} - R_{VIS}}{R_{NIR} + R_{VIS}}$$

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

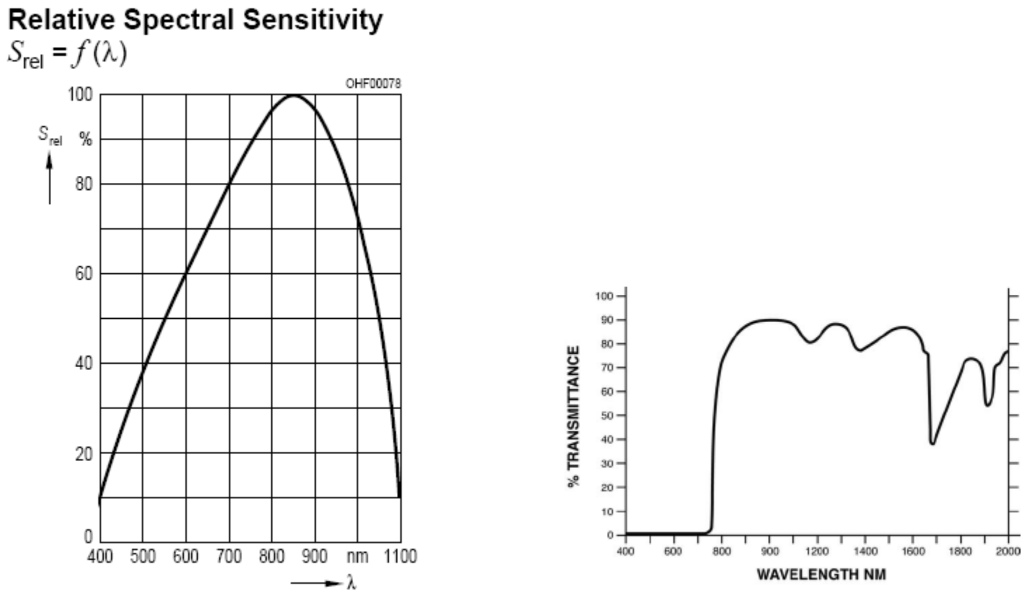
$$\text{DVI}^* = \frac{(R_{NIR} - R_{VIS}) - (R_{NIR} - R_{VIS})_{min}}{(R_{NIR} - R_{VIS})_{max} - (R_{NIR} - R_{VIS})_{min}}$$

$$\text{DVI} = (R_{NIR} - R_{VIS})$$

where $R_{NIR}$ is the near infrared reflectance, $R_{VIS}$ the red reflectance, L is an adjustable parameter between 0 and 1, and $_{min}$ and $_{max}$ refer to the minimum and maximum difference values respectively (used to normalize the data). Theoretically DVI is linearly related to percentage plant.

Calibration of the Pera ‘plant/no-plant’ sensors

The Pera prototype consisted of a light sensor sensitive to visible and near-infrared light ("total light"; figure 7.5a) and the same sensor fitted with a filter to remove the visible light ("filtered light"; figure 7.5b). In theory, the red light could be calculated from the difference between these two. But the two sensors are not scaled the same (figure 7.6). So we need a factor that makes them comparable in terms of R and NIR radiation. We used the narrow bandwidth Skye sensors to calibrate the Pera sensors.



a) b)

**Figure 7.5.** Characteristics of light sensors in Pera prototype. a) "total light" sensor sensitivity; b) transmittance of filter in the "filtered light" sensor.

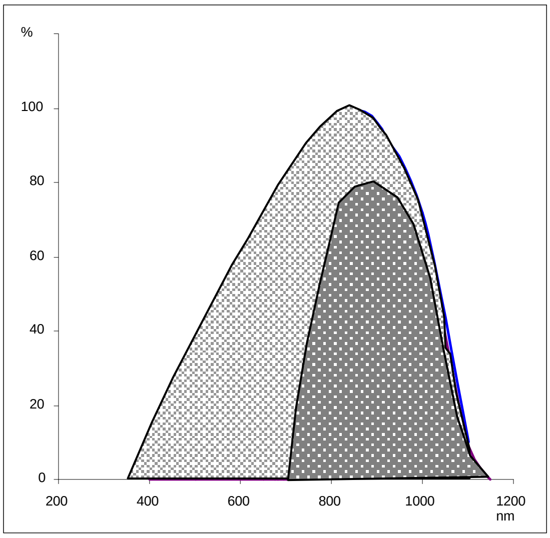


**Figure 7.6.** Combined sensitivity of the two Pera light sensors.

Again, simultaneous readings with Skye and Pera sensors were taken for either no (0%) plant cover or full (100%) plant cover, with different backgrounds and plant species. From this we calculated a correction factor (F) that scales down the "total" reading to the level of the "filtered" reading, so that the red light can be calculated by subtraction.

To calculate reflectances we need to take into account the incident light, which is measured with the two-channel upright-pointing Skye sensor. Again, this has a different sensitivity than the Pera sensors, so another correction factor is needed.

*Derivation of an algorithm to calculate plant temperature*

After several attempts to calibrate the Pera sensors it was obvious that the readings obtained were not stable enough to calculate a meaningful correction factor, even under relatively constant light conditions. Therefore, it was decided to use the Skye sensors for the derivation of an algorithm to calculate plant temperature, and for demonstration purposes.

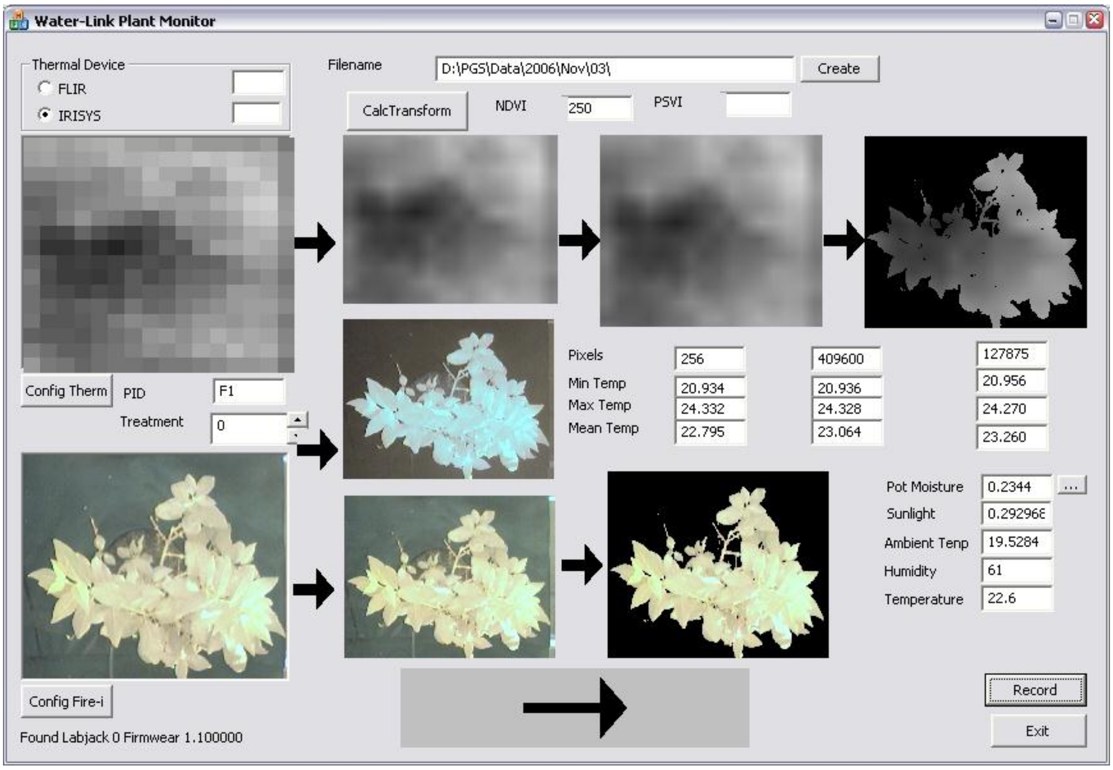
The final system used consisted of two downward-pointing Skye sensors, (650 and 800 nm), together with a two-channel upward-pointing Skye sensor (648 and 802 nm), plus a Calex infrared sensor. These gave readings of reflected light and incident light in the Red and NIR wavelengths, and temperature of the viewed area.

To test the algorithm we obtained data under several light conditions and with different backgrounds (black plastic matting, concrete, dry compost and wet compost).

## Results and Discussion

*Two-camera system*

A screen-shot of the original interface for the first two-camera system is shown in figure 7.7. The left-hand column of images shows at the top the original (real-time) thermal image from the IRISYS camera, and the bottom image shows either the visible or near-IR image (depending on the position of the filter). The second column of images shows (from the top) the resampled thermal image, the near-IR image and the visible image. The next column shows the thresholded NDVI image which is then used to isolate the leaf from the thermal image, as indicated in the rightmost image. The NDVI system can be seen to be working very well for identifying plant material from background. In these images the pots were standing on black sheeting similar to that used in many nurseries for surfacing plant beds.



Thermal Device
○ FLIR
● IRISYS

Filename D:\PGS\Data\2006\Nov\03\

NDVI 250

PSVI

PID F1

Treatment 0

| | | | |
|---|---|---|---|
| Pixels | 256 | 409600 | 127875 |
| Min Temp | 20.934 | 20.936 | 20.956 |
| Max Temp | 24.332 | 24.328 | 24.270 |
| Mean Temp | 22.795 | 23.064 | 23.260 |

Pot Moisture 0.2344

Sunlight 0.292968

Ambient Tenp 19.5284

Humidity 61

Temperature 22.6

Found Labjack 0 Firmwear 1.100000

**Figure 7.7.** Screenshot from the computer controlling image acquisition and analysis, showing the various stages from the raw images on the left to the final image of the leaf temperatures on the right. A full explanation of this image is given in the text.

A further development allowed us to specify within the software up to six preset areas within the field of view; two were used for the reference surfaces, and the other four for separate plant areas, either from the same or different plants (figure 7.8).

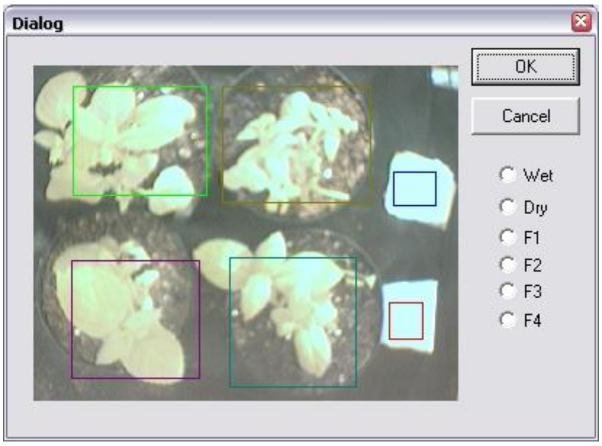


**Figure 7.8.** Screen view showing four areas from which the software extracts leaf temperatures, and two areas from which it extracts reference surface temperatures. Note that the software uses the red and near infrared images to identify and ignore areas within the defined areas.

*Linear array of thermal sensors*

Despite the very low effective spatial resolution of our thermal sensor, the images corresponded very well with independent high resolution visible and thermal images of the same area (figure 7.9).

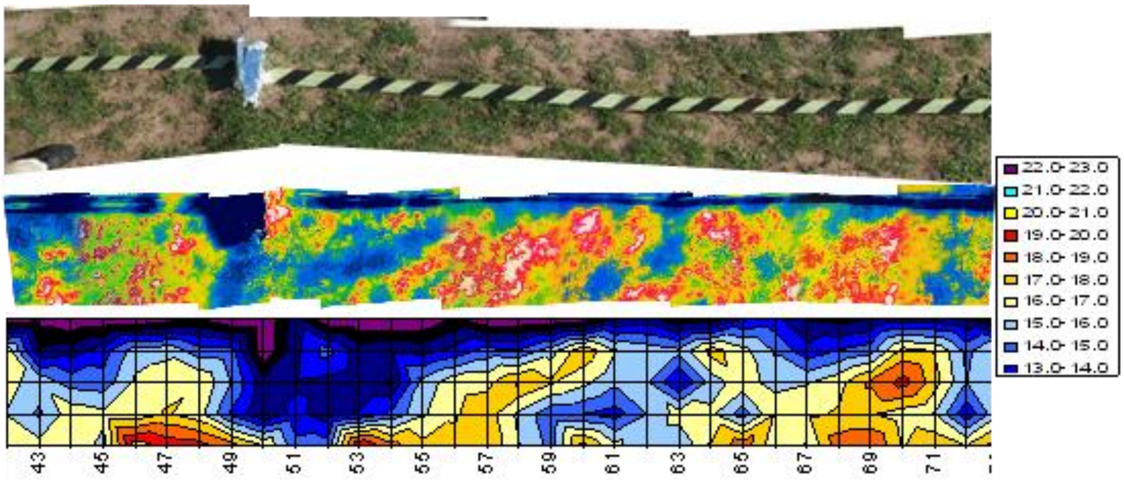


**Figure 7.9.** Typical example showing a comparison of a stitched visible image (top), a stitched thermal image (middle) and a thermal image synthesised from individual spot temperature readings.

*Plant / No-plant sensors*

Calex/Crop Circle system.

Figure 7.10 shows the combined Calex IRT array / Crop Circle™ configuration, together with some results obtained with this system. Despite the low resolution, the main features of the plant canopy were captured well. The breaks in the canopy are apparent as drops in the percentage 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; only to obtain and correct and average temperature reading across the whole field of view.

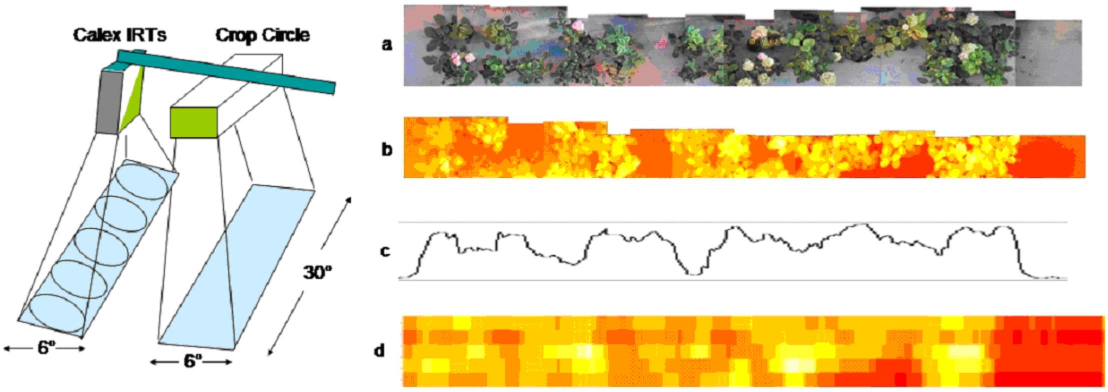


**Figure 7.10.** Left - Combined thermal / Crop Circle™ sensor. Right - a) visible radiation stitched images from camera; b) thermal radiation stitched images from thermal camera; c) Crop Circle™ scan percentage leaf area reading; d) Calex IRT thermal scan.

### Web-cam sensor.

The NDVI sensor based on two web-cams was found to be very precise, but rather sensitive to the incident radiation (data not shown). It was retained only to collect accurate data for calibration of the Red/NIR sensor pairs.

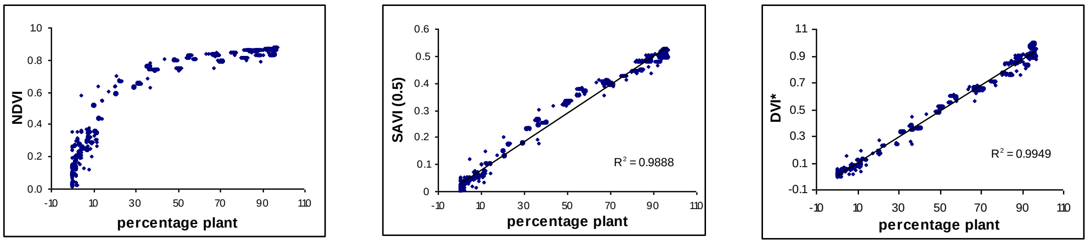
### Red/NIR sensors.

Further data obtained with the Skye sensors confirmed that to allow for environmental variation and to calculate a Crop Water Stress Index a set of additional sensors (e.g. dry and wet reference temperatures) would be beneficial. A measure of the incident radiation is required to calculate reflectances (and hence NDVI); this can be done by using a two-channel light sensor (e.g. Skye SKR1800) which could be mounted on the boom.

## *Year 4*

### Comparison of different vegetation indices

Figure 7.11 shows the relationship between the percentage of plant in the target area, as calculated by the two-camera system, and the vegetation indices calculated from the Skye light sensors data. This calibration was done with a black plastic background and artificial lighting. NDVI doesn't give good discrimination at low (below 15%) or high (over 60%) plant coverage. But SAVI and DVI* were much better at all levels of canopy cover, with linear relations explaining over 98% of the variation.



a) b) c)

**Figure 7.11.** Relationship between different VIs calculated with data from the light sensors and percentage plant calculated from the camera. a) NDVI; b) SAVI with L=0.5; c) normalised DVI.

The relationships were similar when using dry compost as a background (and artificial lighting), although there was more dispersion of points around the fitted line, with $R^2$ values of around 92%. However, calibrations done using natural light gave very poor relationships between the two systems (camera and sensors), particularly when using compost (whether dry or wet) as the background. This was attributed to the high content of organic matter (peat) in the compost, which reflects light in a similar way as green vegetation (data not shown).

Calibration of the Pera light sensors

The readings obtained by the Pera sensors are radiances for total light (Tot) and NIR (N), and the values for Red (R) light can be obtained by subtraction (total *minus* NIR) once the two sensors have been converted to the same scale. To do that, we can calibrate the Pera sensors relative to the Skye sensors by using simultaneous data. We assume that the relative values of N to R are the same for both types of sensor; that is:

$$\frac{N_{Skye}}{R_{Skye}} = \frac{N_{Pera}}{(Tot_{Pera} * F) - N_{pera}}$$

This can be rearranged to give:

$$F = \{[N_{Pera} / (N_{Skye} / R_{Skye})] + N_{Pera}\} / Tot_{Pera}$$

Once $F$ is known, $R_{Pera}$ can be calculated as: $R_{Pera} = Tot_{Pera} * F - N_{Pera}$

To calculate any VI we need reflectances rather than radiances; this corrects for any changes in the incoming light. Reflectances for each wavelength are calculated as the ratio between reflected and incident light. Again we need to take into account the different sensitivities of the sensors and calculate correction factors (CF):

$$\rho_N = \frac{N_{Pera} * CF_N}{N_{incident}} \quad \text{and} \quad \rho_R = \frac{R_{Pera} * CF_R}{R_{incident}}$$

For that we used white paper, which has a reflectance (ρ) of 0.95 in both R and N wavelengths. Therefore:

$$CF_N = \frac{N_{incident} * 0.95}{N_{Pera}} \quad \text{and} \quad CF_R = \frac{R_{incident} * 0.95}{R_{Pera}}$$

From a series of simultaneous readings with the two systems using different backgrounds and plant species, as well as white paper for the calculation of reflectances, we derived the theoretical relationship between NDVI values and percentage of plant. Figure 7.12 shows an example of such relationship.

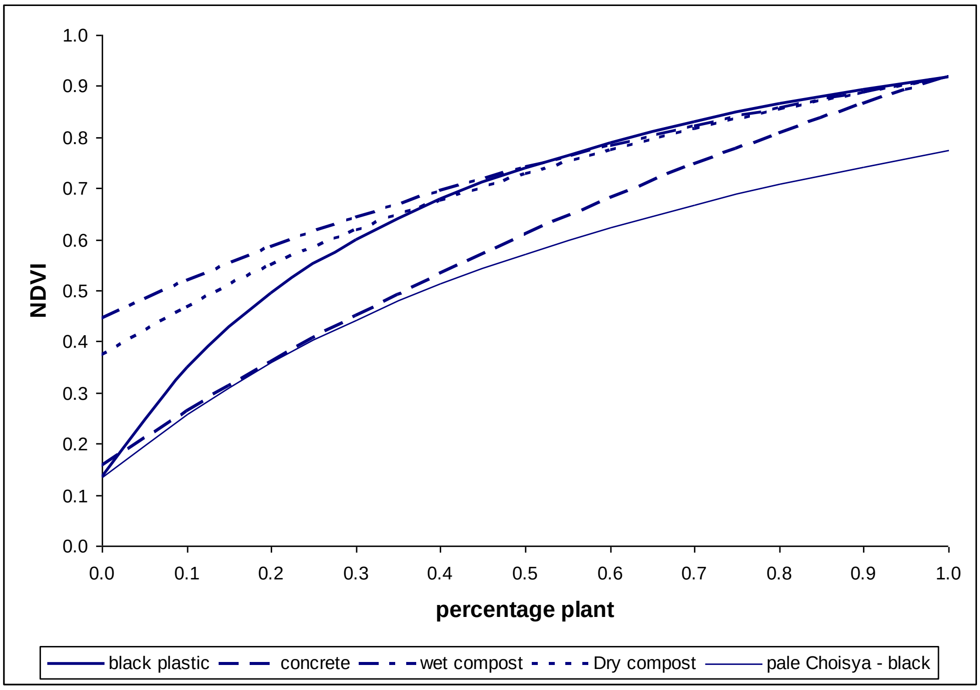


**Figure 7.12.** Relationship between NDVI and percentage plant for Hydrangea plants against different backgrounds, and for a pale Choisya plant against black plastic background. Data taken on a sunny day (21 May).

*Derivation of an algorithm to calculate percentage plant and plant temperature*

Because DVI is proportional to percentage plant, we choose this as the simplest VI to estimate percentage plant in the viewed area. However, in the algorithm DVI is normalised for the actual range of DVIs observed. Therefore, we need to know the DVI of the background (0% plant) as well as the DVI of the plant material (100% plant) to set the lower and upper limits.

Because of the different reflective properties of different backgrounds, the DVI at zero plant, and hence the calibration, will be different. Figure 7.13 shows such an example. Reflectances in the different wavelengths also change with the quality and intensity of the incident light, particularly between bright sun light and the artificial light used in greenhouses to supplement natural light. An extreme example of this effect can be seen in figure 7.14.

However, given a particular set of conditions, the agreement between the values of percentage plant calculated from the DVI calibration data and those obtained directly from the sensors was quite good (figure 7.15). (Percentage plant cover in this case was independently measured from analysis of visible images.)

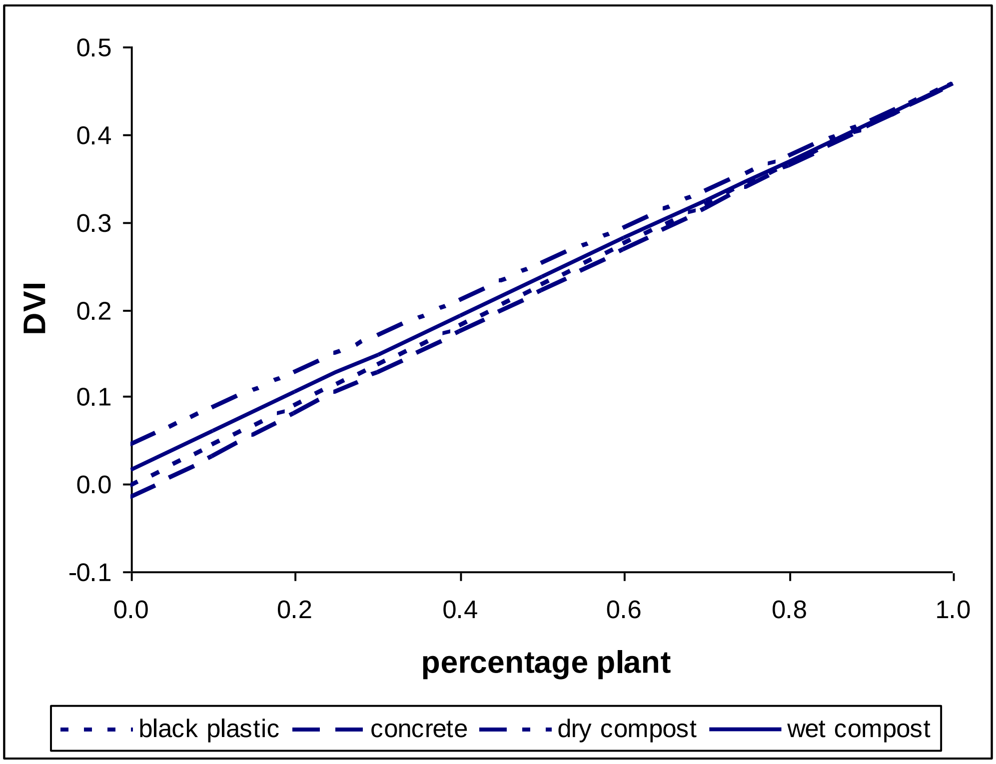


**Figure 7.13.** Relationship between DVI and percentage plant for Hydrangea leaves against different backgrounds. Data taken on a cloudy day (24 August).

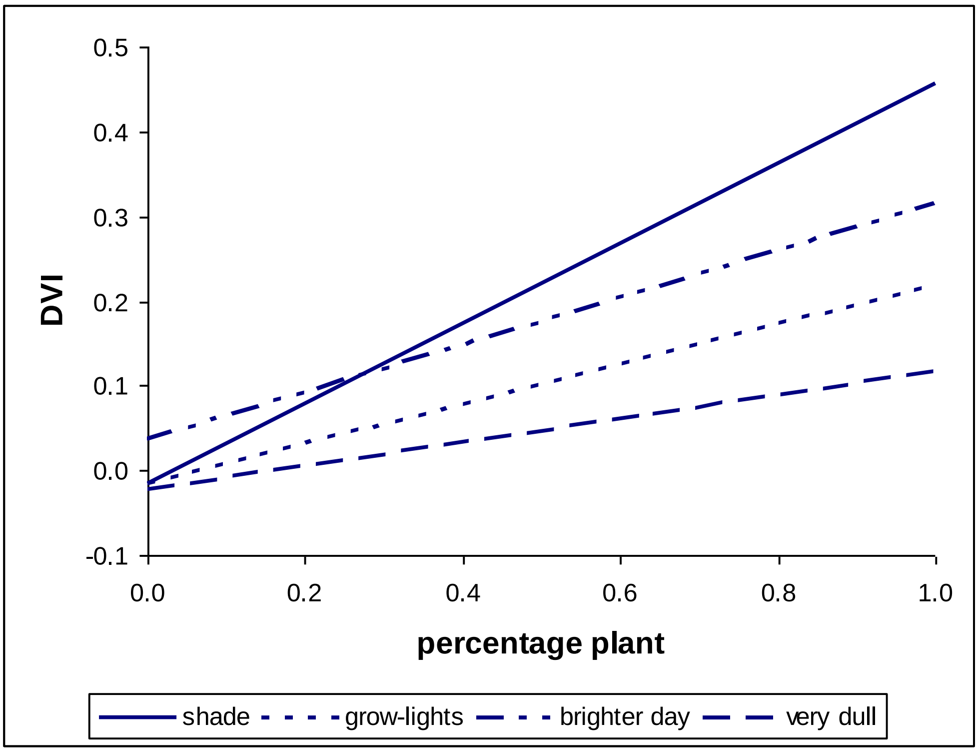


**Figure 7.14.** Relationship between DVI and percentage plant for Hydrangea leaves on a concrete background with different light conditions (24, 20, 25, 21 August respectively).

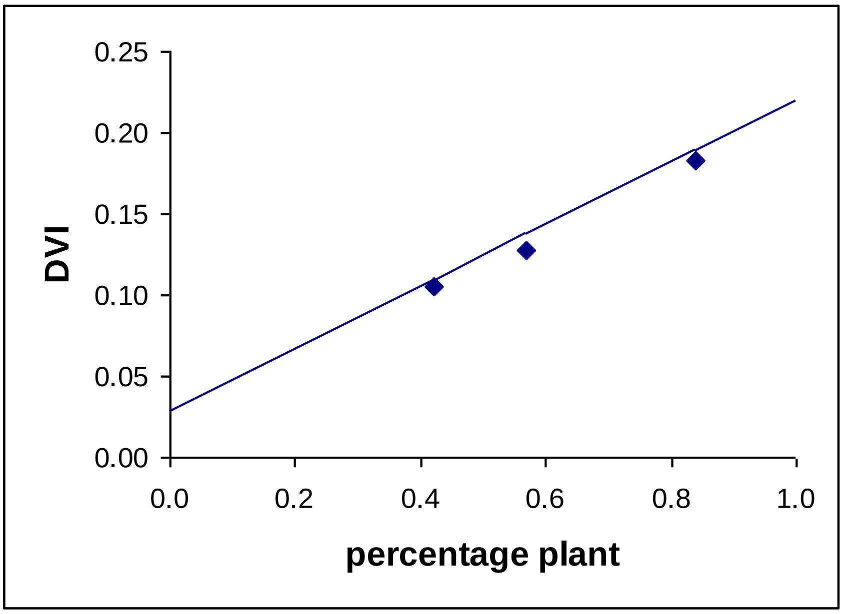


**Figure 7.15.** Measured DVIs for known levels of plant cover (points) and DVI calibration for a dry compost background (line).

Although calibrating for the prevalent conditions will give the best estimates of plant cover, some default values were obtained by simplifying the results from several calibrations. These are given in table 7.1.

**Table 7.1.** Lower (DVI zero) and upper (DVI 100) limits of DVI for different backgrounds and light conditions**.**

| **DVI zero** | natural (bright) light | artificial or low light |
|---|---|---|
| black plastic | 0.00 | -0.01 |
| concrete | 0.04 | -0.02 |
| dry compost | 0.06 | 0.03 |
| wet compost | 0.05 | 0.02 |
| **DVI 100** | 0.37 | 0.20 |

If not all the target area is plant, the temperature measured by the sensor ($T_{obs}$) will be an average of plant temperature ($T_{plant}$) and background temperature ($T_{back}$):

$$T_{obs} = T_{plant} * N_{plant} + T_{back} * (1 - N_{plant})$$

where $N_{plant}$ is percentage plant. Therefore, to calculate plant temperature we need to know the temperature of the background. This can be measured at the start of the run. We also need the temperature of a fully-transpiring plant as a reference ($T_{wet}$), so that plants which are 'too hot' (i.e. water-stressed) can be detected. In practice, this is done by measuring the temperature of a plant sprayed with water. The theoretical plant temperature ($T_{theo}$) is then calculated as:

$$T_{theo} = T_{wet} + (T_{back} - T_{wet}) * (1 - N_{plant})$$

We tested the system and the algorithms at Hilliers nurseries by mounting the sensors on the irrigation gantry and running them over a line of plants of different species, with some spacing between them (figure 7.16). Figure 7.17 shows the DVI calculated from the sensor data. The seven plants are clearly identified against the background, in spite of their different leaf colours (dark and pale green, red, etc).

**Figure 7.16.** Plants tested a Hilliers.

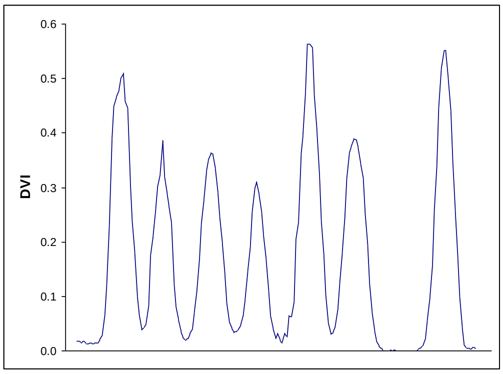


**Figure 7.17.** Time-sequence of calculated DVIs when running the sensors over the plants in figure 7.16.

Percentage plant (from DVI), observed temperatures (from thermal sensor) and calculated (theoretical) plant temperature for the above setup have been plotted in figure 7.18. When the percentage plant is close to 100%, the recorded temperature is closer to that of the plant, whereas when the view area of the sensor is mostly over background (percentage plant close to zero), the recorded temperature is close to that of the background. Our algorithm (used in the plant temperature calculation shown in figure 7.18 takes temperature data and %plant data and calculates the temperature of the plant only. It is clear that some plants have a higher temperature than others.

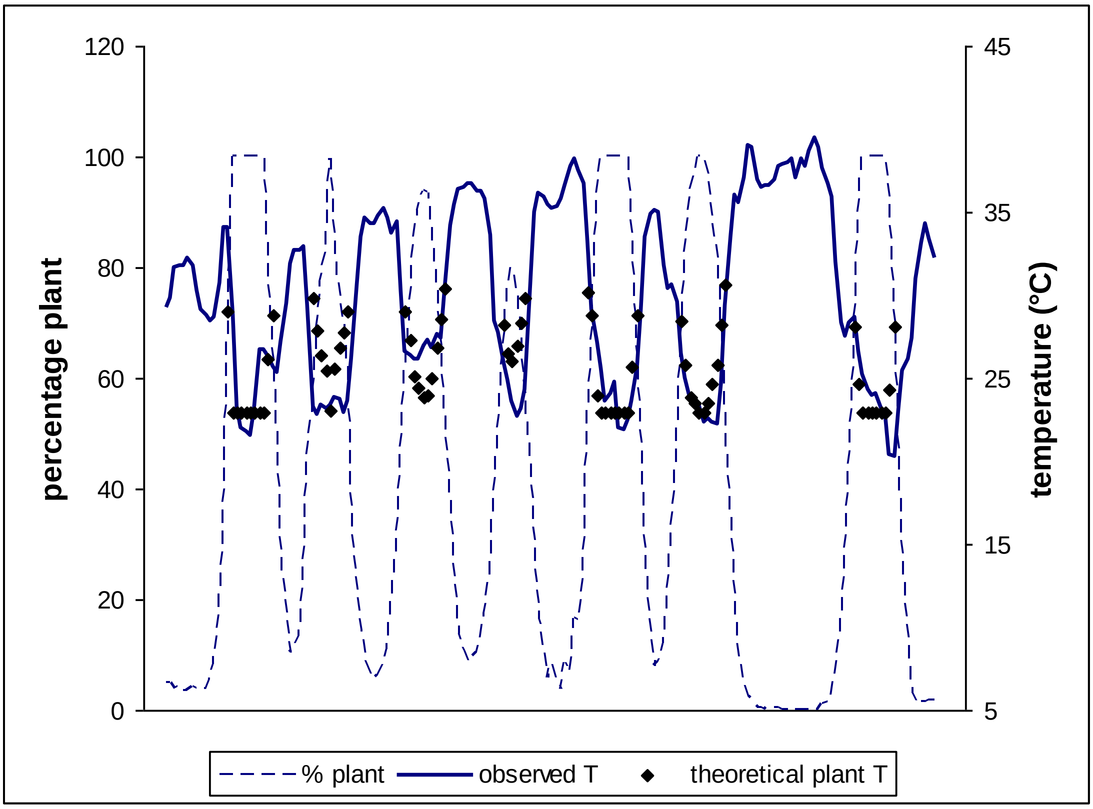


**Figure 7.18.** Percentage plant (dashed line), recorded overall mean temperature at any instant (solid line) and calculated temperature (dots) for the plants shown in Figure 7.16.

## Conclusions

Camera systems can be successfully replaced by a line of point sensors on a boom for both temperature measurement and for estimation of the percentage of plant in the field of view.

Combination of percentage plant and temperature sensing allows estimation of the temperature of the plant alone (and hence the application of this technique in an irrigation scheduling system.

The percentage plant sensor is most reliable if incoming radiation is measured at the same time (as in the system demonstrated at the Water Open day).

Care needs to be taken that in any production system, the R and NIR light sensors used for the percentage plant calculation have an adequate dynamic range to account for varying irradiance conditions. The original PERA sensors tested had too much noise to provide reliable %plant data, though the Skye sensors were excellent.

Effort needs to go into sourcing a cheaper set of light sensors.

### ***Wireless communication of the data and mapping the stress levels in the bed in the glasshouse***

## Introduction

Glasshouse testing of the thermopile on the irrigation boom was conducted to assess the effectiveness of stress mapping on the bed and of wireless communication from the boom to the PC.

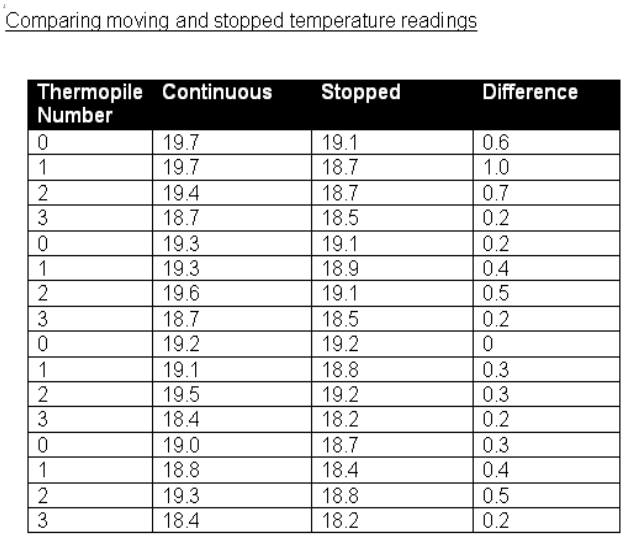
## Results

The transmission/reception distances were improved to distances in excess of 50m at low power with a fourfold increase in resolution. This increase in resolution allows analogue voltages to be sensed and digitised down to 4 millivolts which has the effect of reducing the quantisation error of the system from ±0.5 °C to ±0.1 °C. This improvement allowed better thermal differentiation between healthy and stressed plants.

**Figure. 7.19.** The thermopile system with remote monitoring mounted on a gantry watering system.

*Test 1*

The gantry mounted thermopile was tested recording temperature on the move and at a standstill to determine whether the results when the system was in motion were reliable, as this will be the faster testing method.



Comparing moving and stopped temperature readings

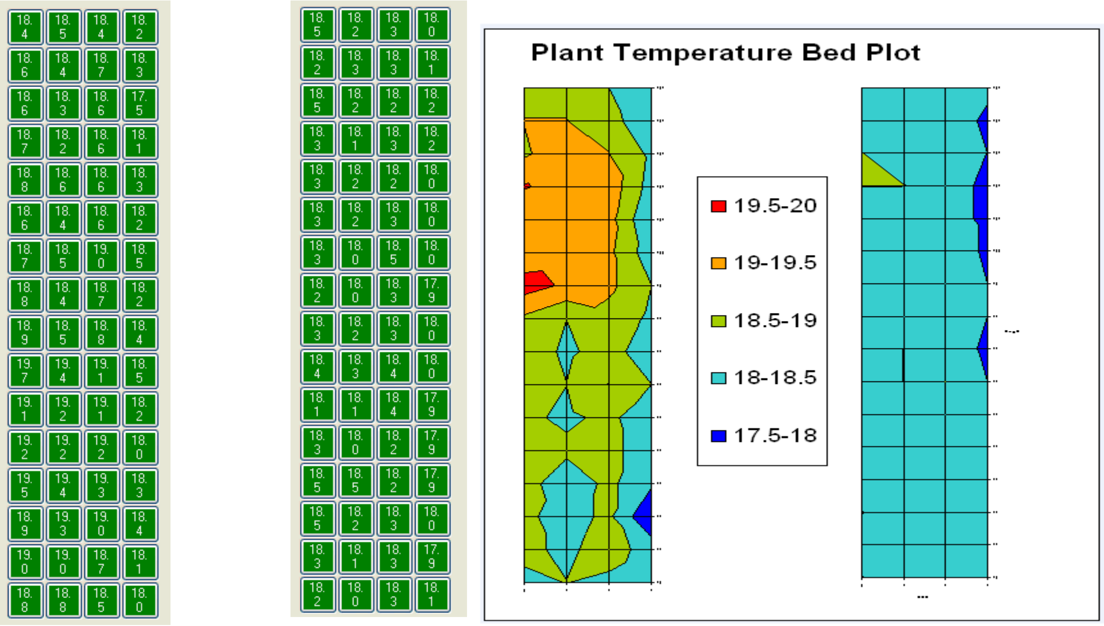
| Thermopile Number | Continuous | Stopped | Difference |
|---|---|---|---|
| 0 | 19.7 | 19.1 | 0.6 |
| 1 | 19.7 | 18.7 | 1.0 |
| 2 | 19.4 | 18.7 | 0.7 |
| 3 | 18.7 | 18.5 | 0.2 |
| 0 | 19.3 | 19.1 | 0.2 |
| 1 | 19.3 | 18.9 | 0.4 |
| 2 | 19.6 | 19.1 | 0.5 |
| 3 | 18.7 | 18.5 | 0.2 |
| 0 | 19.2 | 19.2 | 0 |
| 1 | 19.1 | 18.8 | 0.3 |
| 2 | 19.5 | 19.2 | 0.3 |
| 3 | 18.4 | 18.2 | 0.2 |
| 0 | 19.0 | 18.7 | 0.3 |
| 1 | 18.8 | 18.4 | 0.4 |
| 2 | 19.3 | 18.8 | 0.5 |
| 3 | 18.4 | 18.2 | 0.2 |

The samples taken at a stand still and on the move did differ by up to 1 degree, for the same plants, but the difference was not sufficient to prevent a temperature differential between areas to be identified.

The advantage of being able to test the temperature on a moving gantry will outweigh the accuracy increase of testing at a standstill, although this is still an option if an area of increased accuracy is required.

*Test 2*

Two beds of plants were prepared, with the plants being treated equally until the test. During the test one area of plants were watered fully, the other receiving only 50% of their usual water. This would have resulted in the under watered plants being expected to show signs of stress, which was an ideal test condition for the gantry mounted thermopiles.



|  |  |  |  |
|---|---|---|---|
| 18.4 | 18.5 | 18.4 | 18.2 |
| 18.6 | 18.4 | 18.7 | 18.3 |
| 18.6 | 18.3 | 18.6 | 17.5 |
| 18.7 | 18.2 | 18.6 | 18.1 |
| 18.8 | 18.6 | 18.6 | 18.3 |
| 18.6 | 18.4 | 18.6 | 18.2 |
| 18.7 | 18.5 | 19.0 | 18.5 |
| 18.8 | 18.4 | 18.7 | 18.2 |
| 18.9 | 18.5 | 18.8 | 18.4 |
| 19.7 | 19.4 | 19.1 | 18.5 |
| 19.1 | 19.2 | 19.1 | 18.2 |
| 19.2 | 19.2 | 19.2 | 18.0 |
| 19.5 | 19.4 | 19.3 | 18.3 |
| 18.9 | 19.3 | 19.0 | 18.4 |
| 19.0 | 19.0 | 18.7 | 18.1 |
| 18.8 | 18.8 | 18.5 | 18.0 |

|  |  |  |  |
|---|---|---|---|
| 18.5 | 18.2 | 18.3 | 18.0 |
| 18.2 | 18.3 | 18.3 | 18.1 |
| 18.5 | 18.2 | 18.2 | 18.2 |
| 18.3 | 18.1 | 18.3 | 18.2 |
| 18.3 | 18.2 | 18.2 | 18.0 |
| 18.3 | 18.2 | 18.3 | 18.0 |
| 18.3 | 18.0 | 18.5 | 18.0 |
| 18.2 | 18.0 | 18.3 | 17.9 |
| 18.3 | 18.2 | 18.3 | 18.0 |
| 18.4 | 18.3 | 18.4 | 18.0 |
| 18.1 | 18.1 | 18.4 | 17.9 |
| 18.3 | 18.0 | 18.2 | 17.9 |
| 18.5 | 18.5 | 18.2 | 17.9 |
| 18.5 | 18.2 | 18.3 | 18.0 |
| 18.3 | 18.1 | 18.3 | 17.9 |
| 18.2 | 18.0 | 18.3 | 18.1 |

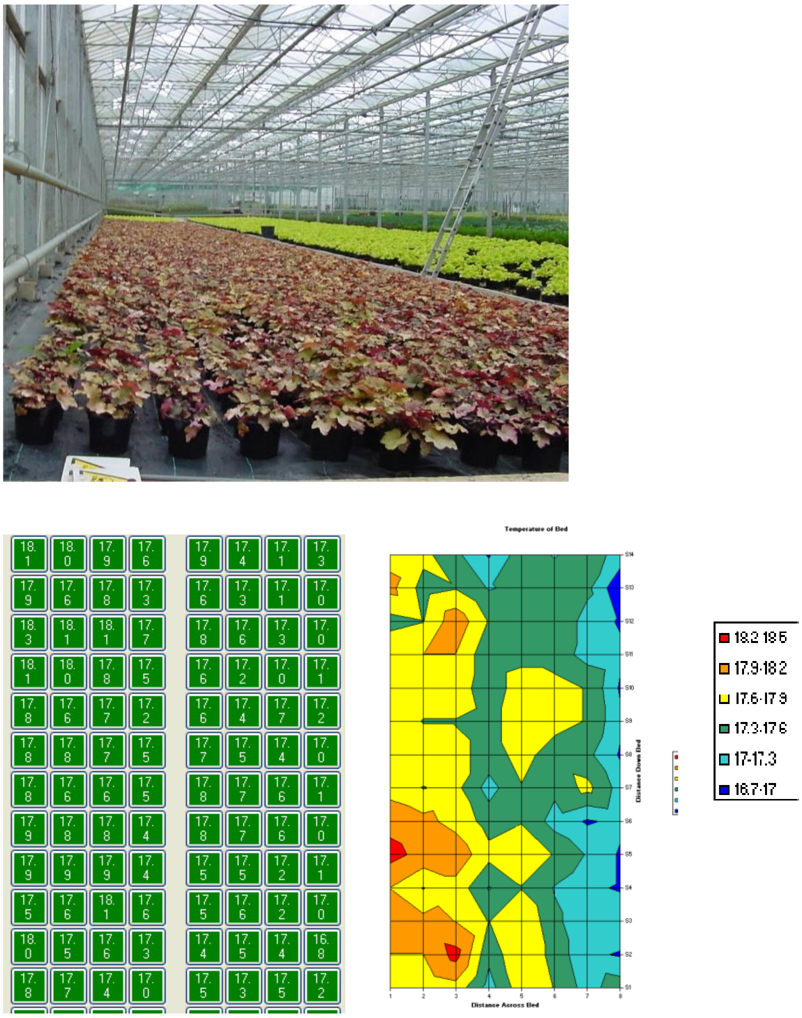
50% water 100% water 50% water 100% water

**Figure. 7.20.** Two beds of plants - One side watered normally, the other watered 50%.

The thermopile system was able to determine a temperature difference between stressed and non stressed plants (the stressed plants having a higher temperature) while mounted on a moving gantry, with the readout from the system being wirelessly communicated.

*Test 3*

An inclined bed was used for this test, with the plants at the top of the incline naturally receiving less water than those at the bottom as the water drained down the slope to a central gully where it was recycled at the next watering stage. The thermopile was mounted on the moving gantry and passed over the growing plant to determine their temperatures.



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 18.1 | 18.0 | 17.9 | 17.6 | 17.9 | 17.4 | 17.1 | 17.3 |
| 17.9 | 17.6 | 17.8 | 17.3 | 17.6 | 17.3 | 17.1 | 17.0 |
| 18.3 | 18.1 | 18.1 | 17.7 | 17.8 | 17.6 | 17.3 | 17.0 |
| 18.1 | 18.0 | 17.8 | 17.5 | 17.6 | 17.2 | 17.0 | 17.1 |
| 17.8 | 17.6 | 17.7 | 17.2 | 17.6 | 17.4 | 17.7 | 17.2 |
| 17.8 | 17.8 | 17.7 | 17.5 | 17.7 | 17.5 | 17.4 | 17.0 |
| 17.8 | 17.6 | 17.6 | 17.5 | 17.8 | 17.7 | 17.6 | 17.1 |
| 17.9 | 17.8 | 17.8 | 17.4 | 17.8 | 17.7 | 17.6 | 17.0 |
| 17.9 | 17.9 | 17.9 | 17.4 | 17.5 | 17.5 | 17.2 | 17.1 |
| 17.5 | 17.6 | 18.1 | 17.6 | 17.5 | 17.6 | 17.2 | 17.0 |
| 18.0 | 17.5 | 17.6 | 17.3 | 17.4 | 17.5 | 17.4 | 16.8 |
| 17.8 | 17.7 | 17.4 | 17.0 | 17.5 | 17.3 | 17.5 | 17.2 |

**Figure.7.21.** Temperature map of a sloping plant bed at Hilliers Nursery

The thermopile system was yet again able to determine a temperature difference between the stressed plants at the top of the slope and the less stressed plants at the bottom of the slope (the stressed plants having a higher temperature) while mounted on a moving gantry. Again the readout from the system was reliably wirelessly communicated.

## Conclusion

Tests showed that the temperature measurement boom can be directly mounted on a watering boom and the processed data can be directly fed into the control system for the watering gantries, which will then apply the appropriate amount of water. 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 weather, feeds, treatments, and pruning etc.

## Objective 8

*Develop user-friendly guidelines for application of different methods of stress sensing and plant manipulation in nursery practice and produce a 'User Manual'*

EMR has delivered guidelines for application of the research conducted in this project at several technology transfer events (see Technology Transfer list).

The possibility of extending the technology to systems other than examined in this project e.g. reduced-peat substrates, to a wider range of HNS e.g. trees, and to other horticultural crops e.g. raspberry, is being considered. These ideas for extension of the research are being developed in concept notes for different HDC panels and fact sheets for HDC.

Lancaster has published a paper detailing the use of pH buffers in irrigation water as a means of saving irrigation water.

Partners are actively involved in discussions over further development of thermography, plant/no plant sensors and gantry technology See Impact Plan.

A single publication forming a 'user manual' was seen as too limiting a route for dissemination of all results and outcomes.

## 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 generation of a company in terms of Net Present Value (NPV), Payback Period (PP) and Internal Rate of Return (IRR).

## Methods

Cost information was gathered for equipment that is already on the market. Data on reduction in hand watering achieved by improved water distribution were collected by Palmstead Nurseries. Further data were obtained from other experienced growers to gather estimates of relevant costs and benefits, including intangibles. In particular, Hillier nurseries provided detailed information regarding the costs associated with their pinjet irrigation system and the gantry system installed in the same glasshouse at Hillier during this project.

### Results

### *The main benefits of irrigation technology*

Growers identified the following costs as the main areas where they expect that improvements in irrigation technology could benefit their business, either by reducing costs or by increasing revenues.

1. Labour costs

    (a) Assessing irrigation need and adjusting irrigation timers

(b) Hand watering to compensate for non-uniformity and for higher evapotranspiration around the edge of blocks, etc.

(c) Hand weeding, especially removal of liverworts and mosses before sale. Capillary beds and running overhead irrigation on a dry regime (i.e. RDI) so that the surface of the growing medium is dry for much of the time reduces the problem considerably. Switching from daily irrigation to less frequent but larger irrigations can also be effective

(d) Pruning and tying-in: the trials at Hillier nurseries showed that RDI saved two prunings of a *Tradescantia* crop and one tying-in of a *Solanum* crop

(e) Order picking: more uniform crops require less time to select a uniform set of plants for dispatch. Increasing the uniformity of irrigation can contribute to increasing the uniformity of crops, although it is not the only factor

2. Maintenance costs

(a) ‘Cheap and cheerful’ irrigation systems may require more maintenance

(b) Mounting nozzles high in a glasshouse may improve uniformity but makes them much more costly to clean or replace

(c) A well-engineered gantry with a small number of easily accessible nozzles can be cheaper to maintain than a system of hundreds of overhead sprinklers

3. Water costs

(a) Water is sufficiently cheap that, even for nurseries using mains water, the monetary value of reducing wastage by as much as 50% is usually small compared with other benefits

(b) For a nursery where the total amount of water available is a limiting factor, then reducing wastage will allow an increase in cropped area and thus in potential crop revenues

(c) Regulatory pressures to demonstrate efficient use of water will increasingly necessitate investment in irrigation infrastructure if a nursery is to retain access to water

4. Crop revenues

(a) Crop wastage: more uniform and accurately scheduled irrigation reduces the percentage of the plants that fail to reach saleable quality

(b) Crop scheduling: RDI provides a non-chemical means to hold back plants which have reached saleable size so as to optimise delivery/marketing date

The above list is not exhaustive, for example good irrigation could contribute to minimising the need for crop protection chemicals, but it covers the main areas raised by growers. 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 can contribute to engendering a company ethos of attention to detail, avoidance of waste and aiming for the highest standards. Such benefits are hard to define or quantify in monetary terms but may be at least as important as the tangible benefits. Therefore, the most realistic approach is probably to assess them subjectively, *alongside* the results of the monetary cost benefit analysis, when coming to investment decisions.

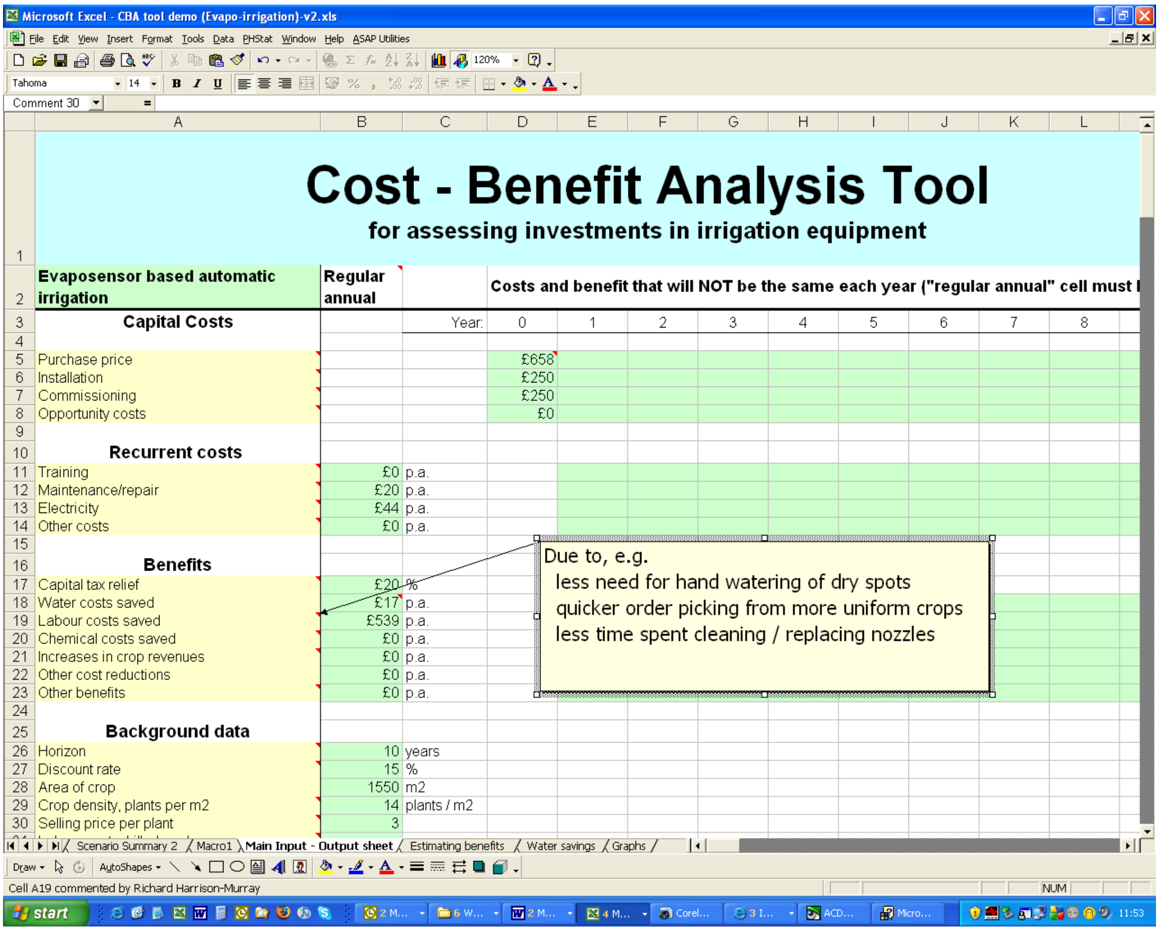
### ***The main costs of irrigation technology***

In most cases the initial capital cost is the major one, but an advantage of a systematic cost benefit analysis is that it helps ensure that the cost of running and maintaining equipment is not overlooked. Over a 10 year planning horizon even the consumption of just 50 watts of electricity by a small control panel is surprisingly large (e.g. see under Evaposensor in Table 9.1). These are the sort of factors that are easily overlooked if decisions are based on a less formal “back-of-an-envelope” assessment.

### *A cost benefit analysis tool*

The costs and benefits of a particular investment in irrigation technology inevitably depend on factors specific to a particular nursery, especially the existing irrigation equipment, the scale of the operation, the crops and the market. These factors vary so much that cost benefit analysis based on industry norms would be hard to establish and of limited value. Instead, a software tool was developed to facilitate cost benefit analysis by nurseries using figures applicable to their particular business and/or a particular site.

The tool takes the form of a Microsoft Excel Workbook with features to suit users with a wide range of experience in Excel. The main spreadsheet, Fig. 9.1, provides for input of estimates of all costs and benefits, either as numbers or as formulae, and either as regular annual values or specified for individual years. The planning horizon can be specified up to a maximum of 10 years. Results appear immediately and include all the main indices widely used in making decisions about investment, i.e. Net Present Value (NPV), Payback Period (PP) and Internal Rate of Return (IRR). For users unfamiliar with these terms, they are defined on the 'Help' sheet. A number of simple graphs are automatically generated, such as pie charts showing the breakdown of costs and benefits, totalled over the planning horizon (e.g. Fig. 9.2). Other spreadsheets help users make estimates of the various costs and benefits and convert all of them to a standard basis (per square metre of crop and per year). Users can readily explore how changes in any of the costs or benefits would affect the business outcome. The results of such "what-if" analysis can be simply written down but more experienced Excel users can use tools such as "Scenario Manager" to partially automate the process, produce more advanced graphs, etc.



Cost - Benefit Analysis Tool

for assessing investments in irrigation equipment

| | A | B | C | D | E | F | G | H | I | J | K | L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | **Evaposensor based automatic irrigation** | **Regular annual** | | **Costs and benefit that will NOT be the same each year ("regular annual" cell must** | | | | | | | | |
| 3 | **Capital Costs** | | Year: | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 4 | | | | | | | | | | | | |
| 5 | Purchase price | | | £658 | | | | | | | | |
| 6 | Installation | | | £250 | | | | | | | | |
| 7 | Commissioning | | | £250 | | | | | | | | |
| 8 | Opportunity costs | | | £0 | | | | | | | | |
| 9 | | | | | | | | | | | | |
| 10 | **Recurrent costs** | | | | | | | | | | | |
| 11 | Training | £0 | p.a. | | | | | | | | | |
| 12 | Maintenance/repair | £20 | p.a. | | | | | | | | | |
| 13 | Electricity | £44 | p.a. | | | | | | | | | |
| 14 | Other costs | £0 | p.a. | | | | | | | | | |
| 15 | | | | | | | | | | | | |
| 16 | **Benefits** | | | | | | | | | | | |
| 17 | Capital tax relief | £20 | % | | | | | | | | | |
| 18 | Water costs saved | £17 | p.a. | | | | | | | | | |
| 19 | Labour costs saved | £539 | p.a. | | | | | | | | | |
| 20 | Chemical costs saved | £0 | p.a. | | | | | | | | | |
| 21 | Increases in crop revenues | £0 | p.a. | | | | | | | | | |
| 22 | Other cost reductions | £0 | p.a. | | | | | | | | | |
| 23 | Other benefits | £0 | p.a. | | | | | | | | | |
| 24 | | | | | | | | | | | | |
| 25 | **Background data** | | | | | | | | | | | |
| 26 | Horizon | 10 | years | | | | | | | | | |
| 27 | Discount rate | 15 | % | | | | | | | | | |
| 28 | Area of crop | 1550 | m2 | | | | | | | | | |
| 29 | Crop density, plants per m2 | 14 | plants / m2 | | | | | | | | | |
| 30 | Selling price per plant | 3 | | | | | | | | | | |

Due to, e.g.
less need for hand watering of dry spots
quicker order picking from more uniform crops
less time spent cleaning / replacing nozzles

Cell A19 commented by Richard Harrison-Murray

**Figure 9.1.** Part of the main spreadsheet of the cost-benefit-analysis tool, illustrating an example of the pop-up help comments

***Some examples based on work at Hillier nurseries***

The tool has been used to analyse potential investment in three of the key technologies investigated in the project: gantry irrigation and automatic irrigation scheduling based either on evaposensor or soil moisture probe (GPI logger/controller + SM200 moisture probe). The analysis made use of estimates of the actual benefits realised in the trials in the large glasshouse at Hillier nurseries. Since the glasshouse is already equipped with a well designed layout of pin jet nozzles, carefully graded beds and water recycling, it is to be expected that the benefit of further investment will tend to be smaller than it would be in a facility with more obvious problems. Nonetheless, the analyses suggest that all three technologies would be viable investments, giving a rate of return over 10 years of at least 24% p.a. (Table 9).

The gantry requires an investment about 10 times greater than either of the automatic scheduling systems but this is balanced by the benefit of eliminating the cost of maintaining the large number of high-level pin jet nozzles and a reduction in crop wastage from more uniform irrigation and hence more accurate scheduling. Crop wastage (including saleable quality plants that are not sold) was already low, at about 3% of the crop, leaving little room for improvement, but this was reduced to an estimated 2% under the gantry. It is not yet possible to put a cost on a system to schedule irrigation based on the advances in thermographic sensing that have been made during the project so it would be premature to attempt a cost benefit analysis.

Automating scheduling, whether by evaposensor or soil moisture sensor, is predicted to show an even higher rate of return on investment based purely on labour savings. These are predicted to come roughly equally from the saving in time associated with manual scheduling and from a reduction in moss and liverwort from more accurate scheduling. The reduced pressure on the time of the skilled staff responsible for scheduling decisions would probably bring benefits beyond the salary cost saved. Skilled staff are in short supply and automation releases time for more profitable activities. However, it is important to recognise that automation does not remove the need for crop inspection but rather that it reduces the amount of crop inspection time that is concerned with irrigation decisions.

The area of crop used in these analyses, 1550 $m^2$, was the area covered by the experimental gantry, which was similar to the area of pin jet beds under evaposensor control in 2009. Testing various values for crop area in the spreadsheet (a “what-if analysis”), demonstrated that this variable is crucial to the economics of the gantry (Fig. 9.3) and automatic scheduling systems (data not shown) because it increases benefits without any increase in cost. Amongst various other factors tested (the different lines in Fig. 9.3), only a four-fold increase in the estimated labour saving associated with moss and liverworts had a large impact on the outcome of the analysis. For a soil moisture probe, application of a single controller to an area of 1550 $m^2$ implies an unusually large area under a single crop or group of crops with similar irrigation requirements. Automatic scheduling by evaposensor is more flexible because it allows for the amount and/or frequency of irrigation to vary between beds.

**Table 9.1.** Cost benefit analysis of adding three alternative irrigation technologies to one bay (1550 $m^2$ of crop) of the glasshouse at Hillier nurseries, showing predicted costs and benefits over a 10 year planning horizon. Figures for the gantry assumed it would be scheduled by soil moisture probe. A discount rate of 15% was used, substantially more than inflation and interest rates, to allow for the risk that predictions are over optimistic.

| | **Gantry** | **Evaposensor** | **Soil moisture** |
|---|---|---|---|
| **Costs, £s** *(at present value)* | | | |
| Purchase price | 6,015 | 658 | 515 |
| Installation | 250 | 250 | 250 |
| Commissioning | 250 | 250 | 250 |
| Maintenance/repair | | 100 | 50 |
| Electricity | 88 | 220 | 80 |
| **Benefits, £s** *(at present value)* | | | |
| Capital tax relief | 556 | 61 | 48 |
| Water costs saved | 82 | 85 | 85 |
| Labour costs saved | 5,291 | 2,707 | 2,707 |
| Increases in crop revenues | 3,162 | 0 | 0 |
| **Investment indices** | | | |
| NPV (Net Present Value) | £2,384 | £1,375 | £1,694 |
| PP (Payback Period, years) | 6 | 3 | 3 |
| IRR (Internal rate of return, %) | 24% | 43% | 53% |

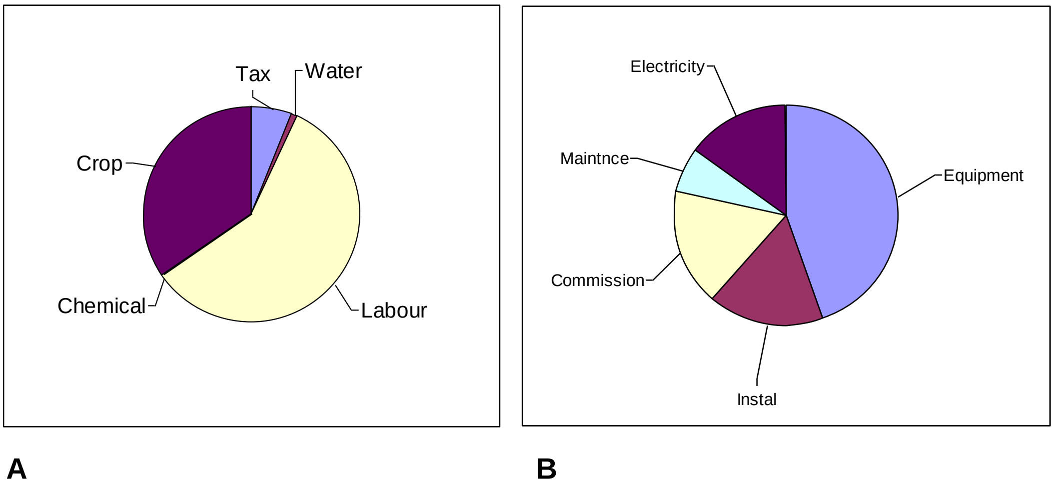


**Figure 9.2.** Examples of the simple graphs created automatically by the cost-benefit-analysis tool showing the breakdown of benefits for the gantry irrigator (A), and the breakdown of costs for automatic scheduling by evaposensor (B)

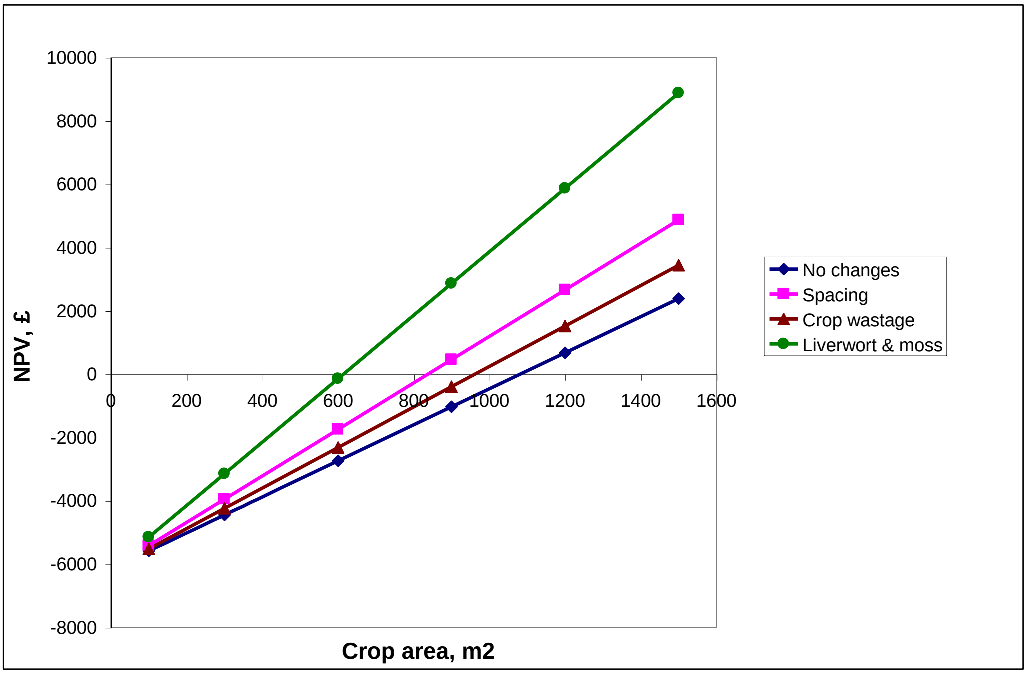


**Figure 9.3.** Examples of the results of “what-if” analysis applied to the cost-benefit-analysis of the irrigation gantry. The four lines show the effect of varying the area of crop irrigated by the gantry, either leaving all assumptions unchanged (i.e. as summarized in Table 9.1, blue line), with the saving in crop wastage raised from 1.0% to 1.3% of the crop (brown line), with plant spacing reduced from 25 × 25 cm to 20 × 20 cm (pink line), or with the estimated saving in time for cleaning off liverworts and moss raised from 10% to 50% (green line).

## Conclusions

Automatic scheduling, whether on the basis of evaposensor or soil moisture sensor, is an economically viable advance in irrigation technology for HNS, as is gantry irrigation. However, there will be circumstances in which these technologies will not show a positive return on investment, particularly those where the area of crop is small. A cost-benefit-analysis tool has been developed that allows the economics of a particular technology to be evaluated for the particular circumstances of an individual nursery. This software tool received an enthusiastic response when demonstrated to growers in the consortium at the October 2008 PMC meeting, and was shown to interested growers at the Water Link Open Day in September 2009. With a little further development, particularly to make it more flexible in the way that the user presents information, it should prove a valuable tool to growers and their advisers.

## TECHNOLOGY TRANSFER

### *Infra-red sensing of plant stress*

Leinonen I., Grant O.M., Tagliavia C.P.P., Chaves M.M. & Jones H.G. (2006) Estimating stomatal conductance with thermal imagery. Plant, Cell and Environment, 29, 1508-1518.

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P G Schofield & H G Jones presented a poster “Combined thermal and visible imaging to detect water stress” at a Workshop on “Imaging plant stress” held at the Society for Experimental Biology annual meeting at Canterbury, 5 April, 2006.

H G Jones and I Leinonen presented talks on “Dynamic thermal imaging for estimating leaf and boundary layer conductances” and “Towards automated analysis of thermal images” at the Society for Experimental Biology annual meeting at Canterbury, 7 April, 2006.

H G Jones, presentation on ‘thermal imaging for irrigation scheduling’ at Water Day (20th July 2006, Warwick).

## Irrigation scheduling and plant growth control

EMR Presentation to members of the Horticultural Trade Association on HNS work, including this project, February 2007.

EMR Presentation to members of the Kent Horticultural Discussion Group, 31 July 2007.

EMR Presentation to China-Britain Business Council, 29 October 2007.

EMR Presentation to the ENAR group of European hardy nursery stock researchers at INRA, Angers, June 2009.

Grant OM (2009). Thermal imaging in precision irrigation. Invited oral presentation 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.

Presentations on EMR's work in this LINK project at the Water Link Open Day, September 2009.

Grant OM, Davies MJ, Longbottom H, Harrison-Murray R (2009). A generic system for establishing crop coefficients across a wide range of hardy nursery stock. Oral presentation at the VI International Conference on Irrigation of Horticultural Crops, Viña del Mar, November 2009.

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Posters on *The East Malling Water Centre* and *Controlling height and improving shelf life of* Poinsettia were presented by Chris Atkinson at the DEFRA Link Water Day at Wellesbourne, July 2006.

Olga Grant presented a poster on on irrigation systems, scheduling methods, and RDI at the East Malling/HDC Water Day, September 2007.

Costa JM, Grant OM, Ortuña MF (2007). Strategies to save water in intensive horticulture. *Fruit and Veg Tech* **7.3**, 12-14.

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Grant OM, Davies MJ, Longbottom H, Herrero A, Harrison-Murray R. Application of deficit irrigation to controlling growth of hardy nursery stock. Submitted to *Acta Horticulturae* November 2009.

**Exploitation of plant signaling science in the development of plant management techniques for HNS and other commodity groups**

Lancaster presentation to Danish Foresight Programme in Sustainable Agriculture (Aarhus), Jan 2007

Lancaster presentation to American Society of Plant Biology Discussion Meeting on Transpiration (Utah), Sept 2007

Enhancing the quality of hardy nursery stock and sustainability of the industry through novel water-saving techniques. Invited oral presentation by Bill Davies to Annual LINK Open Meeting, London, Dec 2007

Using less water in Horticulture. Invited presentation by Bill Davies to Fruition Conference, Berlin, Feb 2008

Saving water in agriculture: an important response to climate change. Invited presentation by WJ Davies to Fylde Schools as part of national science week. Feb 2008

Bill Davies presentation to Gordon conference on Drought (Montana), August 2008

Bill Davies presentation to HTA, summer 2009

Bill Davies presentation to EastGro, summer 2009

Russell Sharp presentation to project Industry day, September 2009

Wilkinson S, Bacon MA**,** Davies WJ (2007) Nitrate signalling to stomata and growing leaves: interactions with soil drying, ABA, and xylem sap pH. *Journal of Experimental Botany* 58, 1705-1716.

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