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The results and conclusions in this report are based on a series of experiments conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

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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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Grower Summary

Headline

Work in year 2, assessed a new prototype overhead gantry irrigation system, examined the use of low precision (low cost) thermal cameras for assessing variations in leaf temperature and demonstrated that significant water uptake may occur via the base of the pot on impermeable surfaces.

Background and expected deliverables

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

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

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

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

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

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

The project is guided by 9 objectives:

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

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

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

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

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

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

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

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

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

Summary of the project and main conclusions

In the second year of this project, the researchers have examined the use of irrigation scheduling, plant growth regulation using chemicals and the automation of irrigation through the use of soil moisture sensing and thermography (thermal imaging to assess water-deficit in plants), to identify ways of improving the efficiency of water use and uniformity of water application.

Irrigation scheduling

A gantry irrigation system coupled to a soil moisture probe (on nursery) which triggers irrigation has been tested and compared with other irrigation scheduling methods. A prototype rig in a laboratory has been developed with integrated hardware, to enable automatic measuring and mapping of crop canopy temperature (to assess the level of water-deficit) and then scheduling irrigation accordingly.

This year, the project has shown that in realistic nursery situations, a quarter to almost a half of HNS water uptake may occur via the base of the pot on impermeable surfaces. Both the plant canopy structure and type of standing base affect the delivery and uptake of irrigation and both of these factors therefore need to be considered in development of scheduling systems. The scientists have found that while overhead sprinklers give very uniform water *deposition* (to a particular area)

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water *delivery* (amount of water per plant) was much more variable than irrigation with dripper lines, partly due to variation in uptake from the standing base.

This year, the research on the effects of plant growth in response to irrigation deficit, demonstrated that in *Lonicera* and *Forsythia* (in separate experiments) reductions in outgrowth could be achieved by applying deficit irrigation. With *Forsythia*, consistent differences were found in growth rate during four months of irrigation. This related mainly to the amount of water applied (measured as a percentage of evapotranspiration measured – Etp), but there was limited influence on the growth rate caused by the way in which water was applied or the substrate in which the plants were growing. Up to 40% substitution of peat with bark did not adversely change the effectiveness of deficit irrigation in controlling plant growth.

Use of chemicals to improve water use efficiency

The first Water LINK project established that simple low-cost alkaline buffer treatments could be used to modify stomatal aperture (the pores on the leaf surface) and thereby regulate (reduce) water loss and increase water use efficiency. This year, alkaline buffers have been assessed as a means of saving water on ornamental nurseries. Alkaline buffers were effective at closing stomata for more than four days after a single application of buffer. Optimum buffer activity was achieved without the addition of adjuvants (additives) to act as 'wetters' or 'spreaders' of the active ingredient of the buffers. However, alkaline buffers have been shown to be toxic to Ericaceous species even when applied as foliar sprays. Similarly, applications of buffers also caused scorching of *Hydrangea* leaves, when applied in high doses.

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

The scientists have developed a prototype sensor system on a test gantry which can move above a stand of plants, sensing the temperature of the canopy (to assess the level of water deficit) as it moves across the plants. This capability is now being integrated into existing commercial gantry irrigation systems to control irrigation scheduling and individual plant application volumes.

Work in year 2 has demonstrated that even low precision thermal cameras have the sensitivity to assess expected variations in leaf temperature due to differing levels of

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water deficit. This is important when considering any necessary additional costs associated with the development of this new technology.

Thermography (the creation of thermal images) has been used to monitor irrigation in an HNS production environment. A handheld thermal imager was not only able to identify individual plants in the early stages of water stress, but was also capable of identifying uneven irrigation and specific irrigation failures, even when no variation in foliage was apparent to the naked eye.

Financial benefits

At this stage in the project, new techniques are still being examined and it is too early to be able to quantify any financial benefits that may arise from the work.

Action points for growers

At this stage in the project (year 3 of 4), it is not yet pertinent to recommend any action points or changes to current commercial irrigation practices.

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Science Section

Introduction

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

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

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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.

In the 1st Annual report 2006 an experiment carried out at EMR to determine responses of HNS plants to application of water via overhead irrigation versus precision drip irrigation was described. Despite substantially more variation in water delivery to individual plants under overhead than drip irrigated deficit irrigation regimes, variation within treatments in average soil moisture content and plant growth were quite similar. This indicated the need to understand better the relationship between water delivery (i.e. the amount of water actually reaching individual plants) and water deposition (i.e. the water deposited into dishes in irrigation uniformity tests). The feasibility of using overhead irrigation for RDI 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. As part of the process of assessing the potential to refine the use of overhead sprinklers to maximise uniformity of water delivery, the match between prediction and performance was examined for Ein dor mini-sprinklers.

This detailed investigation of water delivery at EMR is supported by comparison of different irrigation systems in realistic settings on commercial nurseries.

Materials and Methods

Data collection and trials on nurseries to test performance of 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. Additionally, the use of the Skye Evapometer and/or Delta-T GP1/SM200 irrigation controller and moisture probe for scheduling irrigation was

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compared with grower's standard methods (usually *ad hoc* adjustments to a timer based on crop observation) (Table 1.1).

The trials built on Year 1 experience from the nurseries in using Evapometers and soil moisture probes and recording data. To measure water distribution from overhead sprinklers or gantry 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, and run-through, the same procedure as described in Year 1 annual report was followed.

Table 1.1. Summary of Nursery Trials undertaken in 2007

Nursery	Comparison	Crop	Dates
Hillier Nurseries	1. G'house Gantry x GP1 2. G'house Pinjet x GP1	*Musa* – 3 L	9 Jul – 23 Sept
	1. Gantry x GP1 x Single rate 2. Gantry x GP1 x Double rate	*Solanum* – 3 L	26 Sept – over winter
Wyevale Nurseries	1. Tunnel x Evapometer 2. Tunnel x Standard	*Hydrangea* – 3 L	16 Jul – 9 Sept
Johnson's of Whixley	1. G'house x GP1 2. G'house x Evapometer 3. G'house x Standard	*Choisya* – 5 L	23 Jul – 23 Sept
John Woods Nurseries (formerly Notcutts)	1. Outdoors x GP1 2. Outdoors x Standard	Mixed herbaceous - 2 L	21 May – 23 Sept
	1. Tunnel x Evapometer 2. Tunnel x Standard	*Ilex* – 3 L	21 May – 23 Sept
	1. G'house x GP1 2. G'house x Standard	*Hydrangea* – 3 L	13 June – 9 Jul 8 Aug – 4 Sept
	1. G'house x GP1 2. G'house x Standard	*Fuchsia* – 3 L	Autumn - over winter
Palmstead Nurseries	1. "Old" polytunnel with Ein dor Vibro-spin nozzles 2. New tunnel with MP3000Rotators	*Ceanothus thyrisflorus repens*, *Pyracantha* 'Orange Glow', *Pyracantha* 'Soleil d'Or' – 2 and 3 L	June - October

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 stood 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:

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1. Irrigation in mm applied to irrigated area (litres / 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 x 9.6 m glasshouse bay section with 3 lines of pinjet irrigation per bay. Irrigation lines were spaced 3.2 m apart designed to give overlap with adjacent bays. The monitored bay was not screened from adjacent bays so some overlap in irrigation occurred. Even though slightly different schedules would have been applied to crops on adjacent bays, this arrangement was deemed preferable for achieving better overall irrigation uniformity than screening adjacent bays. During irrigation tests, however, adjacent bays were not run. A similar sized section of a different bay with *Musa* was irrigated with the Denton gantry system. 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.

A 3 L *Hydrangea* crop in tunnels at Wyevale Nurseries received overhead irrigation from impact sprinklers set to give spray arcs inwards from both sides. In contrast to the Hillier trial, the crop was on a gravel standing base.

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A glasshouse crop of *Choisya* in 5 L containers at Johnson's of Whixley's nursery was assessed in mid August. Prior to the 2007 trial, the pinjet overhead irrigation was converted to using two lines of inverted NaanDan modular nozzles per 6.4 m wide bay. The nozzle specification included anti-mist fittings to help allow the application of different schedules to adjacent bays with minimal overlap of irrigation between bays. At John Woods Nurseries, grower-determined irrigation in a tunnel of 3 L *Ilex* was compared with that in an Evapometer scheduled tunnel. Irrigation was via a single line of upside down green swivel NaanDan nozzles on 60 cm dropper tubes down the tunnel. This single line arrangement did not give very high uniformity of irrigation, with some extra hand watering occasionally required for pots near the tunnel side walls.

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}); 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. Water use was monitored under both systems.

<u>Uniformity of water deposition from overhead sprinklers</u>

With a view to optimising the irrigation of narrow beds, such as those being used in current RDI experiments at EMR, studies have focused on layouts of two irrigation lines, spaced at 1.5 m, with sprinklers at 2 m intervals along each line. Sprinklers were Ein dor 861 (50 L h^{-1}) mini sprinklers at a height of 1 m, on two irrigation lines, 1.5 m apart, with 2 m spacing along each line. The pressure was regulated to 2.3 bar at the manifold, which corresponded to about 2.1 bar at the sprinklers. The equipment was laid out in a polythene twin span tunnel on a base of compacted gravel covered with MyPex. There was no crop present and water was collected into 17 cm diameter pot saucers, usually spaced at 50 cm in an array of 30 saucers. Measurements were compared to predictions from the manufacturer's software (Agridor Catalog on CD-rom Version 7.1.0, 15/09/2005).

<u>A "standard absorbency pot" for reproducible measurement of water delivery</u>

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

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away from the pot and this effect will change as the canopy develops. Also, it is difficult to achieve a 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 x 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 2L pot (227 cm^2). Water delivery was then calculated as

$$\text{delivery} = \text{deposition} + \text{surface uptake}$$

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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. Although compacted, the gravel base had become visibly rutted by pedestrian traffic. Measurements were made before and after thoroughly rolling it 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 RDI regimes.

Results and Discussion

Uniformity of output from irrigation systems and effects of foliage canopy and standing base on net uptake

At Hillier Nurseries, uniformity of irrigation output from the pinjet and gantry systems was measured in May (Figure 1.1). For the gantry, in addition to the 9 flat fan nozzles per arm, the additional nozzle at each end of each arm was also turned on, as these are frequently used to give extra irrigation to the more exposed containers along the bed edges, which tend to dry out more quickly. That may have contributed to the non-uniformity of the distribution plot, although there was no consistent pattern across the bay. A mean application rate could not meaningfully be applied to the gantry, as it applied a high rate of water for a short period of time for each pot as it passed overhead. At the middle speed, 'Speed 2', the gantry travelled at about 4.4 m / minute, and each pass at Speed 2 applies about 1.1 mm of water. The pinjet bay uniformity statistics were relatively good considering that the adjacent bays were not run for the test.

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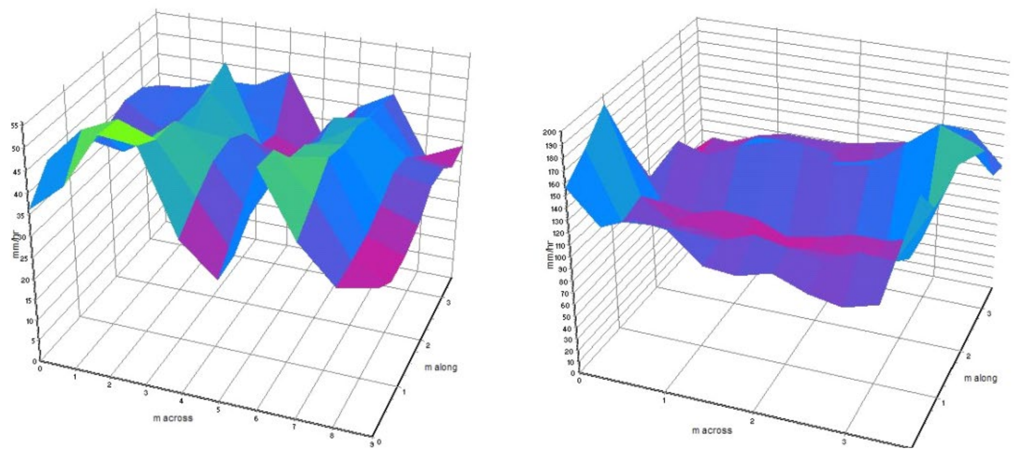

Figure 1.1. Tray test results for pinjet bay (a) and gantry bay (b) 18/5/07 at Hillier Nurseries. The pinjet bay had a MAR of 40.7 mm h^{-1}, CU of 86.0%, and $SC_{5\%}$ of 1.35. The gantry bay had a CU of 84.1% and $SC_{5\%}$ of 1.32.

For the water uptake and run-through test on 18 July, the pinjet bay received 8.4 minutes of irrigation whereas the gantry was given a two-way run on the slowest speed (1) followed by a repeat on the fastest speed (3). Results are summarised in Table 1.2. There was a significant proportion of uptake through the pot base under both irrigation systems. In 2006, a similar assessment with *Syringa* showed 8% basal uptake for the pinjet bay and 18% for the gantry bay. Those plants were at a much later stage with much more shoot growth, and it is likely that a larger proportion of overhead water was intercepted by the foliage and directed into the top of the pot. There was no run-through from the 5.5 – 6.3 mm dose applied to the 3 L *Musa*.

The uniformity of net uptake into the pots on the standing base was similar to that for overhead precipitation into drip trays. Interception by foliage typically results in poorer uniformity of net uptake, but in this instance top growth was still small, and basal uptake may have partly ameliorated any uneven uptake of water via the pot surface.

Uptake and run-through tests were repeated later on 6 September for the gantry bay and 12 October for the pinjet bay, when canopy foliage was more developed and extended beyond the pots (Table 1.3 and Figure 1.2). In early September, there was no run through from the 3.4 mm dose applied to the gantry bay. The mean total

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amount captured by the run-through pots was slightly greater than the mean irrigation applied to the bay area, indicating a possible funnelling of water into the pot by the foliage. Uptake via the pot base was still significant. In October, to prepare for the test, the pots had been dried back to below the point when automatic irrigation would normally have been triggered, and some pots were quite dry with some shrinkage of the growing medium. The 6.9 mm irrigation that the GP1 then applied before switching off, resulted in a mean 25% run-through. However, it is clear from the 20.9 mm equivalent dose captured by the run-through pots that a significant amount of water from beyond the edges of the pot was being funnelled into the container by the extensive foliage canopy, and this would also have contributed to the run-through. Partly because of the high net dose received by the containers and drainage, the influence of basal uptake was smaller.

Table 1.2. 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%

The distribution uniformity measured in the drip trays in June at Wyevale nurseries, and the net uptake by basal pots on 10 July was reasonably good while the foliage canopy was small (Figure 1.3). As expected from a relatively free-draining gravel base, there was little uptake from the pot base. The small mean percentage shown could have been due to sampling error, or if there was slightly impeded drainage below the gravel, there may indeed have been some effect of the standing base in slowing drainage from the pot resulting in more water retention during the period of the test. There was a lot less water capture by the run-through pots than the mean sprinkler output to the irrigated area by the second test in late August. This, coupled with the poorer uniformity of the net uptake for standing base pots, suggests interference by the crop canopy and partial shedding of water *away* from the pots was significant by this stage.

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Table 1.3. Water uptake and run-through test later in season for *Musa* in Hillier pinjet and gantry bays

Irrigation performance	Pinjet	Gantry
Irrigation applied to area	6.9 mm	3.4 mm
Total capture by run-through pot (including drainage)	20.9 mm	4.8 mm
Net uptake by standing base pots	16.2 mm	7.5 mm
Net uptake by run-through pots	15.6 mm	4.8 mm
5. Proportion uptake via pot base (4 as % of 3)	4%	37%
6. Proportion run-through (4 as % of 2)	25%	0%

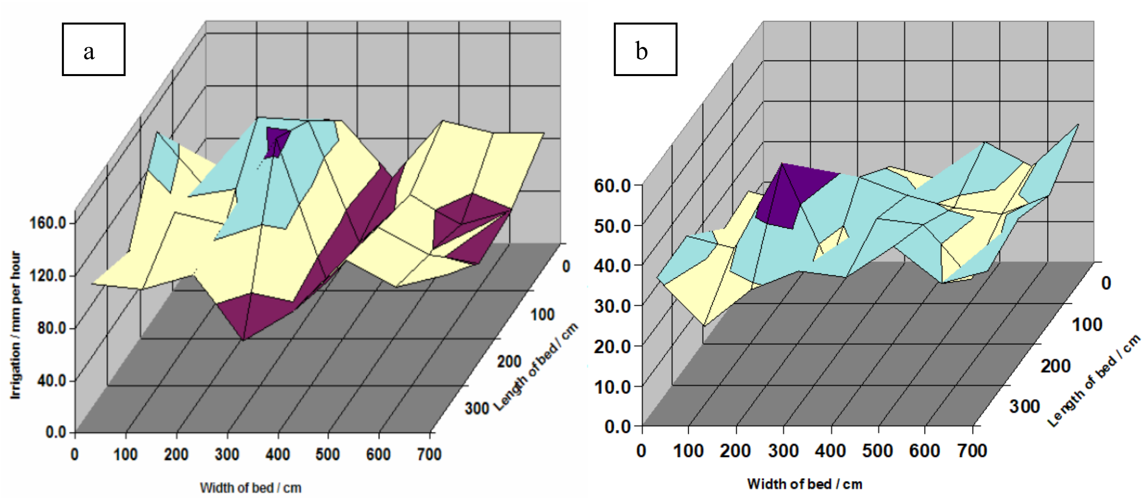

Figure 1.2. Uniformity of net uptake of pots on standing base for pinjet bay (a) 12/10/07 and gantry bay (b) 6/9/07 at Hillier nurseries. The MAR for the pinjet bay was 97 mm h^{-1} and the CU was 77.1% and the $SC_{5\%}$ was 1.66.

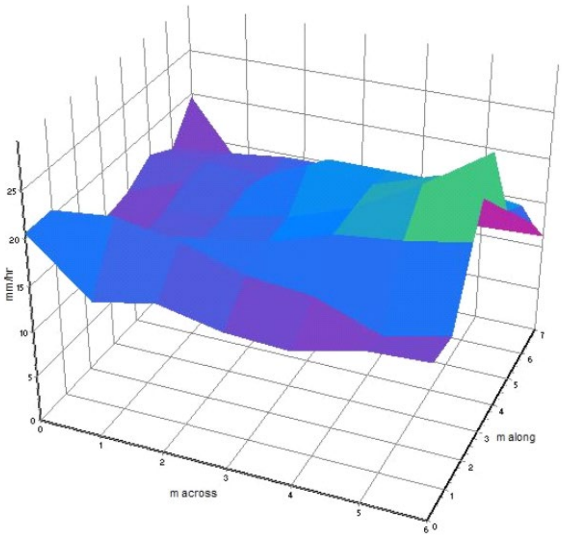

Figure 1.3. Distribution of irrigation over a bed at Wyevale nurseries (overhead irrigation from impact sprinklers) 14/6/07 as determined by tray tests. The MAR was 17.9 mm h^{-1} and the CU was 85.1%. The $SC_{5\%}$ was 1.6.

Table 1.4. Net uptake and run-through tests for *Hydrangea* at Wyevale Nurseries in July and August 2007.

	Application rate	
Irrigation performance	**10/7/07**	**28/8/07**
1. Irrigation applied to area	7.1 mm	9.4 mm
2. Total capture by run-through pot (including drainage)	6.4 mm	6.8 mm
3. Net uptake by standing base pots	5.5 mm	5.3 mm
4. Net uptake by run-through pots	5.4 mm	5.1 mm
5. Proportion uptake via pot base (4 as % of 3)	3%	4%
6. Proportion run-through (4 as % of 2)	15%	27%

At Johnson's of Whixley, the tray test indicated good uniformity in the bay tested where spray line alignment was well set up where just that bay was run. The crop was on a permeable MyPex type ground cover over some hard standing (Figure 1.4). The standing bed surface was slightly uneven, and there was evidence of impeded drainage at one end of the bays, which had caused surface puddles following high rainfall in the summer (Figure 1.4a). The water uptake test was done in the half of the bay where puddles were not so severe. Net water uptake for pots on the standing

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base, following a 4.3 mm irrigation dose, was nevertheless less uniform than sprinkler deposition. The crop varied in size and vigour in some areas, and it is possible that this may have been partly due to variable moisture content between pots. Although the application rate from the irrigation system (MAR 11.1 mm h^{-1}) was much less than the pinjet system at Hillier's for example (MAR 71 mm h^{-1}), and the *Choisya* crop was on a nominally drained standing base, the proportion of 27% basal uptake indicated that there was a significant amount of surface water present during irrigation (Table 1.5). While this can be advantageous and aid uptake on well-graded beds, the presence of bumps and hollows can clearly result in poor uniformity in pot water content.

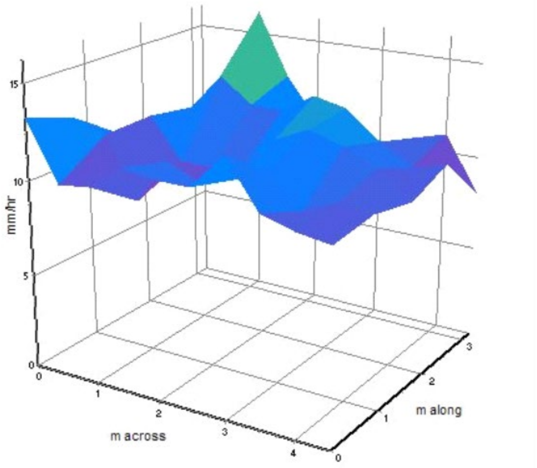

Figure 1.4. Distribution of irrigation as measured with drip trays measured on 17/8/07 at Johnson's of Whixley (2 lines of inverted NaanDan modular nozzles per 6.4m wide bay).

Table 1.5. Net uptake for run-through test for *Choisya* at Johnson's of Whixley in August

Irrigation performance	18/8/07
Irrigation applied to area	4.3 mm
Total capture by run-through pot (including drainage)	3.0 mm
Net uptake by standing base pots	4.1 mm
Net uptake by run-through pots	3.0 mm
Proportion uptake via pot base	27%
Proportion run-through	0%

Irrigation uniformity was found to be higher in the new polytunnel using MP Rotator3000 sprinklers than in an old tunnel using Ein dor sprinklers, at Palmstead Nurseries (Figure 1.5). 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.

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There were also problems with an uneven floor surface and poor drainage, which have now been corrected.

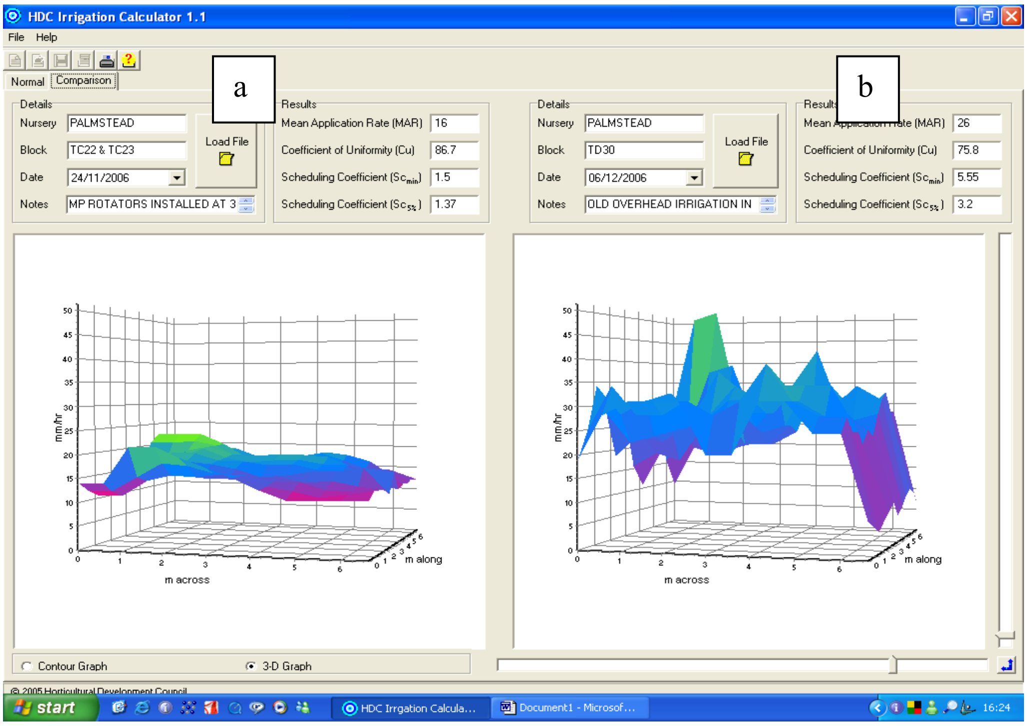

Figure 1.5. Irrigation capture and uniformity measurements under MP Rotator3000 sprinklers fitted at 3 m spacing in the new tunnel (a) and under Ein dor vibro-spin nozzles hanging from the roof of the older tunnel (b) at Palmstead Nurseries. Low water capture was seen along the side of the tunnel in (b) as a result of the position of the sprinklers and their trajectory into the curve of the tunnel.

Conclusions from irrigation tests on nurseries:

1. 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).

2. 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.

3. 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.

4. 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.

5. 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. This is also true when considering the type and design of precision delivery nozzles on a prototype gantry being developed elsewhere in the project.

Water or economic savings on nurseries

Two different arrangements of nozzles in tunnels at Palmstead Nurseries lead 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. Time savings in a hotter year could be greater.

Optimising uniformity of water deposition from overhead sprinklers

With respect to the Ein dor sprinkler arrangement at EMR, the manufacturer's software predicted a coefficient of uniformity (CU) of 95.8%, with a symmetrical repeating pattern as shown in Figure 1.5. Actual measurements were more variable with a CU of 94.9%, even when the results of several tests were averaged (Figure 1.6). Individual tests, based on 30 minutes irrigation, generally had CU between 91.5% and 95.2%. The pattern seen in consecutive tests often matched very closely but gradual changes over time were evident. Any change, such as rotating some of the nozzles in their holders, changed the detailed pattern in an unpredictable way. It seems likely that these minor changes stemmed from slight lack of radial symmetry in the output from individual sprinklers. Sometimes highly anomalous patterns were seen but the cause could never be traced before the pattern returned to normal.

In relation to the problem of achieving uniformity in small research beds, it is interesting to note the effect of turning off sprinklers outside the area of study (further along the two irrigation lines). Figure 1.7 shows that there was a marked drop in

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water deposition at each end of the bed, and CU dropped to 83.3% and SC increased to 1.9. Such a distribution would make successful implementation of RDI very unlikely. In the small bays used in our current RDI experiments, this problem was alleviated by varying the distance between sprinklers across the bed, resulting in a CU of 92.1% and SC of 1.2 (Figure 1.8).

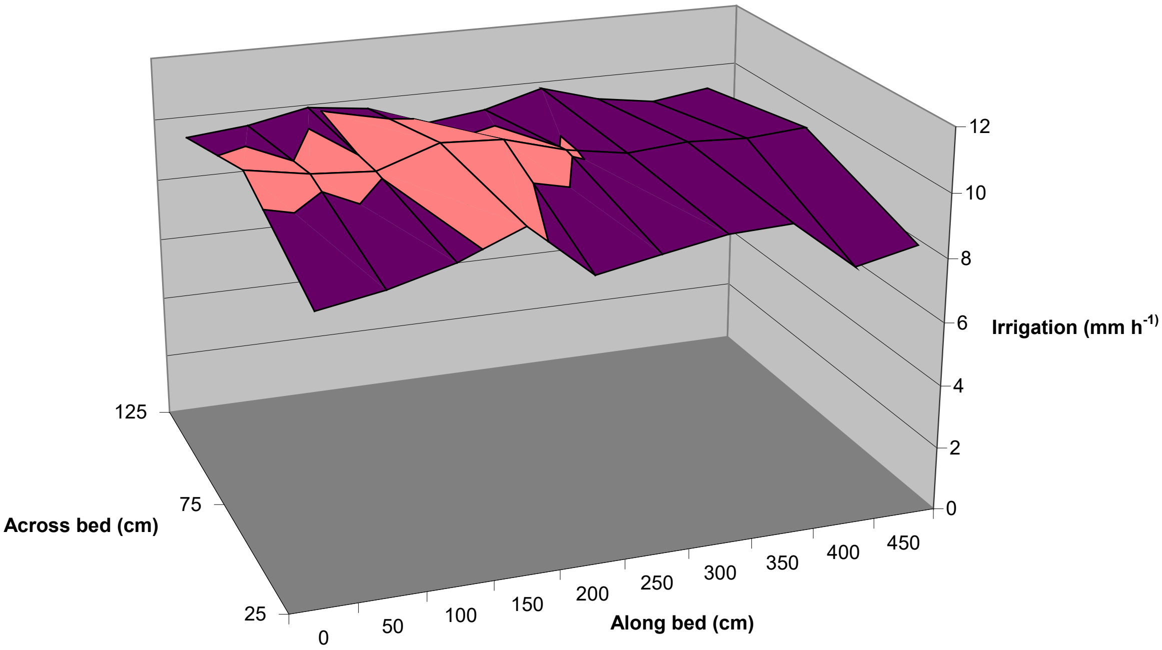

Figure 1.6. Water deposition observed with Ein dor 861 (50 L h^{-1}) sprinklers at a height of 1 m, on two irrigation lines, 1.5 m apart (across bed), with 2 m spacing along each line (along bed). The lines extended by 2 m (i.e. one sprinkler) to right and left of the study area. Plotted values are means (n = 13) of data collected over several days. CU = 94.9%, SC = 1.18, MAR = 9.6 mm h^{-1}. This plot is directly comparable with the predicted distribution shown in Figure 1.5.

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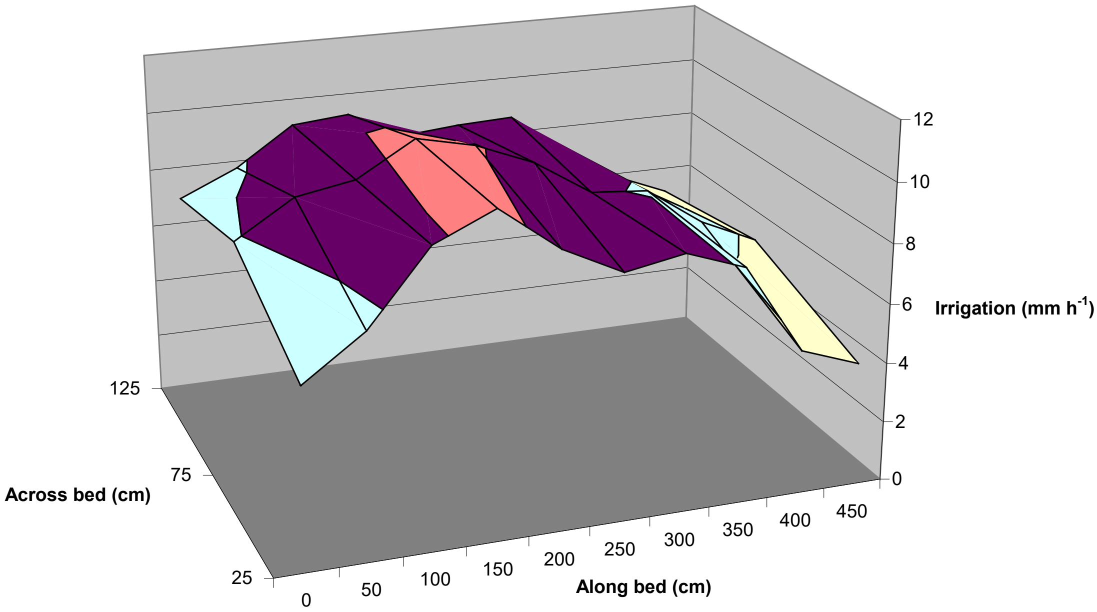

Figure 1.7. Water deposition observed with Ein dor 861 (50 L h^{-1}) mini sprinklers at a height of 1 m, on two irrigation lines, 1.5 m apart (across bed), with 2 m spacing along each line (along bed). In contrast to Figure 1.8, the irrigation lines did not extend beyond the study area, resulting in a marked decline in water deposition towards each end of the bed. CU =83.3%, SC = 1.9, MAR = 7.9 mm h^{-1}.

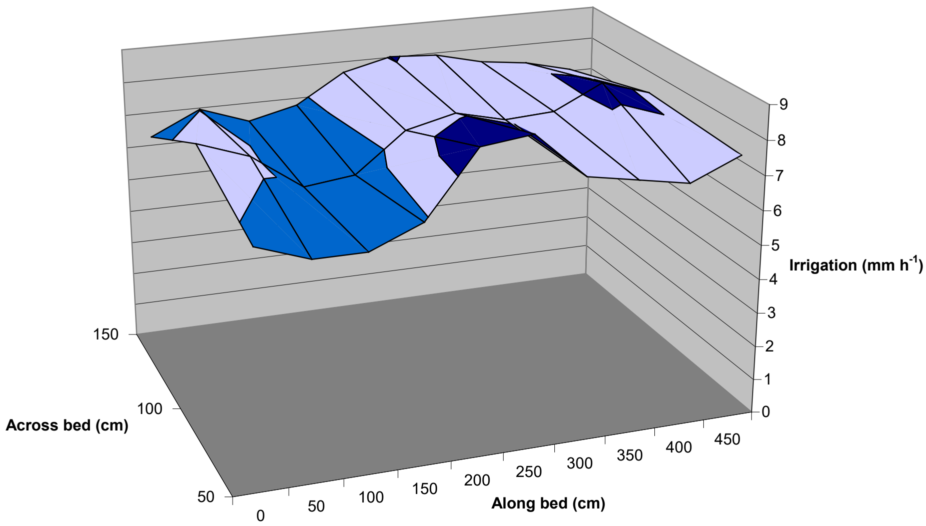

Figure 1.8. Water deposition achieved in the small bays (2.5 x 5 m) created for the RDI experiments in a polythene twin-span house. There were 3 sprinklers down each side of the bay, the middle pair being 200 cm apart while the pairs at each end were 50 cm closer to counteract a fall off in water deposition at the ends. CU = 92.1, SC = 1.2 and MAR = 7.3 mm h^{-1}.

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Factors affecting surface uptake

Water delivery to plants under irrigation depends not only on direct water deposition into the tops of the pots but also uptake from the standing surface through the base of the pot, which we refer to as surface uptake. The uniformity of surface uptake was studied using pots containing a wad of capillary matting to provide a standard absorbency, as described in the Methods section. These pots were laid out on part of the area used to study uniformity of water deposition.

Results show that surface uptake was much more variable than water deposition so that care in setting up irrigation equipment to achieve uniform water deposition is no guarantee of uniform water delivery. CU of water delivery was just 55.9% 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 43.7 % (Table 1.6). Similarly, when it was increased from 10 to 30 minutes (from 1.5 to 5 mm) the CU for water delivery increased from 55.9% to 85.2%. 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%). It is reasonable to speculate that, if measurements had been made on clean gravel without a covering of MyPex, we would expect surface uptake to have been virtually zero so that the high uniformity of water deposition would have been reflected in similarly uniform water delivery.

Rolling the gravel base to eliminate visible unevenness improved uniformity of surface uptake slightly so that CU of water delivery rose from 55.9% to 63.1% (Table 1.6). 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, so it seems likely that slight unevenness must have remained and that this was enough to direct water flow to certain positions even though it was not enough to 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 (Figure 1.9).

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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.

Table 1.6. Results obtained with the standard absorbency pots. The standing surface was compacted gravel (before and after rolling to smooth the surface) covered with MyPex (± a layer of polythene under it). Values are means of 20 pots, which were spaced at 25 x 25 cm. In one test, a 25 cm diameter pot saucer was placed under each pot so that the catchment area for surface uptake was clearly defined (values in brackets are those that would have been obtained if all water in the saucer had been taken up into the pot)

Surface		Duration	Mean application rate (mm h^{-1})			Coefficient of uniformity (%)		
Rolled	Polythene	(minutes)	Surface uptake	Deposition	Delivery	Surface uptake	Deposition	Delivery
No	Yes	10	16.9	8.8	22.3	28.0	96.0	55.9
No	No	30	4.6	10.1	13.9	16.4	96.6	77.0
No	Yes	30	14.0	9.8	21.1	73.3	97.4	85.2
No	Yes	5	12.5	8.7	18.7	-4.4	93.9	43.7
Yes	Yes	10	16.5	9.1	22.4	38.2	96.8	63.1
In 25 cm saucers		10	2.0 (23.0)	9.3	10.9 (27.5)	-7.4 (86)	96.4	83.0 (90.3)

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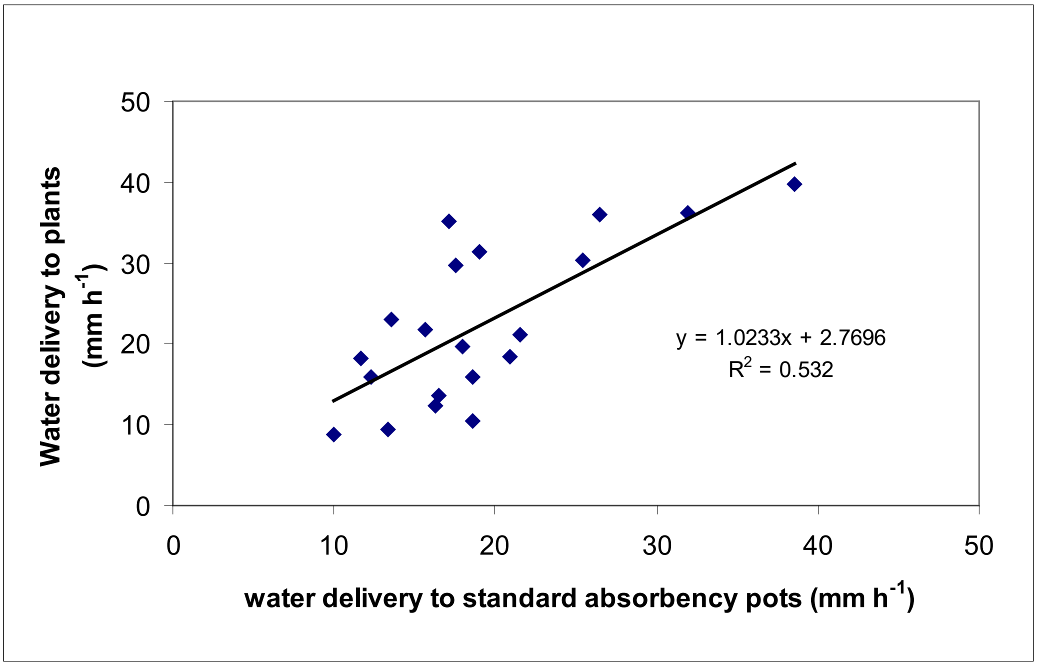

Figure 1.9. The relationship between water delivery to recently potted *Forsythia* plants (in peat in 3 L pots) and water delivery measured using the standard water absorbency pots in the same positions (MyPex over polythene after rolling).

A separate experiment showed that this problem can be overcome by a covering of MyPex over the base of the saucer (Table 1.7). 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 great 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 RDI regimes.

Table 1.7. 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. Tabulated values are means (n = 5) ± standard errors.

	MyPex		
Inclination (degrees)	**–**	**+**	**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

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OBJECTIVE 2

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

Introduction

Experiments described in the 1st Annual Report (2006) were continued through October 2006. Research to determine the influence of factors such as canopy density on the relationship between plant water use and accumulated degree hours undertaken in 2006 was further developed in 2007. This work is required to establish a generic system for the use of Evaposensors on nurseries, without the need for growers to perform time-consuming calibrations. We also undertook an experiment with deficit irrigation as compared to full irrigation, and drip as well as overhead irrigation, which will allow determination of variation across beds in substrate moisture under different irrigation conditions, in different substrates, and under deficit versus full irrigation regimes. Additionally, Evaposensors and soil moisture sensors were trialed on nurseries.

Materials and Methods

<u>Predicting calibration coefficients for use with Evaposensors</u>

Canopy development and water use of *Choisya ternata* 'Sundance', *Cornus alba* 'Elegantissima', *Cornus alba* 'Gouchaulti', *Escallonia* 'Donard Radiance', *Hydrangea macrophylla* 'Blue Wave', and *Lonicera* × *heckrotti* 'Gold Flame' were measured from August until October 2006. In April 2007, liners of 12 species/varieties were potted up in 100% peat (specifications as in HNS 97) in 2 L pots. Groups of plants were arranged in a randomised block design on either of two beds – one indoors and one in a polytunnel. Groups consisted of 9 plants of one variety, with centres of the pots spaced 25 cm apart. The species/varieties were: *Buddleia* 'Lochinch', *Ceanothus thyrsiflorus repens*, *Ceanothus* 'Autumn Blue', *Choisya ternata*, *Cornus alba* 'Gouchaulti', *Cotoneaster* 'Coral Beauty', *Escallonia* 'Donard Radiance', *Griselinia littoralis* 'Variegata', *Hydrangea macrophylla* 'Blue Wave', *Lonicera* × *heckrotti* 'Gold Flame', *Philadelphus* 'Beauclerk', and *Physocarpus opulifolius* 'Dart's Gold'. During two weeks out of every four from 7 May until the end of October water use of the central plant in each group was monitored daily by weighing the plants before and after adding water to bring them to a predetermined mass, and an Evapometer was read every morning. In the case of the outdoor plants, pot mass was not recorded where rainfall would have prevented calculation of water use. As a result, measurements outside were often spread out over a wider period than those in the polytunnel. Light interception and stomatal conductance were measured and percentage cover estimated, as described previously (Annual Report 2006). Total leaf area was either measured (*Cotoneaster*, *Ceanothus*, *Griselinia*) or estimated (*Lonicera, Buddleia*, *Philadelphus*, *Cornus*, *Physocarpus*, *Hydrangea, Escallonia,* and *Choisya*).

Plant height was recorded, and digital images were taken of each group of plants, which will be analysed during the winter of 2007 to determine cover (Figure 2.1). The *Lonicera* were pruned at the end of May 2007 and afterwards trimmed as required to prevent excessive growth beyond the top of their supporting canes. Other subjects were not pruned throughout the following months so as to allow development of differences between subjects and over time in leaf area and cover. By August 2007 growth under the polytunnel had become excessive, and so plants were pruned following the two weeks of measurements which ended on 3 August. These plants were then allowed to grow prior to measurements in October.

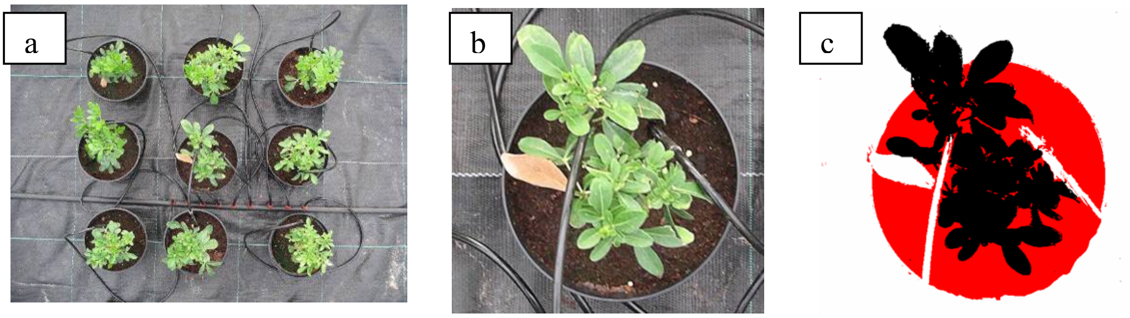

Figure 2.1. Digital images were taken of each block of plants (a), and a 25 cm^2 area around the central plant selected (b) and leaves in the image selected in Photoshop (c). The percentage of pixels in the 25 cm^2 square which are leaves was then assessed in Scion Image – 22% in this example. The unselected leaf in (c) was left out of the analysis because it was dead.

<u>Regulated deficit irrigation</u>

An experiment with both overhead irrigation and drip irrigation, and with crops (*Lonicera periclymenum* 'Graham Thomas' and *Cornus alba* 'Elegantissima') watered at full irrigation and at crop water deficits, carried out in 2006, was described in the Annual Report 2006. Three experimental factors were applied: type of irrigation (drip *vs.* overhead), percentage of evapotranspiration (ET_p) replaced by irrigation (200% *vs.* 50% *vs.* 25%), and saucers (presence or absence under pots; this treatment was included to test whether the catchment area affected variation). Evaposensor degree hours were calibrated against water use for *Lonicera*; a treatment of 25% ET_p therefore implies that both *Lonicera* and *Cornus* were given sufficient water to replace 25% of the water lost by evapotranspiration in the *Lonicera* plants. After 8 weeks of treatments, on 5 October, final heights of *Lonicera* and widths (two perpendicular measurements at the widest point) of *Cornus* were measured. At the end of the experiment substrate moisture was measured with a soil moisture sensor and meter (SM200 and HH2, Delta-T Devices, Cambridge) near the top of each pot in the same manner as during the experiment, and additionally about 6 cm from the base of the pot, after removing the plants from their pots. At this stage half of the experimental plants were harvested and the shoots separated from the root system and oven dried at 80°C for 48 hours. Roots were washed and similarly oven-dried. Root and shoot dry masses were obtained, and root: shoot ratios calculated. Water delivery to pots was measured by determining weight gain during irrigation. This was undertaken early in the experiment as described previously, and repeated on 28 September and 18 October. Uniformity and output of the overhead irrigation and precision drip irrigation used in this experiment was measured before plants were placed on the beds and at the end of the experiment to determine the influence of any degradation during use.

In April 2007, *Forsythia* x *intermedia* 'Lynwood' liners were potted up in 3 L pots. An experiment was set up under a polytunnel, to compare the effects of overhead *vs.* drip irrigation, substrate, and deficit irrigation *vs.* control 'full' irrigation on growth of the *Forsythia*. In the deficit irrigation treatments either 70% or 50% of evapotranspiration (ET_p) was replaced by irrigation, whereas in the control 'full' irrigation 150% of ET_p was replaced by irrigation. 150% rather than 100% was used to ensure that any plants receiving less water than others due to imperfect uniformity of the irrigation system would still receive sufficient irrigation. The substrates compared were 100% peat (specification as in HNS 97) *vs.* 60% peat, 40% bark (Melcourt Potting bark). Both mixes included 1.5 g magnesium limestone and 6 g CRF (Osmocote Plus Spring (15+9+11+2 MgO + trace elements)) per litre. 1 gram

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ammonium nitrate was added per litre of the peat + bark mix to counteract the effect of any nitrogen lock-up. Overhead irrigation was applied in three of the beds: an arrangement of overhead sprinklers that provided as uniform as possible water application was set up using six 50 L h^{-1} sprinklers (Ein dor 861, Access Irrigation) were arranged per bay at distances of 2.25 m between sprinklers across the bay and 1.5 m between the central pair and 1.2 m between the other pairs. Drip irrigation was applied in the remaining bays using 2 L h^{-1} drippers (C.N.L. Junior Dripper, Access Irrigation), one of which was placed into each pot. Overhead irrigation produced, on average, a mean application rate of 8 mm h^{-1} and a CU of 91%. Drip irrigation produced, on average, a CU of 98%.

The water use of *Forsythia* in peat and in peat + bark mix was found to be similar, and therefore calibrations of water use against Evapometer degree hours were based on the average water use (measured by weighing pots) of selected plants in each of the two substrates. Plant heights and the mass of the pots were measured on this date and at frequent intervals through the experiment. The percentage moisture in the compost at one location per pot was measured with a soil moisture sensor (SM200, Delta-T Devices) on 16th May 2007 and throughout the experiment. Daily readings of the Evapometer allowed daily replacement of 50%, 70%, or 150% of the water used by the plants on the previous day. Recalibration was undertaken at intervals as the plants grew.

On 29 June 20 plants were pruned back to 20-30 cm height, in keeping with nursery practice. Eight plants per bay (4 per row) were maintained unpruned. The remaining four experimental plants (2 per row) at this stage became guard plants, separating the pruned and unpruned sub-treatments. For one week from 10 August, plants in the 50% ET_p treatments were given 70% ET_p irrigation, to encourage shoot growth and bud-break, which had been very minimal under 50% ET_p. Final heights and widths were measured on 14 September. A subsection of plants in each treatment was harvested to obtain root: shoot mass ratios.

On 9 August 2007, soil moisture was measured at four locations in the top, four locations in the central, and four locations in the bottom section of the compost, for each of the pruned plants. On 29 August, numbers of buds breaking from the pruned branches was counted for each of the pruned plants. The distribution of water delivery to the plants in the overhead-irrigated bays was measured on 26 April and

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26 June, by weighing plants before and after 30 mins of irrigation (26 April) or 1.5 times the normal daily amount of irrigation (26 June). At the end of the experiment, in October, half of the plants were harvested and root and shoot mass determined. The other half remained *in situ* in order to determine any influence of irrigation treatments on flowering in the spring of 2008.

Evaposensors and soil moisture sensors on nurseries

The nursery comparisons of irrigation scheduling compared use of a Skye Evapometer and Evaposensor and/or a Delta-T Devices GP1 plus SM200 moisture probe 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. litres/m^2 bed area including access paths).

Use of Evapometer

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 am, 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. Typically weekend/bank holiday values needed estimating for many trials, which did not unduly affect weekly summary records. The Evapometer was calibrated to the crop by measuring water loss (pot weights) over a day or so and subsequent weight gain from irrigation from a sample of 10 plants, which was linked to accumulated degree hours over the water loss period. Subsequent irrigations were applied as timed irrigations according to the 'Previous 24 hour Evapometer value' from a look-up chart or spreadsheet record kept by the nursery. Nurseries were encouraged to apply irrigation according to the Evapometer predictions to that treatment wherever possible, but this could be overridden if the crop was becoming clearly too wet or dry, and a record made of the actual irrigation time. Irrigations to standard and Evapometer scheduled treatment areas were made independently by different staff to try to avoid the application of one treatment being influenced by the other. Recalibration of the Evaposensor was encouraged during the season to cope with crop growth or other factors, and if the predicted irrigation values appeared to be consistently too high or low over a week or so.

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Use of GP1 and SM200 probe

The GP1 has a capacity to monitor soil moisture from two probes. The controlling moisture probe located in a single representative pot within the crop, and a second probe used simply to monitor a second pot nearby. The previous 'Water LINK 1' project, and subsequent experience, has established that the sensor pins are best positioned within the central zone (horizontally and vertically) within the growing medium in the container. 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.

Use of GP1 to trigger gantry irrigation

At Hillier nurseries, the Denton gantry used in 2006 was moved and extended to a 200 m bay along the side of the glasshouse for use in 2007. A section of this bay was used for the trial with *Musa lasiocarpa* (ornamental banana) in comparison with a similar section using pinjet irrigation, with both under automatic control with a GP1. 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. The same gantry was used to irrigate other crops within the bay. This was done 'manually' by starting the gantry via buttons on the control panel. In this mode, the gantry was programmed not to irrigate the *Musa* accidentally while over that section of the bay.

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Water meter readings were taken daily, plus at the start and finish of when the gantry was used in manual mode. Together with cross-checks of relay activity from the GP1 data, it was thus possible to calculate water applications to the *Musa* experiment. An Evapometer was used to monitor the glasshouse environment in the Hillier experiment.

Results and Discussion

<u>Water use in relation to degree hours and canopy development</u>

A linear relationship was seen between average water use per degree hour and total leaf area, both outside and in the polytunnel (Figure 2.2a, b). We also mentioned that light interception showed a poorer relationship to water use than leaf area, perhaps as a result of the very different growth forms of these diverse subjects. However, in October a fairly good relationship was found between light interception and water use per degree hour (Figure 2.2c).

Combining data collected at different times during the experiment, for all outside plants the R^2 was 0.65 for leaf area versus water use per degree hour. However, for some of the species (*Choisya*, *Hydrangea*, *Lonicera*), there was little or no relationship between leaf area and water use. For the others there is a very strong relationship between leaf area and water use (R^2 = 0.88, 0.86, 0.85 for *Cornus alba* 'Elegantissima', *C. alba* 'Gouchaulti', and *Escallonia* respectively). For all the plants in the polytunnel together, R^2 was 0.77 for leaf area versus water use per degree hour. As outside, in the twinspan there was a very noticeable difference between species in the relationship between water use and leaf area, with a very strong relationship between water use and leaf area for *Lonicera* and *C. alba* 'Elegantissima' (R^2 = 0.93 and 0.92 respectively), fairly strong correlations for *Hydrangea* and *Escallonia* (R^2 = 0.82 and 0.76 respectively), and little or no relationship between water use and leaf area for the remaining two species. It is surprising that water use of *Hydrangea* and *Lonicera* did not relate to leaf area outside but did in the tunnel, whereas water use of *C. alba* 'Gouchaulti' was closely related to leaf area outside but not in the tunnel. Only for *C. alba* 'Gouchaulti' on the outside bed was a strong relationship between stomatal conductance and water use found.

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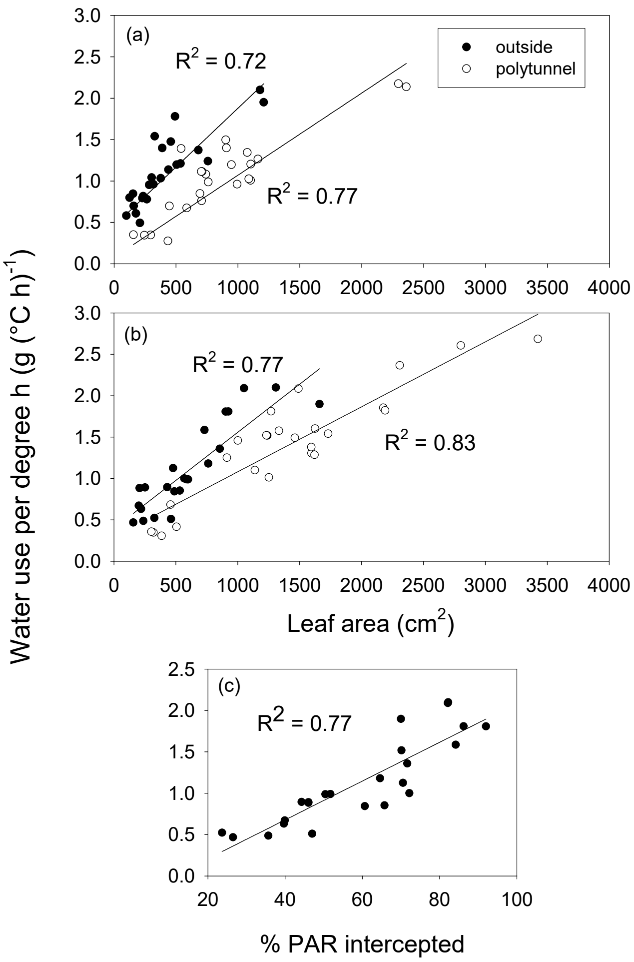

Figure 2.2. Relationship between average water use per degree hour and total leaf area, in September (a) and October/November 2006 (b) and between average water use per degree hour and intercepted PAR (c). Water use per degree hour refers to the mean of daily values collected during the interval 9 Sept to 24 Sept (a) or the mean of daily values collected during the interval 17 Oct to 2 Nov (outside, b, c) and 10 Oct to 2 Nov (polytunnel, b).

A linear relationship was seen for several species/varieties between water use per degree hour and a subjective estimate of cover (Figure 2.3a, d). The same species did not necessarily show good correlations both outside and in the polytunnel. The relationship between water use per degree hour and cover was very strong for *Cornus* and *Physocarpus* when grown outside (R^2 = 0.87 and 0.76 respectively), but there was little relationship between water use per degree hour and cover for these species when grown in the polytunnel. On the other hand, for *Ceanothus* 'Autumn Blue' and *Hydrangea* there was a strong correlation in the polytunnel (R^2 = 0.87 and 0.81 respectively) but not outside. *Escallonia* showed strong correlations between water use per degree hour and cover both outside and under protection. Inclusion of

October data (not shown) deteriorated the overall relationship for outside plants, perhaps due to loss of leaves.

For plants grown in the polytunnel, water use per degree hour showed fairly strong correlations with leaf area for all species/varieties (Figure 2.3b, e). The relationship was also strong for several species grown outside, but not for *Choisya*, *Griselinia*, or *Ceanothus thyrsiflorus repens*. For *Choisya* and *Ceanothus thyrsiflorus repens*, therefore, water use cannot be predicted from either leaf area or an estimation of cover. These both use relatively little water. Limited water use in *Choisya* may relate to the low stomatal conductance (and therefore transpiration) found for this species (data not shown), but stomatal conductance was relatively high in leaves of *Ceanothus thyrsiflorus repens*. Limited water use in *Ceanothus thyrsiflorus repens* may relate to its growth habit, with its small low-growing leaves and compact canopy perhaps being less exposed than in other species and canopy boundary layer resistance to water loss may be greater. In the polytunnel, the relationships between leaf area and water use remained strong even after hard pruning (examples in Figure 2.4).

For outside plants, water use increased with greater interception of PAR only for a few species: *Cornus*, *Cotoneaster*, *Escallonia*, *Lonicera* and *Physocarpus* (Figure 2.3c, f). As with leaf area, *Cornus* in the polytunnel did not show an increase in water use with increasing interception of PAR, despite being the species for which the relationship between water use and PAR seemed most evident outside. Water use of *Hydrangea* increased both with increasing interception and increasing leaf area in the polytunnel, but there was little relationship between water use and either of these variables outside.

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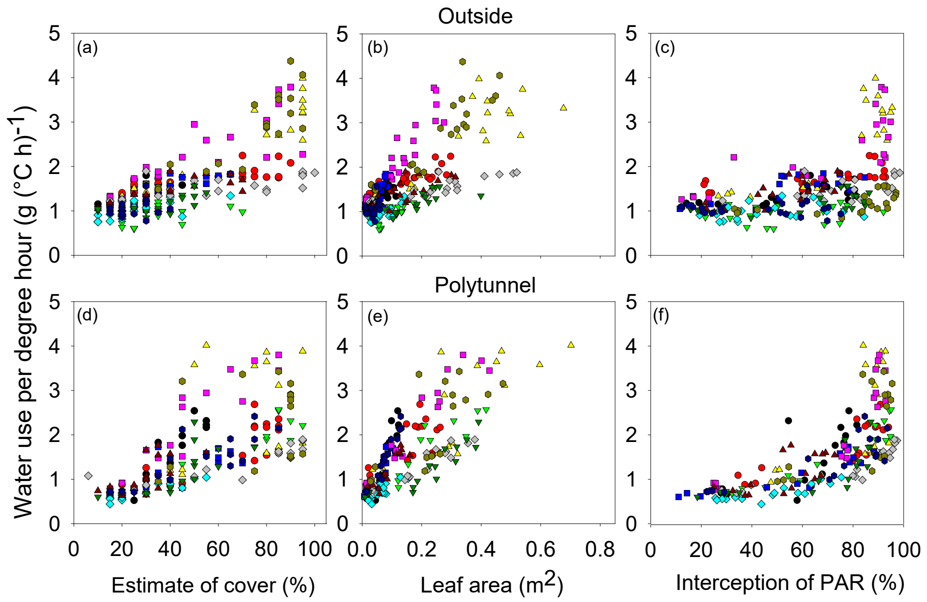

Figure 2.3. Relationship between average water use per degree hour and estimated canopy cover (a, d), leaf area (b, e), and interception of PAR (c, f) for the same species outside (top graphs) and in a polytunnel (bottom graphs). Each point represents an individual plant; the same plants are represented 5 times (one measurement in each month May – September) for outside plants and 4 times (one measurement in each month May – August) for polytunnel plants. Different shades/symbols represent different species. Water use per degree hour refers to the mean of daily values collected during two week periods in each month. Cover was estimated by eye during each of these two week sets of water use measurements.

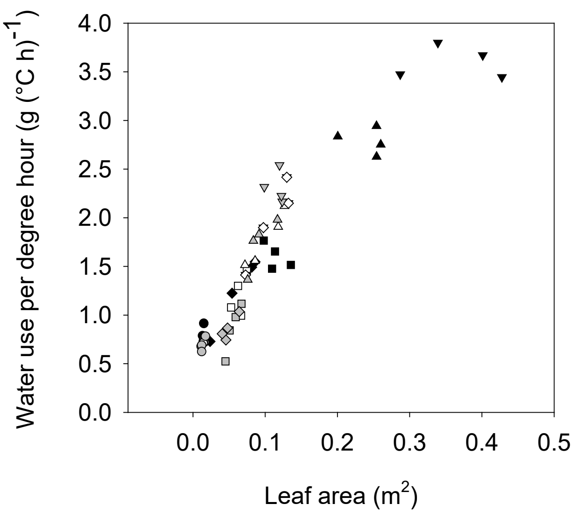

Figure 2.4. The relationship between water use and leaf area for ***Escallonia*** (black symbols), ***Ceanothus thyrsiflorus repens*** (open symbols) and ***Ceanothus*** 'Autumn blue' (grey symbols) in May (circles), June (squares), July (up triangles), August (down triangles), and October (diamonds) 2007, in a polytunnel.

Regulated deficit irrigation

Water delivery was measured at intervals throughout the experiment in 2006, by weighing pots before and after irrigation. Results indicated that *Cornus* under overhead irrigation took up less water than *Lonicera* (Figure 2.5). This is partly due to water hitting and rolling off *Cornus* leaves rather than going directly into the pots, and partly due to canes funneling water into the pots of *Lonicera*.

One objective of this project is to determine the scale of variation in soil water content of apparently representative plants within a single container bed under different levels of RDI. On different dates of measurement, there was little variation in substrate moisture under 200% overhead irrigation where the pots were placed directly on the ground (no saucers), 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 or pots were placed on saucers (data not shown). Another objective is to devise protocols for adjustment of set points for turning irrigation on and off. 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.

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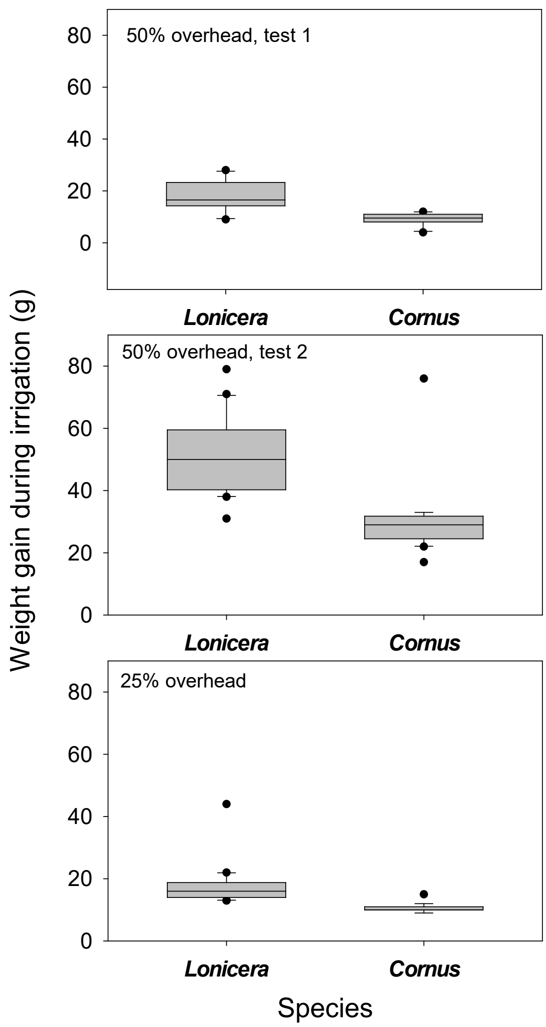

Figure 2.5. Uptake of water during irrigation, as measured by weight gain of pots of ***Lonicera*** and ***Cornus*** in the 2006 RDI experiment. Boxes indicate the 25^{th} to 75^{th} percentile range, whiskers extend another 15% either way, and outliers are represented by circles. ***n*** = 20 except in “test 2”, where ***n*** = 10.

While growth of ***Cornus*** leveled off even under 200% ET_p relatively early in the experiment, fairly rapid growth continued in ***Lonicera*** under 200% and 50% ET_p (Figure 2.7). The final heights of ***Lonicera*** showed a significant effect of % ET_p applied (Figure 2.8a). There was no significant difference between drip ***vs.*** overhead irrigation. ***Cornus*** plants showed significantly wider diameters at the end of the experiment under drip than overhead irrigation, and under higher % ET_p application (Figure 2.8b).

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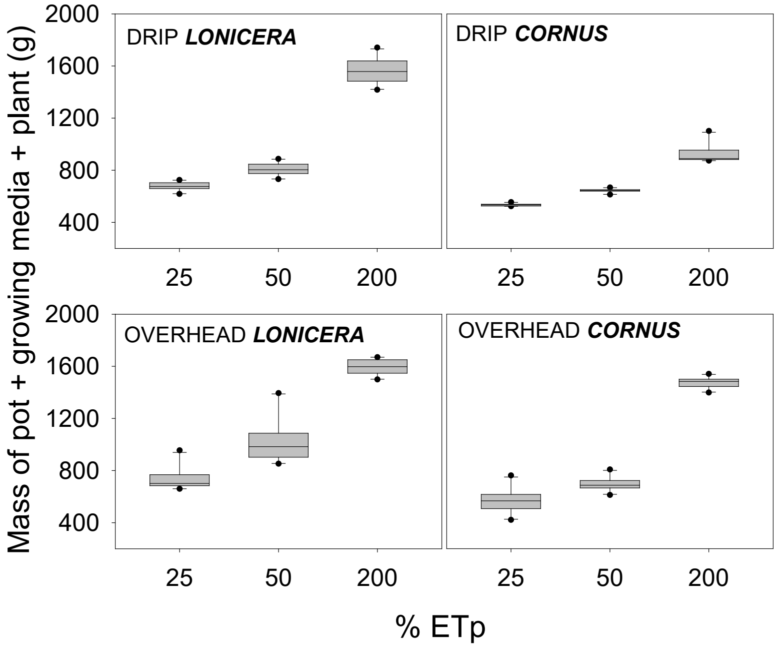

Figure 2.6. Mass of pots of ***Lonicera periclymenum*** 'Graham Thomas' and ***Cornus alba*** 'Elegantissima' under drip irrigation and overhead irrigation, on 21 Sept 2006 i.e. 49 days after imposition of deficit irrigation treatments. ***n*** = 10.

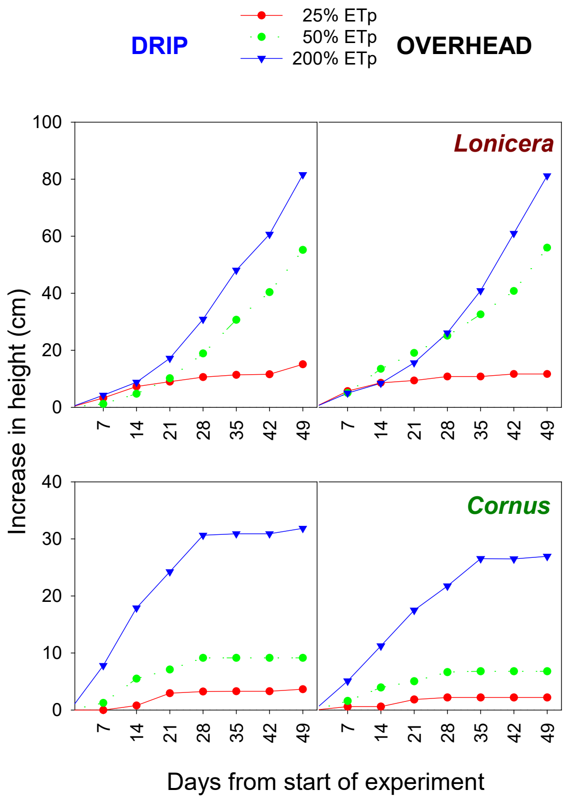

Figure 2.7. Increase in height of ***Lonicera*** and ***Cornus*** under drip and overhead irrigation and three % ET_p regimes, from the imposition of deficit irrigation treatments onwards. ***n*** = 20.

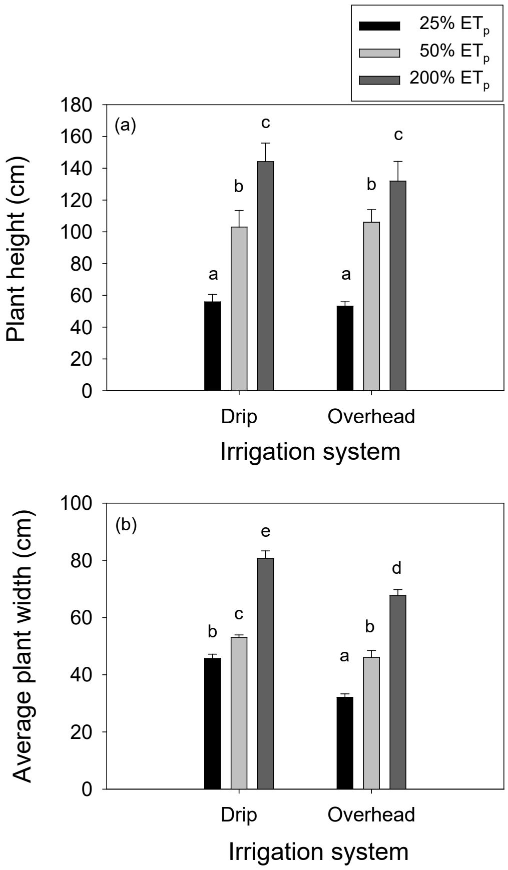

Figure 2.8. Height of *Lonicera* plants (a) and average width of *Cornus* plants (b) on 5 October 2006, after 8 weeks of drip and overhead irrigation and three % ET_p regimes. Bars represent means ± s.e. Different letters represent significant differences between means (LSD) at $P < 0.05$, $n = 20$.

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, 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% (Figure 2.9a, 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* (Figure 2.9b, d), showing the same pattern as seen in pots of *Lonicera*. In the lower part of the pot only, there was a significant interaction of irrigation and sub-treatment, with less moisture in pots without saucers than in pots on saucers under drip, but no difference between pots with or without saucers under overhead irrigation. Finally, there was a significant interaction of ET_p and sub-treatment (pots placed on saucers *vs.* pots directly on the MyPex; this subtreatment was included to determine the influence of water uptake from the base) in both sections of the pot, with lower

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substrate moisture content for pots on saucers (S) than without (NS) under 25% ET_p, but higher moisture on S than NS under 50% ET_p. These interactions probably relate to the greater importance of uptake from the MyPex when water is very sparse compared to the greater importance of preventing irrigation running away into the MyPex when water is less sparse.

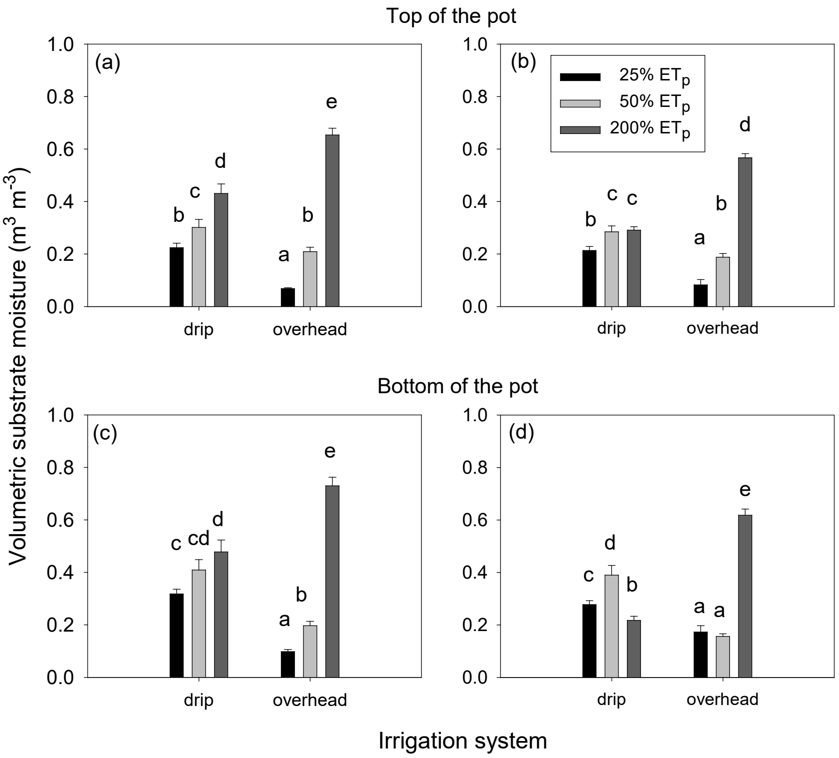

Figure 2.9. Substrate moisture at the top and 6 cm from the base of pots of *Lonicera* (a, c), and of *Cornus* (b, d) after 8 weeks of drip or overhead irrigation. Bars represent means ± s.e. Different letters represent significant differences between means (LSD) at $P < 0.05$, $n = 20$.

At the end of the experiment, when plants were separated into shoots and roots, it was found that for *Lonicera*, neither shoot nor root dry mass were significantly affected by the type of irrigation (drip *vs.* overhead). There was a significant effect of % ET_p on dry mass (Figure 2.10a, c). Root:shoot ratio decreased significantly as % ET_p increased. For *Cornus*, both shoot dry mass and root dry mass were significantly affected by % ET_p, with increasing dry mass at higher % ET_p (Figure 2.10b, d). There was also a significant difference in both shoot and root dry mass between drip and overhead irrigation, with greater dry mass under drip than overhead. Root:shoot ratio was significantly affected by % ET_p, with a lower root:shoot ratio under 25% ET_p than under the other two treatments. It is more usual to find a higher root:shoot ratio where plants receive little water: perhaps in this case under the more severe deficit regime rapid imposition of a severe stress stunted root development. It should be noted that scheduling was determined from water use by *Lonicera*, and that 200%, 50% and 25% ET_p treatments actually translate respectively as approximately 134%, 33% and 17% ET_p for *Cornus*. This highlights the difficulty of scheduling deficit irrigation for different species under the same irrigation system.

Comparing the output of the irrigation systems in use in this experiment at the beginning (before plants were placed under the irrigation) and at the end of the experiment, there was little change in the coefficient of uniformity under overhead irrigation and just small decreases in this coefficient under drip irrigation (Table 2.1).

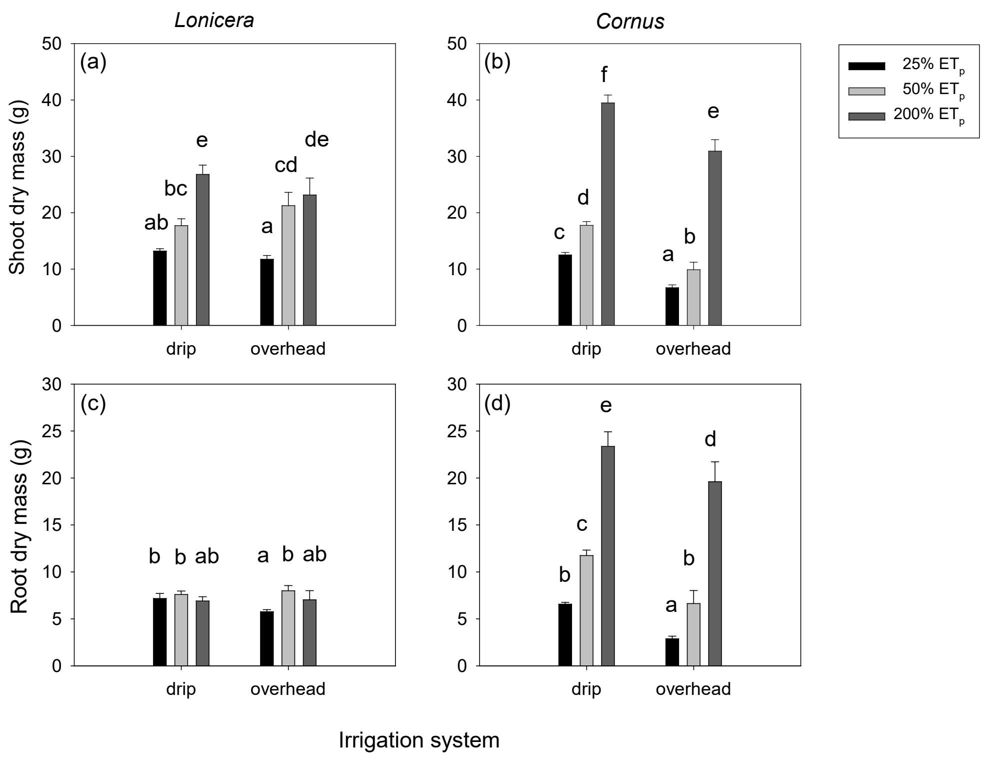

Figure 2.10. Shoot and root dry mass of *Lonicera* (a, c) and *Cornus* (b, d), harvested at the end of an experiment where plants were watered at different percentages of evapotranspiration. Bars represent means ± s.e. Different letters represent significant differences between means (LSD) at $P < 0.05$, $n = 20$.

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Table 2.1. Water output characteristics under drip and overhead irrigation systems, when installed (start) and after irrigating plants for three months (end).

a) Drip irrigation

Coefficient of uniformity (CU), scheduling coefficient (SC) and output in L h^{-1} for three lengths of pipe, each with 30 drippers.

	Drip line					
	1		2		3	
Irrigation variable	**Start**	**End**	**Start**	**End**	**Start**	**End**
CU (%)	98.01	97.59	97.82	97.43	98.02	97.44
SC	1.04	1.07	1.05	1.09	1.09	1.93
L h^{-1}	1.97	1.90	1.98	1.92	1.98	1.90

b) Overhead irrigation

Coefficient of uniformity (CU), scheduling coefficient (SC) and output (mm h^{-1}) for three bays of overhead irrigation, with six 50 L h^{-1} sprinklers (Ein dor 861) per bay, running at a pressure of 2.3 bar, at the start and end of an experiment. The sprinklers were arranged at distances of 2.25 m between sprinklers across the bay and 1.5 m between the central pair and 1.2 m between the other pairs.

Irrigation variable	**Start (average over several runs)**	**End**		
		Bay		
		1	**2**	**3**
CU (%)	91.00	93.60	90.58	90.07
SC	1.2	1.09	2.07	1.23
mm h^{-1}	7.7	7.90	7.15	6.76

The moisture in the compost in deficit treatments fell during the first two weeks after the initiation of treatments and then began to stabilise (Figure 2.11a, d), although considerable variation was seen between days. After pruning, the effect of adding water to the 50% treatment to bring them to approximately field capacity and assist in bud formation was seen as an increase in substrate moisture content late in August. Some of the day-to-day variation in substrate moisture content follows variation between dates in pot weights (Figure 2.11b, e). This variation partly reflects differences between dates according to the weather – irrigation was applied to replace water lost the previous date, so on hot, dry days following cool, higher humidity days some stress may occur before the plants receive the irrigation needed

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to replace the high transpiration on the hotter day. Some of the variation also reflects changing water use due to growth. Calibrations of water use against Evaposensor readings were undertaken frequently, but nonetheless at times of rapid growth they will have led to underestimation of water use before a new calibration was undertaken.

From the start of the experiment until pruning, rapid growth was seen in all treatments, but growth slowed in the 50% treatments from 14 days after the initiation of treatments (Figure 2.11c, f). Growth also slowed down in the 70% drip treatment. Differences between treatments in shoot growth are reflected in the average mass of shoot material harvested per plant in the different treatments: 10 – 12 g under 50% ET_p, 12 – 18 g under 70% ET_p, and 22 – 24 g under 150% ET_p.

After pruning, rapid growth was seen in the 150% treatments, with growth much reduced in the deficit irrigation treatments. Twenty-one days after pruning and onwards, growth was significantly reduced in the plants in the peat only substrate. Reduced height under deficit irrigation led to more compact plants. However, bud break was considerably reduced after pruning in the 50% ET_p treatment. This was largely alleviated by bringing the 50% ET_p plants to full pot capacity and then watering them to 70% ET_p for a week, leading to similar bud break as in the 70% treatment, but less extension growth, by 29th August. The average bud break at this time was significantly lower in the deficit treatments than in the full 150% ET_p treatments.

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 (Figure 2.12). However, there is no clear pattern under the 150% ET_p. On 26 July, again there is 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.

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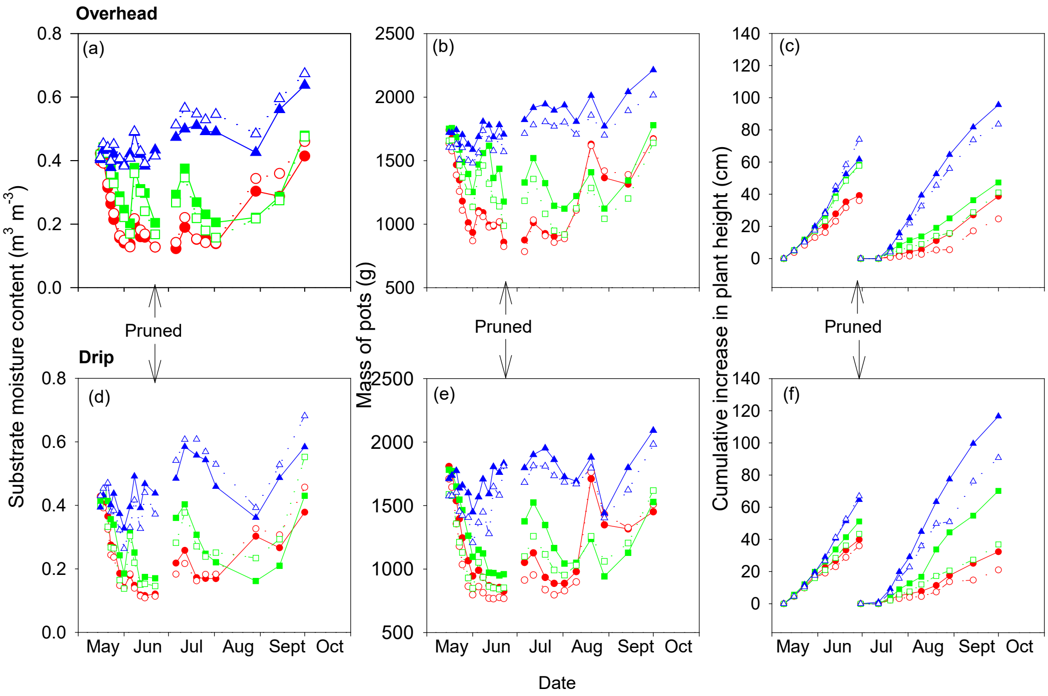

Figure 2.11. Moisture content in pots of *Forsythia* x *intermedia* 'Lynwood'(a, d), mass of the pots (b, e), and cumulative increase in plant height (c, f) after receiving 50% ET_p (circles), 70% ET_p (squares), or 150% ET_p (triangles) and with irrigation applied either overhead (top graphs) or by drippers (bottom graphs). Plants were potted in either peat (open symbols) or a peat/bark mix (closed symbols). Data are means of 16 replicates up until pruning and of 10 replicates thereafter.

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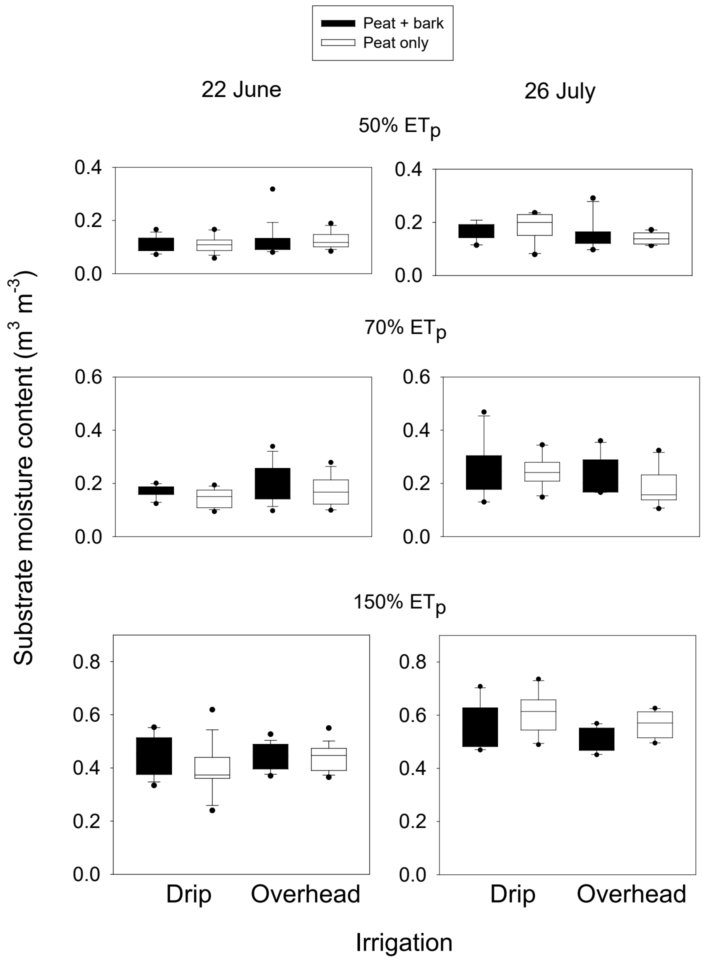

Figure 2.12. Box plots showing variation in substrate moisture content in pots of *Forsythia* under drip and overhead irrigation on two example dates: 22nd June (left, before pruning) and 26th July (right, after pruning).

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

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Deficit irrigation led to more compact plants than full irrigation. Pre-pruning (June), there was a lot of variation in plant height under both overhead and drip irrigation at 150% ET_p (Figure 2.13a, c, e). At 50% ET_p there was more variation under overhead than drip irrigation. By the end of the experiment (Figure 2.13b, d, e), a lot of variation in plant height was seen under both overhead and drip, but it was no greater under overhead than drip.

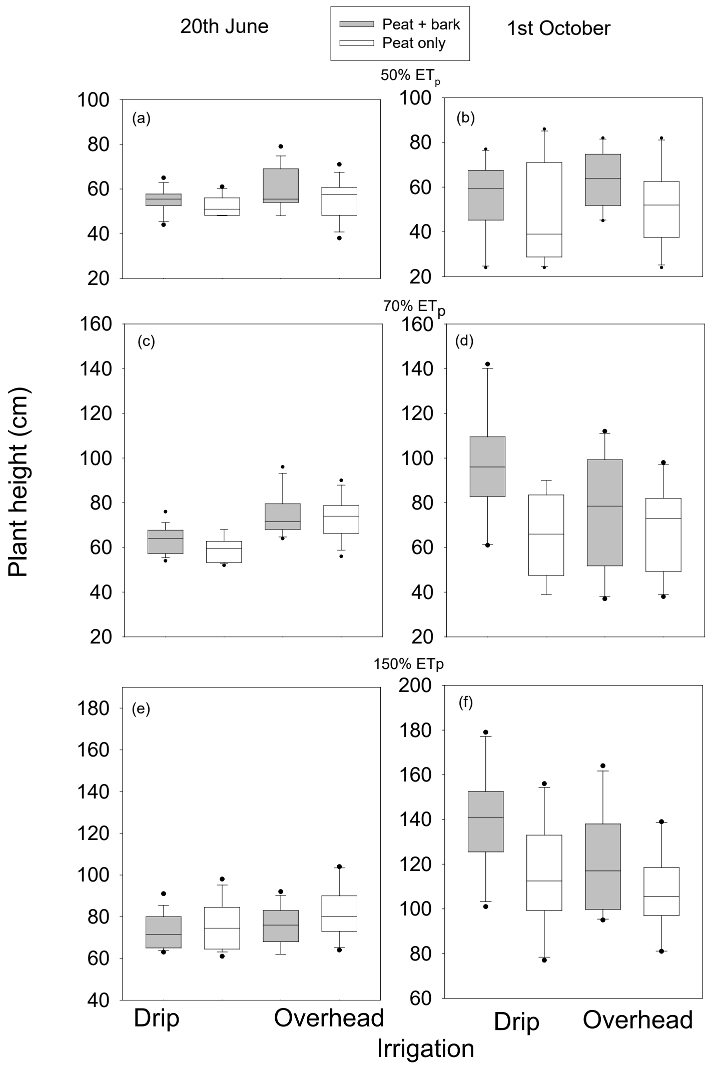

Figure 2.13. Variation in plant height early in an irrigation experiment (left) and at the end of the experiment (right) under two methods of applying irrigation and 3 different % ET_p.

At the end of the experiment, shoot dry mass was affected only by % ET_p applied, Figure 14a), with increasing shoot dry mass at increasing % ET_p. Root dry mass was

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affected by % ET_p (Figure 2.14b), also increasing with % ET_p, and by the interaction of % ET_p with the type of irrigation. Root:shoot ratio was affected by % ET_p (Figure 2.14c), type of irrigation, and the interaction of these two treatments. The root:shoot ratio decreased with increasing % ET_p under drip irrigation, but there was less difference between the different % ET_p treatments under overhead irrigation. Pruning of the plants in June means that differences in shoot mass relate only to the following three months, whereas differences in root mass will have been contributed to throughout the season May – September. Roots were generally distributed in the lower section of the pot under deficit irrigation where drip irrigation was used, but were more evenly distributed through the pot were overhead irrigation was applied.

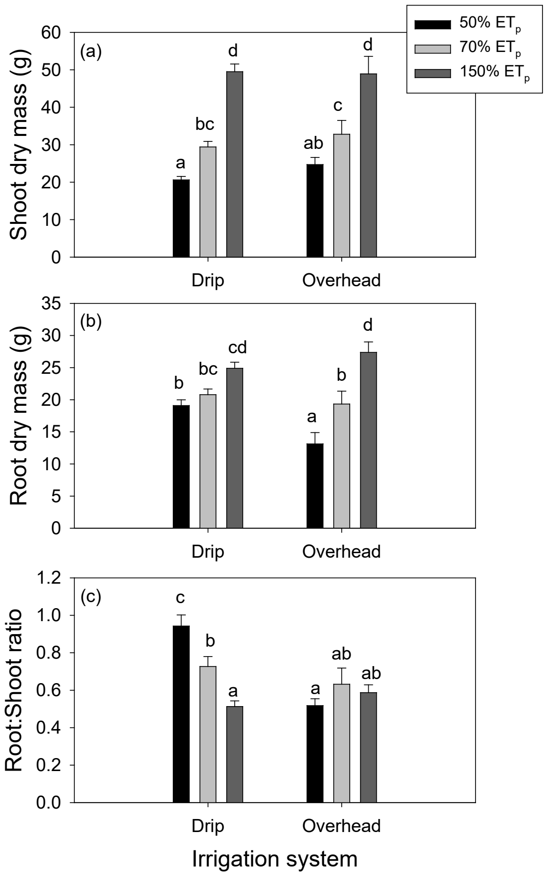

Figure 2.14. Shoot dry mass (a), root dry mass (b), and root:shoot ratio (c) under different % ET_p and overhead and drip irrigation. Data are means ± s.e., *n* = 10.

Scheduling on nurseries

At Wyevale Nurseries, there were occasions when either more or less irrigation was actually applied to the tunnel in which irrigation was to be scheduled with the Evapometer than was actually indicated by the Evapometer. Three calibrations were undertaken on 3 July, 8 August and 6 September. Overall, scheduling using the Evapometer used less water (mean 6.6 mm/day) than grower-determined irrigation (9.0 mm/day). Individual irrigations of 10 – 15 mm were applied on several occasions. This is likely to have resulted in a lot of run-through.

Figure 2.15 summarises water use from Johnsons of Whixley's trial with 5 L *Choisya*. In addition to the three scheduling treatments being compared under the NaanDan sprinklers, another bay using pinjet irrigation with grower-determined scheduling, was also monitored. The main feature in this trial was the relatively low water use in this 5 L crop. Consequently the Evapometer predicted irrigation times were not applied daily and somewhat heavier doses applied at less frequent intervals. The GP1 was set to apply irrigation at soil moisture values of 32% on and 38% off, and the system worked well over the trial and automatically applied irrigation satisfactorily. Figure 2.16 shows that only 9 irrigations were required over a 7 week period. This treatment used slightly more water than the Evapometer or grower scheduled bay, but less than the pinjet irrigated bay. It is likely that the setting of 32% on actually resulted in wetter compost than necessary to allow replacement of water lost via transpiration. In addition, the grower determined schedule probably was designed to effectively apply deficit irrigation – hence the lower water use in this treatment.

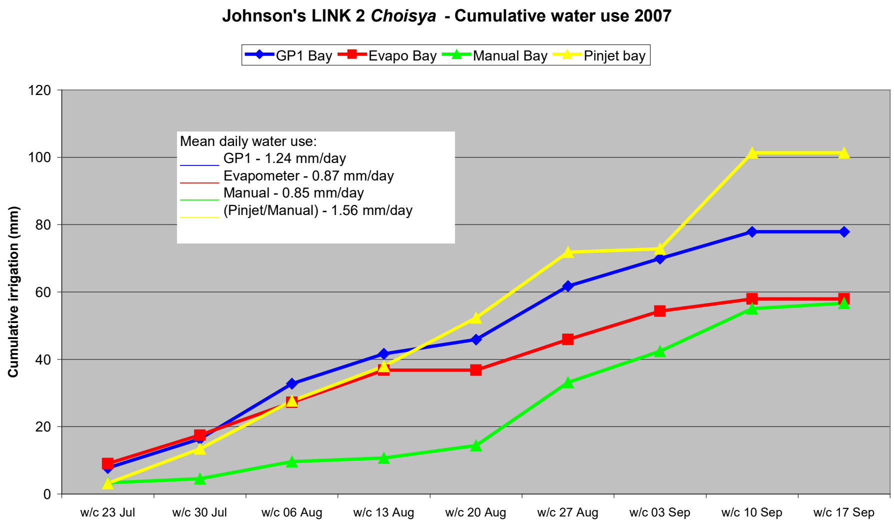

Figure 2.15. Cumulative water use and mean daily water use on different beds of *Choisya* at Johnson's of Whixley. NaanDaan sprinklers were used for all treatments other than the pinjet. As the Evapometer readings were frequently not followed, it is

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not possible to determine the true potential of the Evapometer in this case; similarly, if the GP1 settings were too high, this will have lead to greater water use than necessary.

At John Woods, an Evapometer calibration was carried out in mid-May, and indicated a mean water use per container of 1.3 ml per degree hour (°C h) requiring about 10 seconds of irrigation time per °C h for replacement, or 8.3 minutes per 50°C h. In practice, however, the grower wished to grow the *Ilex* crop relatively dry, so would apply the scheduled dose to this treatment on some occasions, and then nothing on other days. If it was desired to grow the crop on a ‘dry’ regime, it may have been more appropriate to introduce a deficit irrigation factor (e.g. 0.6 or 0.5) into the calculation so that the Evapometer schedule could be followed, but proportionately less water applied on each occasion. Mean water use over the trial was 2.9 mm/day for the Evapometer scheduled tunnel, and 2.3 mm/day for the manually scheduled tunnel.

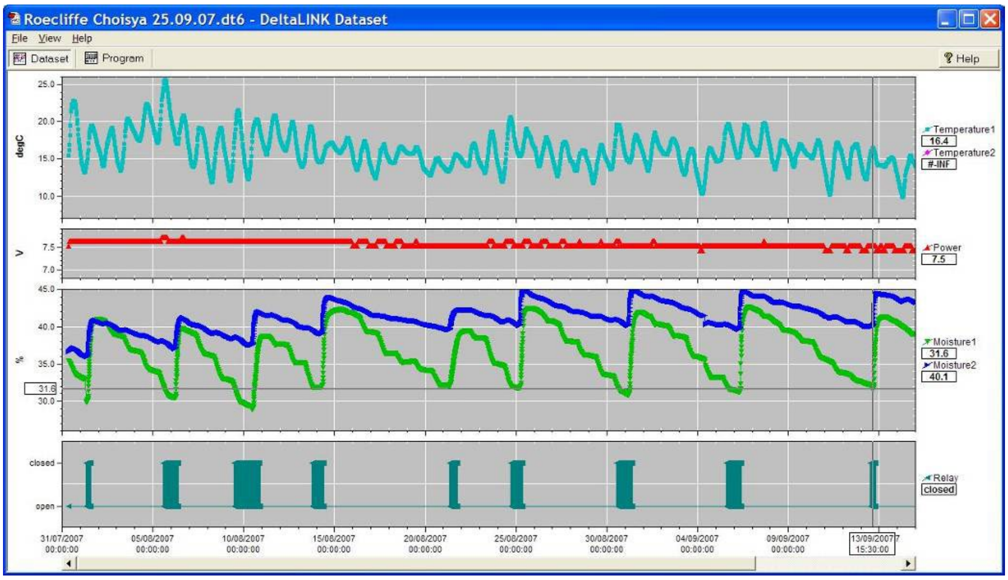

Figure 2.16. GP1 data from Johnson’s *Choisya* trial. “Moisture 1” refers to the control probe, set at 32% ON/38% OFF.

A GP1 *vs*. Manual scheduling comparison was also trialled on outdoor beds at John Woods Nurseries. However, a large mixed range of subjects were being grown, and the range of species were not identical on both beds. This meant that scheduling for either treatment could only be optimised for one subject, and compromised to some extent for the remainder. In addition, beds were part cleared of crops at different times during the season. Finally, high rainfall during the summer meant that fewer

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and less predictable irrigations were applied. This meant that no meaningful treatment comparisons could be made.

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. 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 for the pinjet bay and 1.7 mm/day for the gantry bay. 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 (Figure 2.17). Some of this was due to a time delay in water applied to the surface reaching the growing medium around the probes.

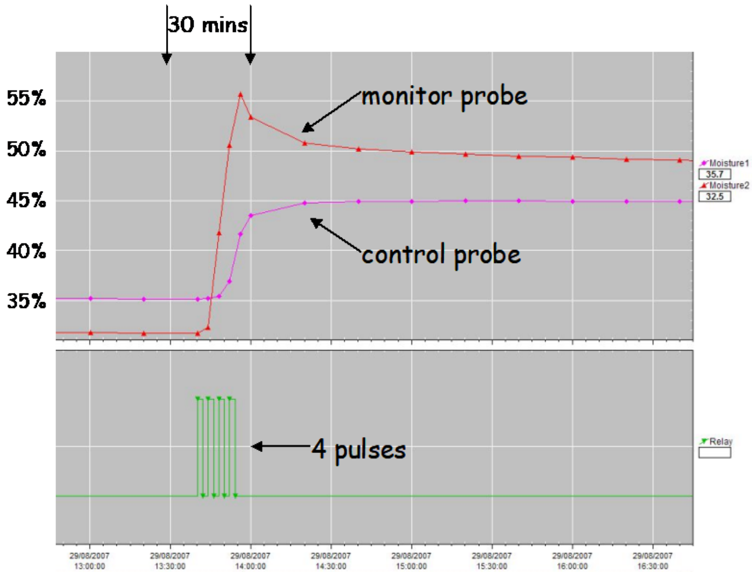

Figure 2.17. Detail of one irrigation event for the pinjet bay at Hillier Nurseries, with the program set at 35% ON/40% OFF. Four x two minute pulses were applied (b); the pot (centre of bed) and monitoring pot (edge of bed at bottom of slope) continue to wet up after the irrigation stops (a).

Garden Centre Plants trial of moisture probes

The trial at GCP was fully operational at the start of 2007 on beds in a polyspan tunnel. One SM200 (Delta T devices) probe was used to monitor moisture levels on one bed and set the irrigation for the bed accordingly. Another SM200 probe has

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been installed on the adjoining bed to monitor, but not control and hence act as a reference bed. Both probes were placed in the centre of Japanese *Acer* crops on each bed. Overhead irrigation was used rarely in autumn/winter, but the SM200 probe-controlled bed cancelled any sporadic irrigation occurrences (seen as vertical spikes on Figure 2.18) in this period where the plants were already adequately watered.

The FLIR infra-red camera was used to assess the leaf temperature of a number of crops on the beds. The camera was operated by Dr Russell Sharp (Lancaster University) and GCP's Production Manager Shaun McDonald.

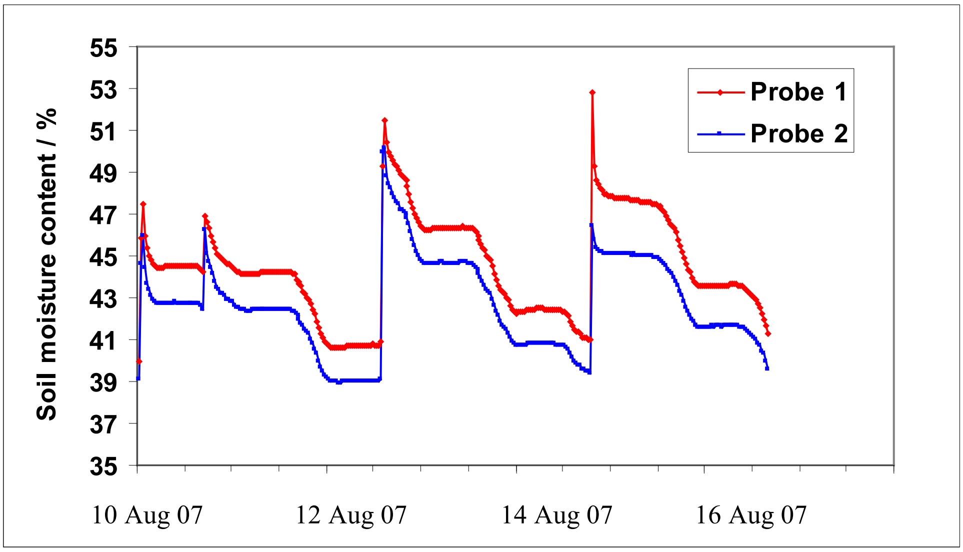

Figure 2.18. The soil moisture content of the *Euonymus* plant used to control the bed irrigation at Garden Centre Plants. As the system is set to turn on the water supply at 39% moisture you can see there is good control with approximately a 12% fluctuation.

Conclusions

- A quarter to almost half of HNS water uptake may occur via the base of the pot on impermeable surfaces. Both type of standing base and the type of plant foliage canopy affect uptake of irrigation, and both therefore need to be considered in development of scheduling systems and of precision irrigation nozzles

- Overhead sprinklers gave very uniform water *deposition* but *delivery* to plants was much more variable than with drip, partly due to variation in surface

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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

- Growth control of *Lonicera* and *Forsythia* (in separate experiments) was achieved by applying deficit irrigation, with similar results whether overhead or drip irrigation was used. With *Forsythia*, the consistent differences found throughout four months of irrigation related to the % ETp applied, with limited influence from the irrigation system or substrate (40% substitution of peat with bark did not adversely affect the effectiveness of deficit irrigation).

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OBJECTIVE 3

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

Introduction

Theoretical sensitivity of thermal imaging

The results from a number of previous studies were collated and further analysis of the basic energy balance equations was undertaken to determine variation in leaf temperatures, determine the optimal conditions for use of thermal imaging in HNS irrigation scheduling and to derive strategies for the deployment of thermal sensing of stress or stomatal closure.

First it is necessary to determine whether *absolute estimates* of stomatal conductance are required or whether *relative measures* are adequate. The latter approach would be adequate if a well-watered control plant could always available, but in most cases decision must be made in the absence of a well-watered control, so absolute estimates are preferable, and we will concentrate on the accuracy of absolute measures of conductance. Nevertheless for evaluation purposes at least, relative measures can give a good measure of sensitivity.

Concentrating on the key linkage between stomatal conductance and thermal measurements obtained with a thermal camera or other infrared sensor. Figure 3.1 and Figure 3.2 show the calculated sensitivity of thermal sensing for the detection of a 20% reduction in stomatal conductance from a typical well-watered value of 200 mmol m^{-2} s^{-1}.

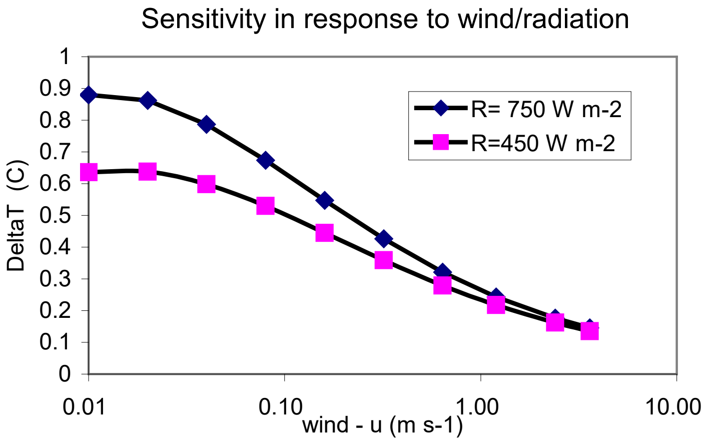

Figure 3.1. The leaf temperature change expected for a 20% decrease in stomatal conductance from a typical well-watered value of 200 mmol m-2 s-1 (= 5 mm s-1): response to varying wind-speed. Calculations shown for broad leaves (10 cm across) under bright sun conditions.

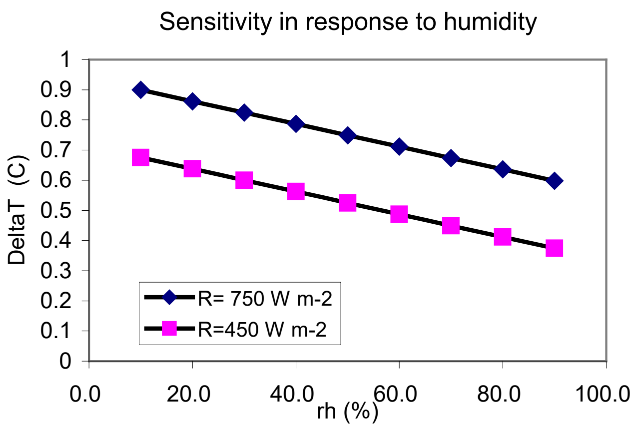

Figure 3.2. The leaf temperature change expected for a 20% decrease in stomatal conductance from a typical well-watered value of 200 mmol m-2 s-1 (= 5 mm s-1): response to varying air humidity. Other conditions as for Figure 3.1.

It is apparent from these figures that thermal approaches are most sensitive at low windspeeds, at low humidity (relatively dry air) and with high irradiance. The responses to radiation and to humidity are both linear, but the response to wind-speed is non-linear with the sensitivity being much the greatest in still- or relatively still-air. 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 windspeed can be partly offset by the higher humidities often encountered. Figure 3.3 shows that a 20% reduction in conductance is almost equally detectable for conductances above about 100 mmol m^{-2} s^{-1}.

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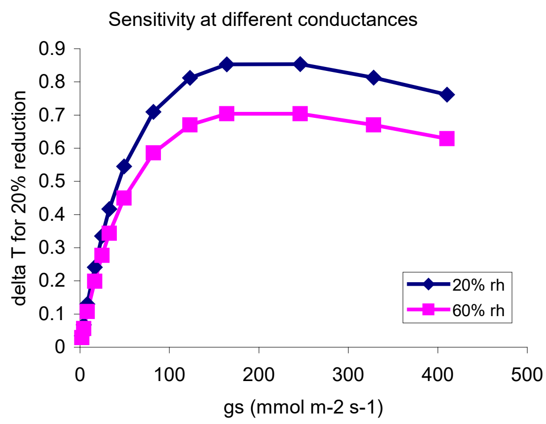

Figure 3.3. This illustrates for two different humidities how the sensitivity of temperature to a 20% reduction in conductance depends on the initial control value (given on the x-axis).

Potential sources of variability and error in the use of thermography for detecting plant stress were considered.

Canopy variability: Leaves in any HNS canopy will be receiving differing amounts of incoming radiation and therefore heat up differentially. This problem is less severe under low irradiance conditions than in full sunlight. There is, however, a trade-off between the advantage of doing measurements in lower light and the advantage of getting greater sensitivity at higher light. This trade-off needs to be evaluated specifically for different HNS subject species. It is also worth noting the fact that stomata tend to show a diurnal trend in opening, with partial closure in the afternoon and complete closure at night; this implies that 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 sensors arrays in thermal cameras produce a grid of data points or pixels that cover the field of view. Generally the more expensive the instrument the more individual sensors there will be in the array and the smaller the proportion of the total image each sensor will be recording. In an array such as the IRISYS 1002 where there are only 16 x16 sensors the individual sensors cover relatively large areas. This means individual sensors may often be recording temperatures from multiple objects, such as leaf and background compost or pots.

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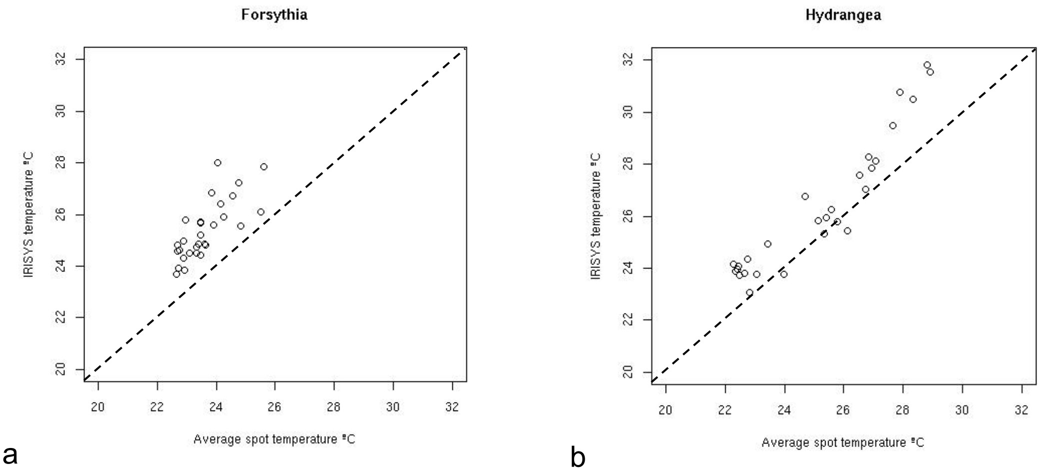

a b

Figure 3.4: IRISYS 2001 temperature measurements for (a) Forsythia and (b) Hydrangea, against average spot leaf temperature measurements. The dashed line indicates the 1:1 relationship

This can lead to errors in leaf temperature measurements as shown in Figure 3.4 where thermal image acquired temperatures are plotted against spot temperature measures. The background was warmer than the plant leading to higher leaf temperatures recorded by the imager especially with sparse canopies and small leaved species.

Sensor thermal resolution (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.

Sensors thermal accuracy: (the precision with which 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.

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*Reference Surfaces:*A further advantage in the use of comparable reference surfaces is that this approach also takes account of most of the effects of fluctuating environmental conditions (e.g. varying wind speed or radiation). There are two ways in which reference surface temperatures can be used, to calculate the stomatal conductance directly or to calculate an index that is indicative of the degree of stomatal closure. Direct estimation of stomatal conductance requires some supplementary environmental information. Therefore initial tests have used a simple index, based on Idso's Crop Water Stress Index, that calculates a temperature index (T_i) as

$$T_i = \frac{(T_l - T_w)}{(T_d - T_w)} \qquad \textbf{(3-1)}$$

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. The use of this simple index will be compared in future work with alternative indexes/models that have differing requirements for supplementary environmental information. These alternative systems include (see Leinonen et al., 2006 for details):

(a) use of wet and dry reference surfaces to calculate a stomatal resistance (r_s or conductance):

$$r_s = (r_{aW} + \frac{s}{\gamma} r_{HR}) \frac{(T_l - T_w)}{(T_d - T_w)} \qquad \textbf{(3-2)}$$

where r_{aW} and r_{HR} are measures of the boundary layer resistance (a function of windspeed and leaf size) and s and γ are physical constants.

(b) use of only a dry reference surface to calculate a stomatal resistance (r_s or conductance):

$$r_s = -\rho c_p r_{HR} \frac{(s(T_l - T_a) + D)}{(\gamma \rho c_p (T_l - T_d))} - r_{aW} \qquad \textbf{(3-3)}$$

where ρ and c_p are physical constants and D is the atmospheric humidity.

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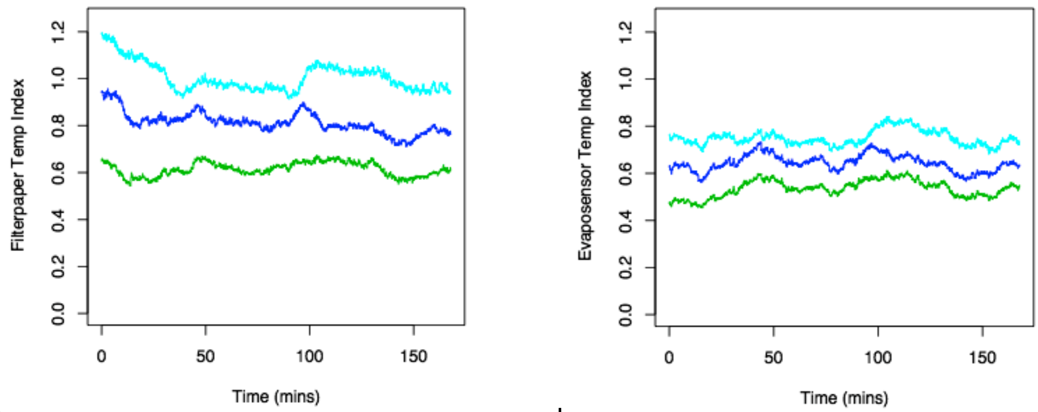
Evaluation of the performance of alternative reference temperature sources

Two methods of generating reference temperatures were initially investigated. Firstly using 9cm discs of wetted and of dry filter second using a Skye EvapoSensor and taking the temperatures of the dry and the wet arms as the dry and wet reference surfaces.

Figure 3.5 shows the temperature stress index calculated using equation 3.1 for three differentially stressed *Hydrangea* plants over a period of 3 hours with fluctuating environmental conditions using either wet/dry filter paper references or the EvapoSensor references.



a b

Figure 3.5. Temperature index for Hydrangea over time for (cyan) 16% soil moisture, (blue) 45% soil moisture and (green) 75% soil moisture, using (a) filter paper references (b) EvapoSensor references.

In both Figure 3.1a and b the top cyan line is for a plant with soil moisture of 16% and a measured stomatal conductance of 45 mmol m^{-2} s^{-1}, the middle blue line is for a plant with soil moisture of 34% and a measured stomatal conductance of 70 mmol m^{-2} s^{-1} and the bottom green line is for a plant with soil moisture of 75% and a measured stomatal conductance of 120 mmol m^{-2} s^{-1}. The wet/dry filter paper references give a better resolution of temperature index as shown in Figure 3.6.

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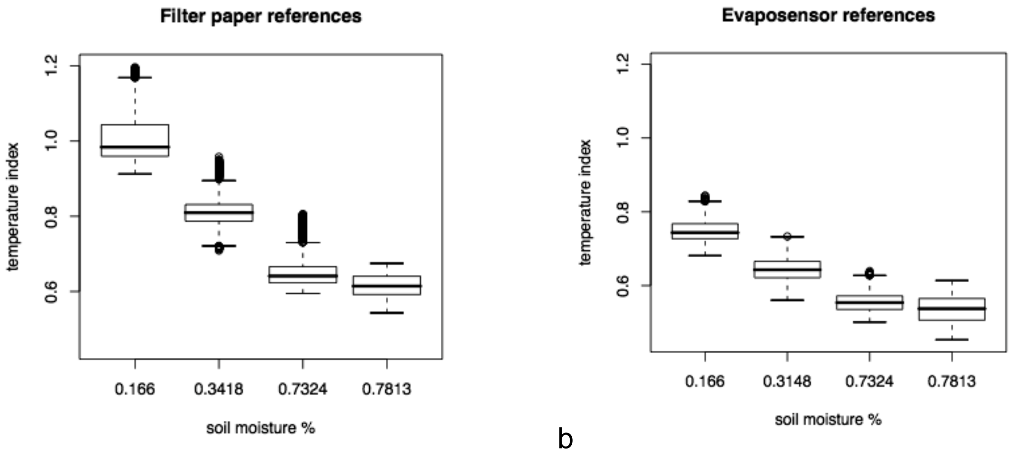
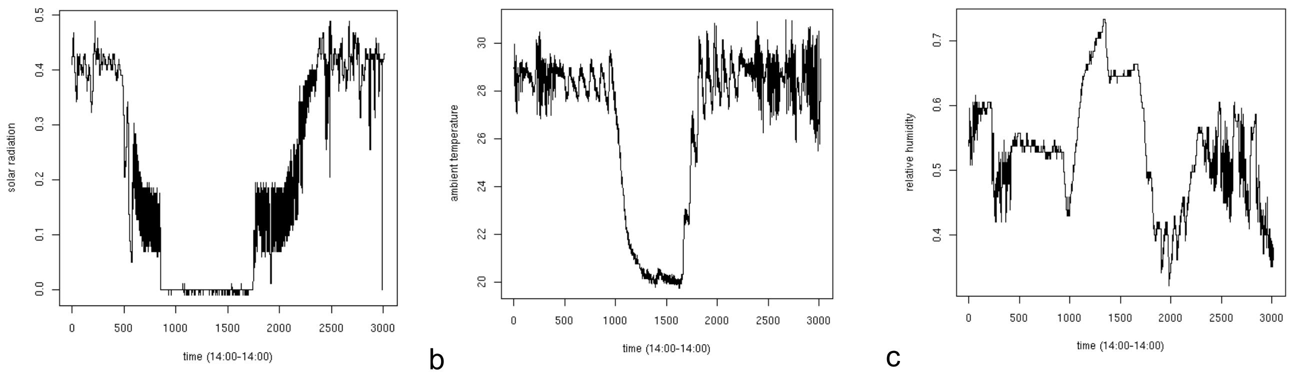


a b

Figure 3.6. Box-whisker plots of the simple temperature index (Ti) for Hydrangea plants with different substrate moisture contents.

Predicting plant temperatures from a dry reference: The possibility of using a simplified model using a single dry reference to predicted expected canopy temperature was also investigated. Using a 9cm disc of dry filter paper as the dry reference, temperature of two well-watered Choisya plants were monitored over a 24 hour period from early afternoon through to the same time the following day, using the thermal camera system described in objective 6 and 7. Figure 3.7 shows the fluctuation in environmental conditions over the 24 hours.



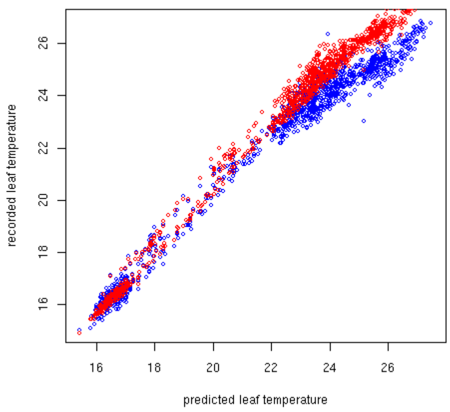
a b c

Figure 3.7. Variation in a) incident radiation b) ambient temperature c) relative humidity over a 24 hour period (14:00-14:00) for a well watered (pot moisture content 0.4 ml/ml) Choisya.

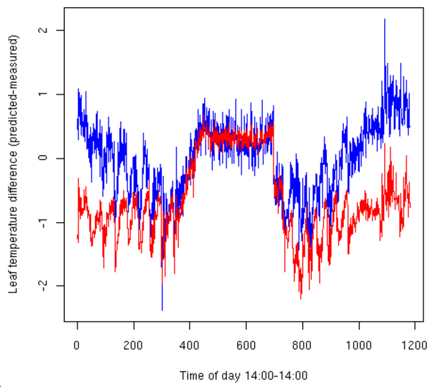
A simple model for canopy temperature T_l as a linear function of dry reference temperature

$$T_l = a + bT_d \, , \qquad \textbf{(3-4)}$$

where T_d is the dry reference temperature, was fitted to the data giving the values *a*= 2.3202 *se*=0.0968 and *b*=0.8733 *se*=0.0042. The fitted model was then used with these values to predict expected temperatures for pairs of different well watered and droughted Choisya plants measured over a different 24 hour period. Figure 3.8a shows a plot of the predicted and the recorded leaf temperatures for a pair of Choisya plants recorded simultaneously over a 24 hour period (14:00-14:00). The red points are for a droughted plant, pot volumetric water content at the start of the time was 0.16 ml/ml, and the blue points are for a well watered plant pot volumetric water content at the start of the time was 0.45 ml/ml. Figure 3.8b shows a clear distinction between the two treatments during the daylight period when stomata should be open.



a



b

Figure 3.8: (a) predicted temperature leaf temperatures against measured leaf temperature for a droughted (red) and well watered (blue) Choisya. (b) The data plotted against time over a 24 hour period.

<u>Use of hand-held thermal imagers for rapid monitoring of plant stress</u>

Tests were performed at Johnsons of Whixley near York during June 2007 to investigate the use of uncalibrated hand-held thermal imagers for irrigation monitoring. In order to determine whether hand-held thermal imagers could be used successfully to detect droughted plants in field conditions, a range of plants with varying water status was produced. Plants of a selection of common HNS species were taken from open-air beds and placed in an unheated glasshouse for a short period to dry while the plants left in the beds were irrigated as normal. The plants were then returned to the beds and a thermal imager used to survey the beds and identify stressed plants.

Materials and Methods

Plants of twelve ornamental species normally grown at the nursery were selected (listed in Table 3.1). Groups of 3 to 5 plants of each species were taken from locations on the main Johnsons Head Office site. Due to the pot sizes and the amount of rainfall in the previous few days, however, the pots were very wet so plants were removed to an unheated glasshouse and then left unwatered for 5 days. The plants were then returned to their locations they were left for a minimum of 2 hours to acclimatize to the outside conditions. Weather conditions on the day the plants were replaced were cloudy with some break providing periods of full sun.

The volumetric moisture content of the returned pots was measured using a Delta-T MX2 Theta Probe and the moisture content of a similar number of randomly chosen pots in the surrounding bed was also measured. To give an indication how much drier the removed pots had become over the drying period than the plants left in the bed a moisture loss ratio m_L was calculated,

$$m_L = 1 - \frac{m_R}{m_C}, \quad \textbf{(3-5)}$$

where m_R is the average volumetric moisture content of the removed and m_C the average volumetric moisture content of the surrounding control pots (Table 3.1). Images of the plants were recorded *in situ* using a Canon PC1001 digital camera for visible images and a FLIR P25 thermal imager for thermal images. The images were then analysed to look for detectable temperature variations between the water-restricted and control plants and for detectable changes in the visible images alone.

Results

*Detecting stressed plants***:** figure 3.9 shows the analysis for the *Hydrangea lacecap white* images. In this case the droughted leaves had wilted and dried and differences were clearly visible to the naked eye from both leaf shape and condition. This can also be seen from the RGB histograms which show a clear colour shift between the droughted and non-droughted plants. To quantify this visible change in the leaf colour a single hue value was calculated from the red, green and blue component of the pixels for plants. The average hue for droughted and non-droughted plant areas are indicated on the hue colour wheel at the right of figure 3.9. There has been a shift from the green/yellow region of the spectrum to the blue/green region. Figure 3.9. The droughted plant (area AR01) in the image is substantially (c. 0.7°C) warmer than the non-droughted plant (area AR02) this can be seen by the graph (inset bottom left) showing the temperature distribution for droughted (red) compared to non-droughted areas (green).

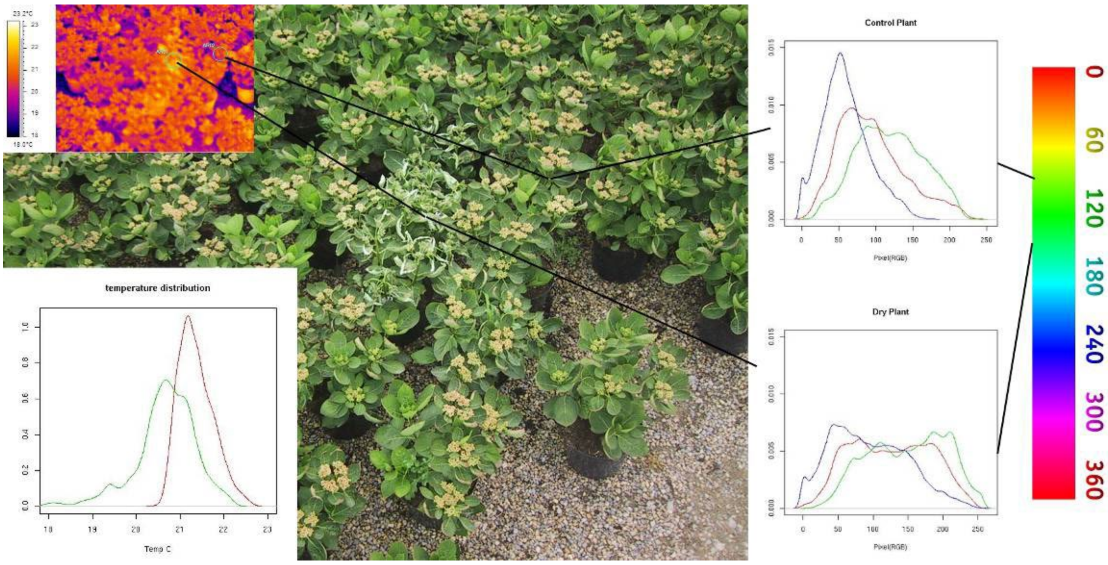


Figure 3.9. Analysis of images of H. lacecap white. thermal image (top left) temperature distribution (bottom left) of droughted area AR01 (red) and non-droughted area ARO2 (green). RGB pixel intensity (top right) for non-droughted area AR02, pixel intensity (bottom right)

Figure 3.10 shows a similar analysis for the *Hebe ping sutherlandii*, again the thermal, image inset top left, shows very clearly the droughted plants with higher temperature. In this case however there is little visible difference between the droughted and control plants with the hue being almost identical.

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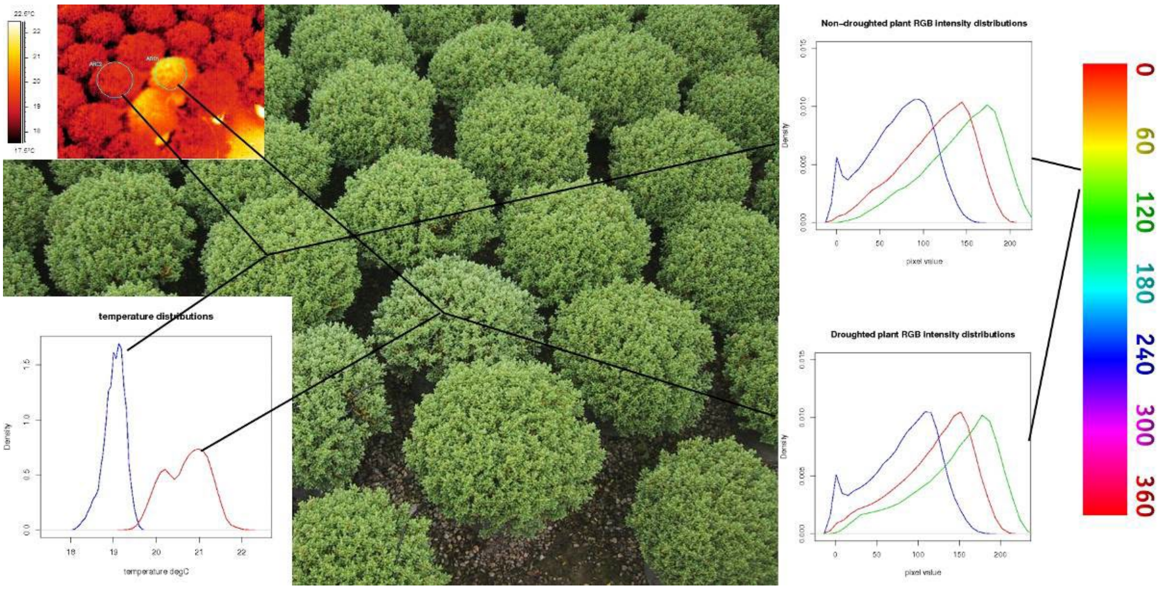

Figure 3.10. Analysis of images of Hebe ping sutherlandii, thermal image (top left) temperature distribution (bottom left) of droughted area AR01 (red) and non-droughted area ARO2 (green). RGB pixel intensity (top right) for non-droughted area AR02, pixel intensity (bottom right).

Equivalent analyses were performed for all the species in the trial (see Table 3.1). In all cases for green leafed plants there was a blue shift in the hue value though in many cases this was less than a 1%. It should be noted that the change in hue was dependent on the visible camera used. Due to battery failure the images for *Amelanchia Canadensis* and *Prunus lusitanica* were taken using the visible light camera built into the FLIR. This was a lower resolution camera than the Canon used for the other readings. Further investigation of this is being undertaken.

Table 3.1. Summary of mean temperature for droughted and non-droughted plants,† Incident solar radiation was not measured however the cloud cover was noted.

Species name	air temp	†Light	moisture %loss	droughted plant temp	control plant temp	Hue shift
Hydrangea lacecap white	20.97	overcast	48	21.34	20.65	7.4
Hydrangea lacecap red	21.34	overcast	53	22.10	21.14	11.2
Hebe ping sutherlandii	21.96	overcast	74	20.69	19.02	0.4
Cotinus royal purple (15 l)	22.64	overcast	33	21.58	21.55	10.3
Cotinus royal purple (7.5 l)	21.58	overcast	57	21.54	19.64	2.6
Amelanchia canadensis	20.79	overcast	74	20.68	20.39	24.1
Prunus lusitanica	21.45	overcast	35	21.52	20.25	25.8
Cornus alba ivory	24.52	overcast	50	20.21	19.51	0.1
Brachyglottis sunshine	25.21	patchy sun	67	24.10	21.04	8.7
Prunus etna	23.25	full sun	78	24.40	22.80	0.1
Prunus otto luykens	23.25	patchy sun	66	24.60	22.40	0.7
Viburnum tinus	23.45	patchy sun	35	23.65	23.95	0.1
Philadelphus virginal	24.01	full sun	81	32.15	29.98	1.2
Viburnum burkwoodii	24.42	full sun	24	28.77	27.65	0.1

Irrigation coverage: Figure 3.11 shows *Prunus etna* and *P. otto luykens*. Although the treated plants are not detectable in the visible image (top left) they are clearly highlighted in the thermal image (top centre & top right).

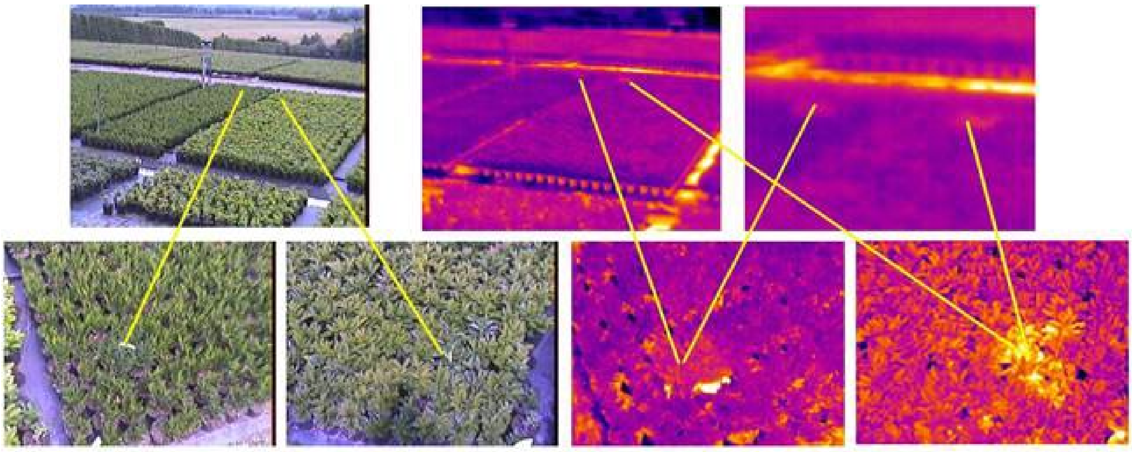

Figure 3.11. Visible light image of Prunus otto luykens and Prunus etna beds (top left), thermal image of same beds (top centre), enlargement of droughted plants region of thermal image (top right). Close up visible image of P. otto luykens (bottom left outer) and P. etna (bottom left inner) and corresponding thermal images P. otto luykens (bottom right inner) and P. etna (bottom right outer).

Figure 3.12 shows an area of a bed of *Cotinus royal purple* plants with the corresponding thermal image. The pots outlined in the yellow regions had an average volumetric soil moisture content of 28.3% whereas those in the region outlined in green had and average volumetric soil moisture content of 44.9%. This is reflected in the thermal image where the yellow region has an average temperature of 20.2°C and the green region has an average temperature of 19.5°C; again there was no distinguishable visible difference.

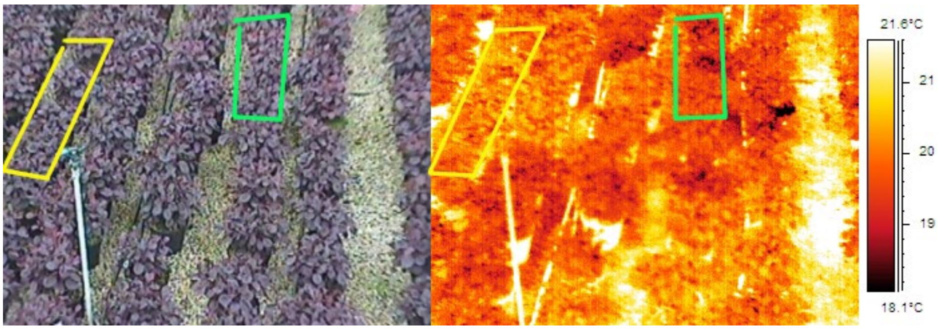

Figure 3.12. Thermal (right) and visible light (left) images of Cotinus royal purple plants in a sprinkler irrigated bed. The yellow outlined region had an average volumetric pot moisture content of 28.3% whereas the green outlined region had and average volumetric soil moisture content of 44.9%. This is reflected in the thermal image where the yellow region has an average temperature of 20.2°C and the green region has an average temperature of 19.5°C. There was no distinguishable difference in the thermal image between the wetter and dryer plants.

Figure 3.13 shows a third example for *Hebe pin*g *sutherlandii* where again there was substantial variation in temperature across this bed with no visible variation. We suspect this temperature variation was related to variation in plant water relations.

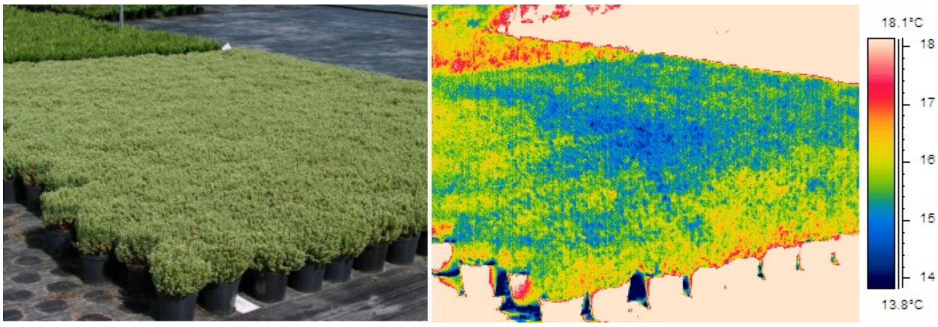

Figure 3.13. Variation of temperature presumably related to soil moisture content variation in Hebe ping sutherlandii, where no visible differences were discernable between plants

Cross species comparison: Figure 3.14 a shows a plot of the average leaf temperature against average volumetric soil moisture content for all the plants in the trial. In this raw data presentation there is substantial variability as the effect of soil moisture is overshadowed by the environmental variation with time (especially sunshine).

However when the data are plotted as temperature difference against percentage moisture reduction as in Figure 3.14b the effect of reduced moisture on temperature becomes much clearer with increasing temperature difference 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, though more data are needed.

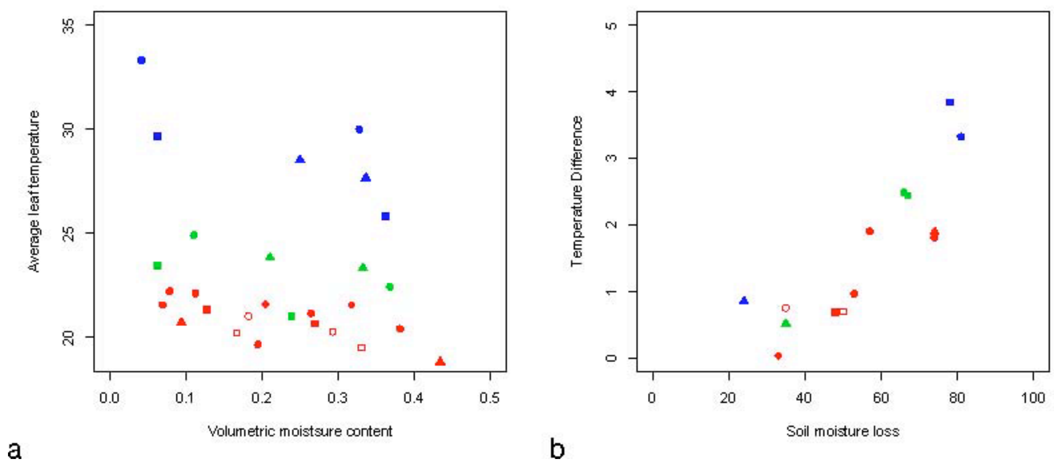

Figure 3.14. (a) A plot of leaf temperature (°C) against soil moisture content (m3 m-3): matching symbols and colours represent dry and wet data for the same species. (b) leaf temperature difference (°C) against percentage moisture loss, (blue) full sun (green) patchy sun (red) overcast.

Effects of palette and temperature scaling: Many thermal imagers available have the ability to adjust the colour palette and temperature range of the live image in the view finder and most come with software that permits enables the manipulation of these properties in saved image files.

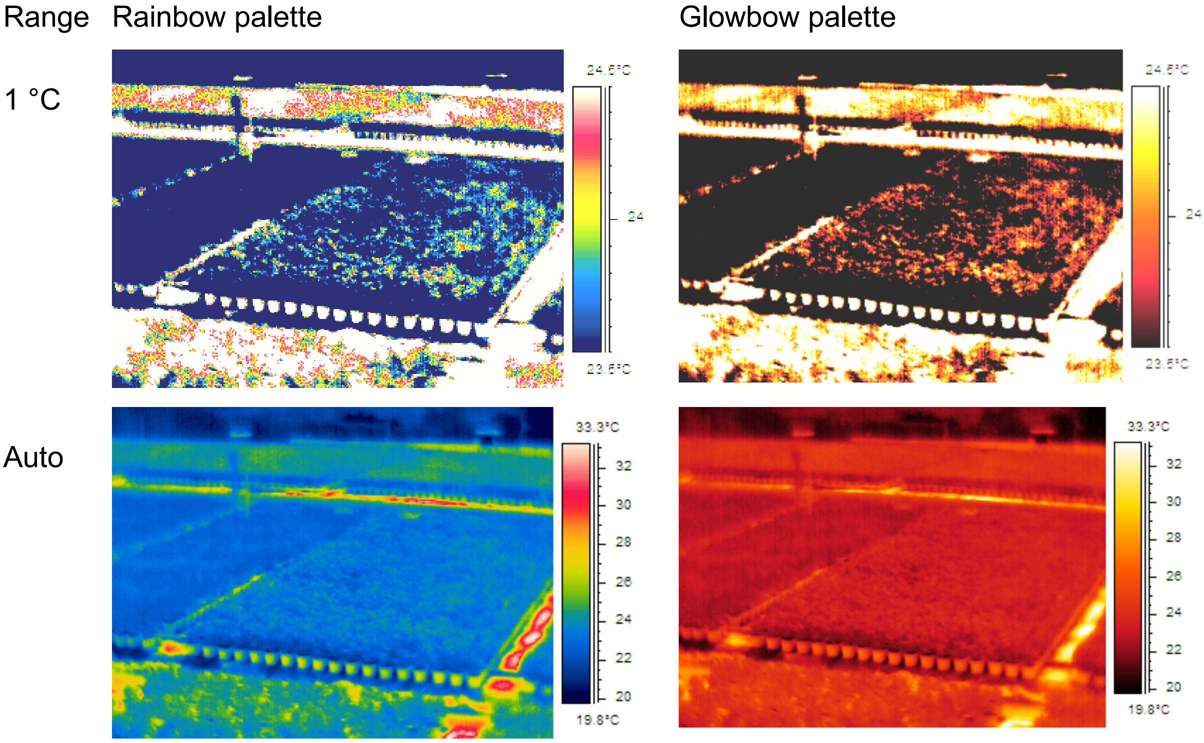

Figure 3.15. Visual effects of selecting various temperature ranges for thermal images using the rainbow and glowbow palettes. The auto range is the range selected by the camera.

Most thermal images have an automatic setting for the temperature range, this range is normally set to be from the minimum to the maximum temperature visible in the field of view. While this is a natural choice for many applications and permits good visible resolution of objects in the view finder it is not necessarily a good option for spotting overheated, dry plant. This is illustrated in Figure 3.15 which shows examples of different 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", while 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.

Use of thermal imaging camera at Garden Centre Plants

IR images were taken on several of the growing beds at GCP to assess a) the uniformity of irrigation application and b) the ability of the thermal imaging camera to discern differences in temperature between plants in a nursery situation. It also

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showed that there were significant effects of pesticide residues on leaf temperature. The ability to detect differences in leaf temperature varied from species to species. It was found that the best images were obtained if you could exclude pots, floor and metal objects from the view (Figure 3.16). These conditions were obtained most often in closed canopy crops such as thyme and grasses. However on climbers such as clematis, which represent a major species for GCP, no differences could be easily detected as the cane supports and pots obscured any differences in leaf temperature (Figure 3.17). With IR technology developing rapidly, we could soon have a cheap camera available for use on nurseries to quickly assess plant stress levels. Cameras can also be used in conjunction with gantry irrigation systems (see elsewhere in report).

Figure 3.16. Garden Centre Plants' Production Manager Shaun McDonald using the thermal imaging camera to assess the plants on outside beds.

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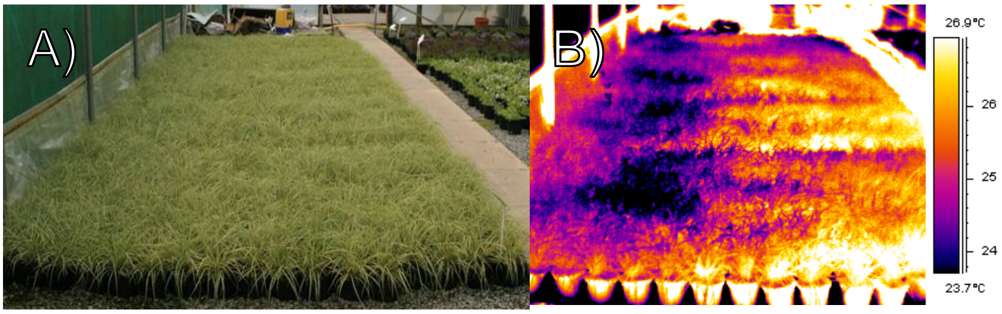

3.17. A) a visible spectrum and B) infrared image of grasses at Garden Centre Plants. The lack of metal objects and plastic sheeting between the plants allows you to easily see the differences in leaf temperature in the crop.

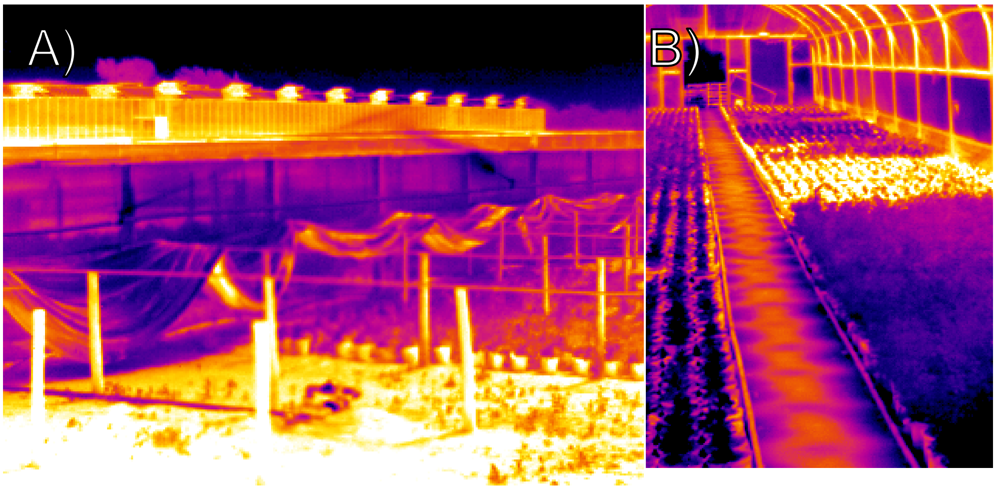

Figure 3.18. Areas of the nursery set aside for growing climbers often have large support structures which obstruct the capturing of decent images of leaf temperature. B) An image showing clear differences between crops on a bed in a polytunnel.

Conclusions

- It is clear that even low precision thermal cameras have adequate sensitivity in relation to the expected variation in leaf temperature, with the primary determinant of success being more likely to relate to biological and irradiance heterogeneity.

- 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.

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- Our studies have confirmed that sensitivity to stress is greatest at low humidity, high irradiance and low windspeeds - we therefore recommend that development of practical sampling protocols will need to take these factors into account.

- Monitoring tests demonstrated the power of thermography for monitoring of irrigation in an HNS production environment. Using a handheld thermal imager, not only was it possible to identify individual plants in the early stages of water stress, but it was also possible to identify 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/scale that would maximise the ability to discriminate. The best results are obtained with high resolution cameras.

- Our trial also indicated potential scope for water conservation with at least 20% of water loss occurring before any thermal differences were apparent. These results may have been a result of the large amount of rainfall in the week prior to the trial and may suggest scope for delaying irrigation after rainfall without stressing the plants.

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OBJECTIVES 4 & 5

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

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

Introduction

The regulated deficit irrigation undertaken at EMR that has been described under Objective 2 also addresses Objective 4.

Last year we reported that alkaline buffers applied both as foliar sprays and root drenches were effective in controlling growth and closing stomata. This response is consistent with previous reports from the Lancaster group that alkaline buffer treatments can regulate water loss from HONS (Wilkinson and Davies, 2008 JXB in the press). In the present study, these responses were observed in a range of HONS species and were independent of the species' natural pH responses to drought stress. Here we report that the effects of buffer treatment on stomatal closure are translated into tangible savings in water use by crops.

The work in 2007 has furthered the development of protocols for the application of buffers on nurseries. Adjuvants have been ruled out as a requirement for optimum buffer performance as efficacy was not significantly improved by their addition. We have worked towards determining the optimum concentration of buffer required and the most suitable compounds to use to alkalise the apoplast of the crop. We have found that the alkaline buffer concentration needs to be higher in HONS species to be effective at closing stomata because xylem sap of HONS species has greater buffering capacities than herbaceous species. We have also ruled out the possibility of buffers being used on Ericaceous species, with toxicity to the plants found even when the buffer was applied only to the foliage.

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Materials and Methods

Experiments were conducted in the glasshouses at Lancaster University. The rooting medium used for all plants that were re-potted was a standard compost mix containing: peat, magnesium limestone and Osmocote CRF. MiracleGrow/Miracid liquid fertiliser was applied to all plants before the imposition of treatments.

Data were analysed using Genstat software. Results were analysed by analysis of variance and significance amongst mean values was determined by least significant difference (LSD) values where P = 0.05. LSD values were calculated from standard error of difference of means (SED) and the relevant degrees of freedom.

Results and Discussion

The effects of alkaline buffers on plant water use

Previously we have reported that alkaline buffers can control plant growth and development. However, here we wanted to also investigate whether stomatal closure leads to a significant effect on plant/crop water use. Applications of pH 8.0 buffer were made as a foliar spray twice weekly to *Euonymus* in 2 L containers. 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 (20 mM) due to a lack of activity on other species tested. Water use was monitored every other day and plants were maintained at an optimum container capacity.

The effects of alkaline buffer on xylem sap pH

The alkaline buffers have been designed to manipulate the plant's natural signalling pathways. Therefore, it is essential to know that any treatment you apply is actually having the desired effect on the signalling pathways. Here we tested whether or not the buffers were actually alkalising xylem sap and then investigated the persistence of the effects.

Cortaderia and *Hydrangea* plants were sprayed with a single foliar spray of alkaline buffers. Water potentials and xylem sap pH was monitored in the subsequent days

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to ascertain whether or not the sap pH was significantly increased and for how long the effects lasted.

The buffering capacity of xylem sap from HONS species

We investigated how the buffering capacity of sap from different species differs. This information is essential for designing any future treatments because it may be that a buffer concentration active in one species may be ineffective in another HONS species. Xylem sap was collected from well-watered plants of the species that were growing in the glasshouse and that had anatomies conducive to sap extraction. Collection was completed once 400 µL of sap was collected into Eppendorf tubes and placed on ice. A sub-sample of 200 µL was gradually alkalised with 10 µL of 0.01M NaOH and the pH of the sap was noted after each alkalisation until a pH of 10.0 was achieved. 10 µL of 0.1M HCl was then added until the pH reached 3.0. 200 µL of fresh sap was also directly acidified for comparison.

The use of adjuvants to increase activity of alkaline buffers

At a previous meeting of the project steering group, it was suggested that adjuvants may help in the delivery of buffers across the leaf surface and into the transpiration stream (Cole, pers comm.). The adjuvant ‘Sprayfast’ was chosen as it is registered for use in the UK and is designed as a wetter/spreader and its properties suited the role required. *Forsythia* cv. ‘Lynwood’ plants in 3 L pots were maintained in a well-watered regime and all treatments were applied as foliar sprays. Application were either water controls, alkaline buffers (100mM, pH8.0) with or without an adjuvant (Sprayfast, Mandops, Hampshire), and the one treatment of the adjuvant alone. Stomatal conductance was measured one day, and one week after the first application. If the adjuvant increased the effect of the buffer it would be seen by a further reduction in stomatal conductance below the level seen in alkaline buffer alone.

Use of alkaline buffers to protect plants from atmospheric ozone pollution

As we have found that alkaline buffers can close stomata relatively rapidly and the effect persists for several days, we have investigated the possibility that they could be used in situations were environmental stresses can result in stomata being locked open leading to leaf desiccation and accelerated senescence. The locking open of stomata can occur under high atmospheric ozone and during periods of low temperature. If the stomata can be closed when these conditions are forecast, we might be able to mitigate some of the harmful effects on the plants. Under high atmospheric ozone (often found on still sunny days) it is thought that the ozone prevents the closure of stomatal guard cells and the ozone then breaks down internal membranes and components of the cell wall and membrane.

Buddleja davidii plants in 1L pots were maintained in well-watered conditions and sprayed with either water controls of pH8.0 buffer six hours before being placed in either chambers with ambient levels of ozone or with elevated levels of ozone (mean concentration of 80ppb). Stomatal conductance was then measured one day and three days after being placed in the chambers.

<u>The potential use of alkaline buffer sprays on Ericaceous species</u>

In general, Ericaceous plants will not tolerate an alkaline growing medium. However, this does not necessarily mean that alkaline buffer treatments cannot be applied as a foliar spray. If the buffer is restricted to the foliar tissues, the buffer is weak and the growing media well buffered, then the roots will not come into contact with the high pH. It was suggested that we look at the effects of buffers on Ericaceous species to see if this is the case (Hennessey, pers comm.). The azalea *Rhododendron*. cv. Kazuko was chosen for its small size and being typical of the cultivars currently grown by the nurseries. Water was sprayed onto control plants, 100mM potassium hydrogen carbonate was applied as a single application of buffer treatment, and a deficit irrigation treatment was included to compare any physiological responses to the natural responses under droughted conditions. The same treatments were also applied to *Buddleja davidii* to compare results with a species that we know to generate no toxic response to alkaline buffers. Stomatal conductance and stem water potential were measured daily to determine if the buffer action was the same in both species. To determine if there were any detrimental effects of buffers on the plants, the efficiency of photosystem II (Fv/Fm) was assessed with the Plant Efficiency Analyser. In addition, leaf samples were taken to analyse the Iron content of the leaves. Iron was chosen because it is thought that in *Rhododendron,* toxicity in

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alkaline soils results from aluminium preventing the uptake of iron with a resulting inhibition of metabolic processes.

Results and Discussion

<u>The effects of alkaline buffers on plant water use</u>

The saving on irrigation achieved in the *Euonymus* crop depended on the prevailing evaporative demand in the growing environment. An average saving of 11% was achieved, but often rose to ~20% (Table 4.1). This translates in to potentially massive savings in irrigation during the growing season. Hopefully in 2008 we will be able to demonstrate that these savings can be obtained by applying buffer treatment to HONS species on a nursery.

<u>The effects of alkaline buffer on xylem sap pH</u>

Hydrangea developed alkaline sap pH six hours after the foliage was sprayed with the buffer (figure 4.2A). The degree to which the sap was alkalised was variable from sample to sample and day to day (probably due to a number of factors that influence in the uptake and movement of xenobiotic compounds). Sap pH was elevated in three out of the four days after buffer application. On a day that the control plants had elevated sap pH (possibly due to a high heat/radiation load in the growing environment), the buffer treated plants did not have an additionally high pH. Therefore, it may be the case that buffers can only raise sap pH levels to those of a naturally-stressed plant.

The alkaline buffer treatment also resulted in less negative internal water potentials (figure 4.2B). This effect was consistently observed on every sampling day after buffer application. These findings indicate that the buffers over-stimulate the signalling mechanisms involved in maintaining plant water status. *Cortaderia* plants showed no alkalisation of xylem sap after the buffer treatment (data not shown). This finding can be explained by the high buffering capacity of the sap in this species between pH 5.5 and 6.5 (see below for further details). The *Hydrangea* xylem sap pH was raised for at least 4 days. These results demonsrate that buffer signals are persistent and if applied to crops would not need to be repeated more frequently than weekly.

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Unfortunately, the positive findings of this treatment were associated with some leaf scorch and powder deposits on the *Hydrangea*'s younger leaves (figure 4.1). Further work will establish at what concentrations alkalisation of pH can be achieved without these associated phytotoxic effects. Owing to the success of this initial experiment, we shall continue the study to determine when the effects on sap pH fully disappear and if the effects are reduced by overhead irrigation washing buffer from the leaf surface. This information is essential for determining the frequency at which treatments need to be applied.

<u>The buffering capacity of xylem sap from HONS species</u>

HONS species have a greater buffering capacity compared to herbaceous model species. These results are important as it is essential for transferring knowledge from the pure science (using herbaceous species) to the applied work for the HONS industry. In the physiological representative region of pH 5.5-7.0 *Cortaderia* sap has the greatest buffering capacity. *Buddleja* has a high buffering capacity, but not in the physiological region. The findings for *Cortaderia* and *Buddleja* goes some way to explain the reasons why *Buddleja* is able to quickly raise xylem sap pH when suffering drought stress while under the same stress *Cortaderia* does not (or maybe cannot?) change it's sap pH. It is hypothesised that *Buddleja* can quickly change it's sap pH with a comparatively small adjustment in hydrogen ion concentration. This study has helped develop concentrations of buffers needed to alter xylem sap pH in different HONS species. Currently we are screening different types of buffers for activity/persistence at closing stomata in HONS species and thus give the greatest savings in irrigation.

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Figure 4.1. Leaf scorch and powder deposits on hydrangea treated with potassium hydrogen carbonate (300mM) alkaline buffer.

Table 4.1. 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 saved
0	15
2	19
4	0
6	5
8	21
10	11
12	22
14	0
Mean	**11.6**

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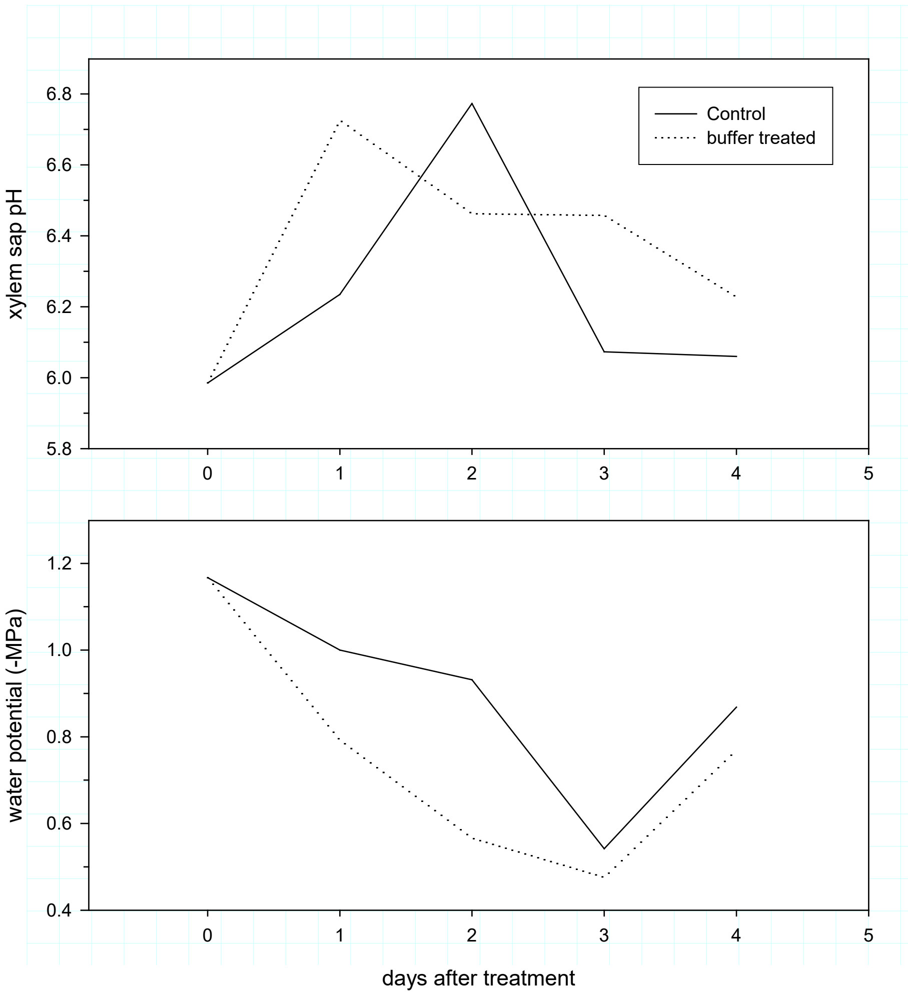

Figure 4.2. The effects on Hydrangea of a single application of pH8 buffer (300mM potassium hydrogen carbonate) on A) xylem sap pH and B) stem water potential. Buffers were applied on the morning of day 1. Plants were kept at optimum water capacity for the duration of the experiment. Data are means of at least six replicates.

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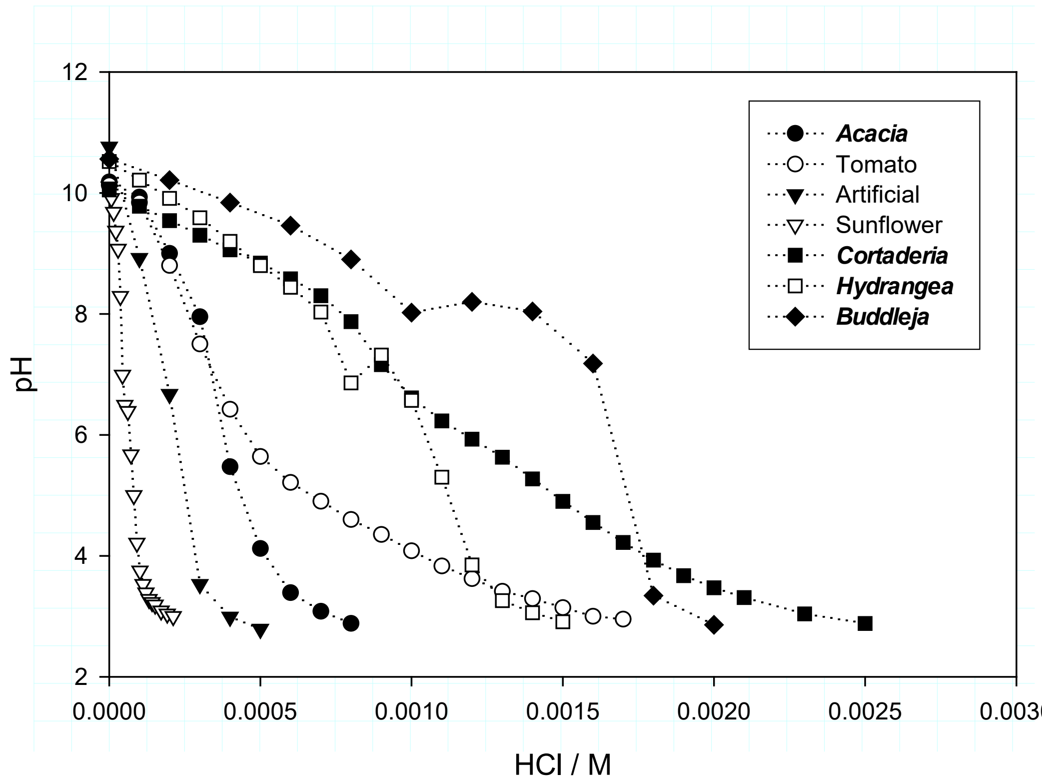

Figure 4.3. The buffering capacity of the xylem sap extracted from a number of horticultural species. The response of artificial sap was included for comparison. Sap was first acidified to at least 10.0 with NaOH then acidified with 0.1M HCl.

The use of adjuvants to increase activity of alkaline buffers

There was no significant difference in effect on stomatal conductance between applying just the buffer as a foliar spray or buffer + adjuvant (Figure 4.4). The buffer treatment alone work well at reducing stomatal conductances below control values and the effect persisted for at least one week. We can safely say that future buffer protocols will not require the addition of an adjuvant for optimum activity. This has the additional advantage of reducing the environmental impact of any treatment as adjuvant in spray drift/irrigation won't be returned to water courses or drains.

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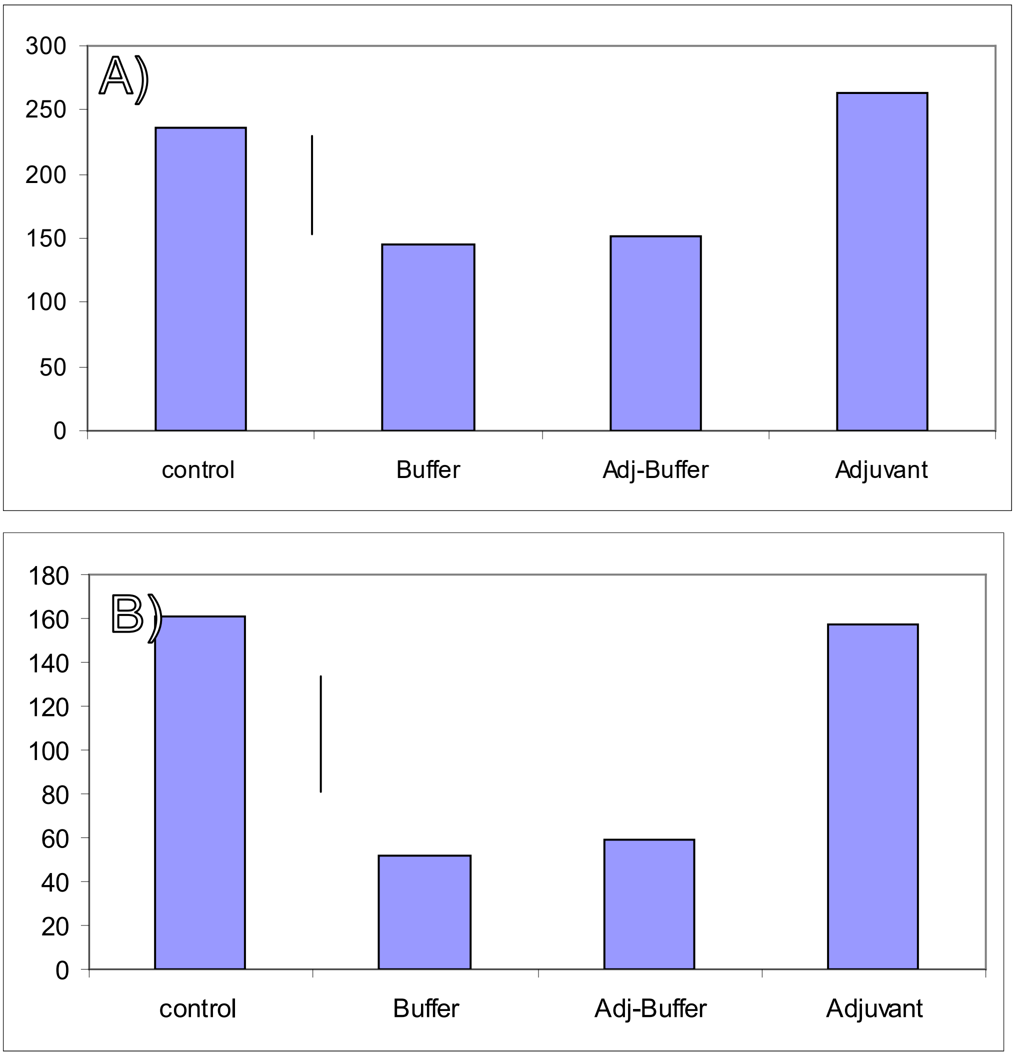

Figure 4.4. Stomatal conductance of *Buddleja davidii* treated with water controls, pH8.0 buffer, buffer combined with 'Sprayfast' adjuvant and adjuvant alone A) one day after foliar spray and b) five days after spraying. Data are means of 16 measurements. Least significant differences (LSD) at P = 0.05.

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Table 4.2. The response of stomatal conductance, stem water potential and efficiency of photosystem II to treatment with pH8.0 buffer or regulated deficit irrigation. Responses were compared in *Rhododendron* cv. 'Kazuko' and *Buddleja davidii*. Measurements taken on application day (day 1) and continued for four more days. Data are means of 16 measurements. Least Significant differences (LSD) at P = 0.05

	Stomatal Conductance / mMol m^{-2} S^{-1}					
	Day	1	2	3	4	5
Rhododendron	Control	232	**368**	287	329	232
	Buffer	249	**216**	200	251	252
	RDI	296	**435**	286	293	296
	LSD	110.3	**101.3**	106.4	118.4	123.2
Buddleja	Control	456	498	364	464	692
	Buffer	503	566	289	530	726
	RDI	646	546	337	523	581
	LSD	110.3	244.1	180.2	47.5	239

	Stem Water Potential / MPa					
	Day	1	2	3	4	5
Rhododendron	Control	-0.7425	-0.822	-0.87	*	-0.772
	Buffer	-0.766	-0.831	-0.955	*	-0.928
	RDI	-0.766	-0.731	-0.794	*	-0.783
	LSD	-0.1271	-0.1174	-0.2156	*	-0.2602
Buddleja	Control	-0.6325	**-0.666**	-0.651	*	-0.698
	Buffer	-0.73	**-0.474**	-0.774	*	-0.616
	RDI	-0.73	**-0.506**	-0.486	*	-0.76
	LSD	-0.1442	**-0.1886**	-0.229	*	-0.1839

	Efficiency of Photosystem II / Fv/Fm					
	Day	1	2	3	4	5
Rhododendron	Control	**0.821**	0.82	0.828	0.8094	0.8104
	Buffer	**0.816**	0.823	0.847	0.815	0.80775
	RDI	**0.831**	0.822	0.83	0.8204	0.8088
	LSD	**0.009**	0.013	0.034	0.012	0.013
Buddleja	Control	0.861	0.865	0.8605	0.85225	0.857
	Buffer	0.856	0.8618	0.8572	0.8578	0.844
	RDI	0.861	0.8638	0.8538	0.8564	0.853
	LSD	0.007	0.007	0.034	0.006	0.012

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Table 4.3. The Iron content (mg L^{-1}) of *Forsythia davidii* and *Rhododendron* cv. 'Kazuko' plants in control, regulated deficit irrigation, and pH 8.0 alkaline buffer treatments.

Forsythia davidii			*Rhododendron* cv. Kazuko		
Control	RDI	Buffer	Control	RDI	Buffer
0.0314	0.0324	0.0352	0.0285	0.0286	0.0414

<u>The potential use of alkaline buffer sprays on ericaceous species</u>

All the *Rhododendron* plants treated with the foliar alkaline buffer spray exhibited leaf scorch one week after the initial treatment. This is compared to 0% in control and 10% in RDI treated *Rhododendron*. No *Buddleja* plants exhibited leaf scorch. Although xylem sap pH was seen to significantly increase from 5.47 to 7.20 three days after buffer treatment, the effects on stomatal conductance, plant water status (as indicated by stem water potential) and photosynthesis (as indicated by Fv/Fm) were not consistent over the time-period of the experiment or when leaf scorch effects were visible (Table 4.2). There was also no reduction in iron content of the foliage in either *Buddleja* or *Rhododendron* (Table 4.3). These results seem to indicate that the toxicity to high pH in Ericaceous species is independent of direct effects on photosynthesis, transpiration signalling mechanism or iron accumulation/aluminium toxicity. It also means that toxicity of high pH in *Rhododendron* is not necessarily a response to effects in the roots and is seen in foliage as well. It is clear that alkaline buffers cannot be used on sensitive Ericaceous species.

<u>Use of alkaline buffers to protect plants from atmospheric ozone pollution</u>

Although the alkaline buffer spray closed stomata in the ambient environments (Table 4.4), reductions in conductances were not achieved in the elevated ozone environments. This goes some way to support the hypothesis that ozone locks stomata open by making guard cells insensitive to ABA. Even if the alkaline buffers increase the supply of ABA to the guard cells in high ozone environments they are still unable to respond to the hormone. These results suggest that on days with high ozone levels buffer treatments may be less effective at preventing water loss and controlling growth, and they cannot prevent the ozone damage to foliage and growth.

Table 4.4. Stomatal conductance of *Buddleja davidii* leaves pre-treated with foliar sprays of either water control or pH8 buffer then placed in elevated ozone cabinets (mean concentration of 80ppb) and control cabinets (mean concentration of 20ppb). Results were analysed using two-way ANOVA, P = 0.05.

Ambient		Elevated Ozone		
Control	Buffer	Control	Buffer	LSD
300	194	265	235	83.6

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OBJECTIVE 6

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

Introduction

Glasshouse experiments were performed with three HNS species, *Hydrangea macrophylla*, *Choisya ternata* and *Forsythia intermedia* under different irrigation regimes to investigate relationships between leaf temperature, soil moisture, stomatal conductance and plant performance.

Materials and Methods

Young plants were obtained from Johnsons of Whixley and grown in an unheated glasshouse, 48 plants of each of the three species were then potted up into 3 litre pots in peat based compost, obtained from Johnsons of Whixley, and transferred to a controlled environment glasshouse and irrigated using a 4-line spider drip irrigation system. Three irrigation treatments were providing 45, 90 and 180 seconds of irrigation, this equated to 175, 350 and 700 ml of water per lace per day. Experience from a previous trial had showed that Hydrangeas were most prone to drying out and wilting, therefore the Hydrangeas were setup with 2 drip lines per pot and the Choisya and Forsythia with just one drip line per pot. This resulted in treatments of 175, 350 and 700 ml/day for the Choisya and Forsythia and 350, 700 and 1400 ml/day for the Hydrangeas.

Two measurements, maximum height and maximum width, were made per plant before the trials began to enable the increase in plant size during the trial to be estimated. The plants were then left to grow for a six weeks under the scheduled irrigation regimes.

The plants were regularly monitored over the next six weeks and the following data recorded: average pot moisture, leaf temperature, stomatal conductance and the three size measurements. The following environmental parameters were measured at the same time each plant was monitored: the surface temperatures of a wet and of a dry filter paper discs, ambient air temperatures (Skye thin-wire thermistor), incident solar radiation (Skye pyranometer) and relative humidity (Skye combined humidity and temperature sensor).

Results

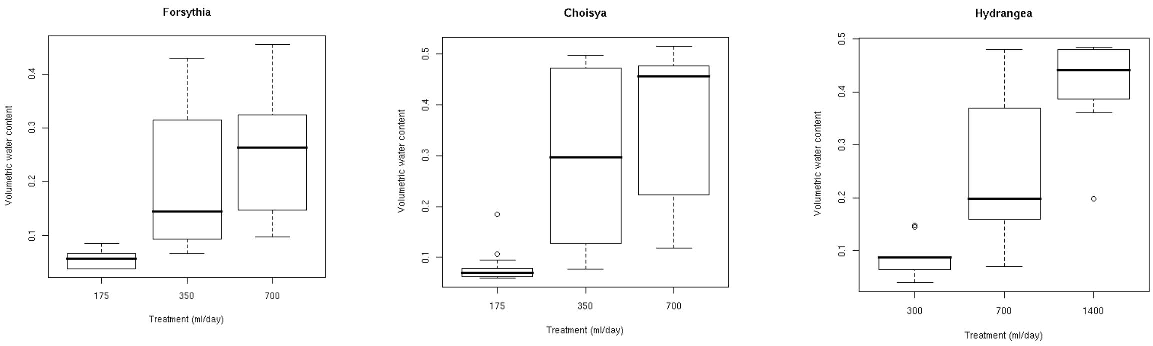

Figure 6.1 Average volumetric moisture content against irrigation treatment

By plotting measures of volumetric water content (ml/ml) against treatment in figure it can be seen that although there was considerable variation in water content within any treatment, treatment differences were highly significant. The variability was partly due to differences in plant size and partly to how recently the irrigation system had run before the reading was taken.

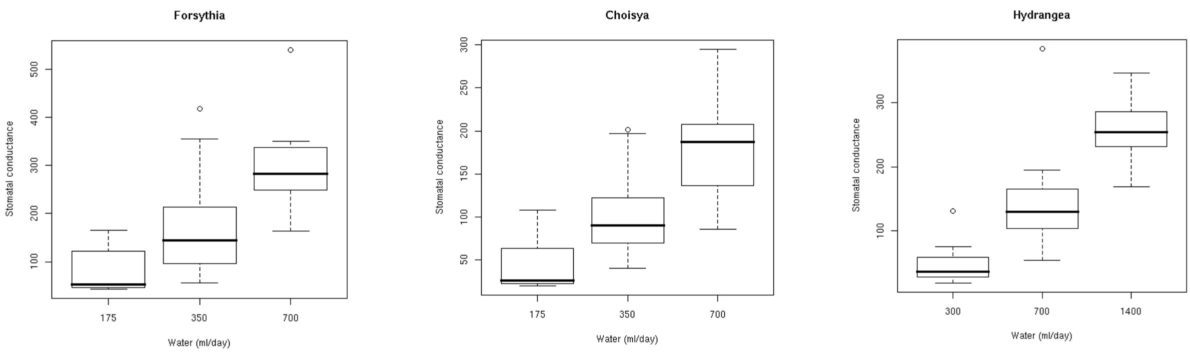

Figure 6.2 Average stomatal conductance against irrigation treatment

Figure shows that average treatment differences in stomatal conductance for the different irrigation treatments showed much less variability. Here treatment differences were highly significant with stomatal conductances from around 300 mmol m^{-2} s^{-1} in controls to less than 50 mmol m^{-2} s^{-1} in the severe drought treatment for both Forsythia and Hydrangea. Similar differences were found for Choisya, though the absolute conductances were slightly lower, suggesting that thermal imaging may be less suitable for this species.

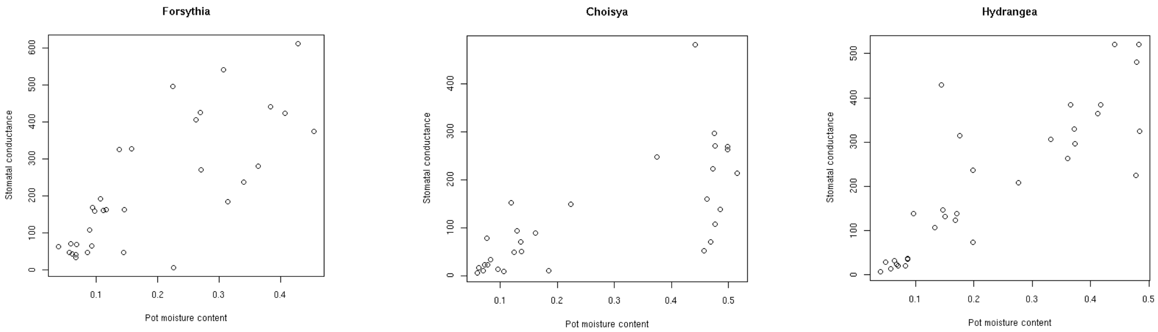

Figure 6.3. Stomatal conductance against pot volumetric moisture content.

Figure 6.3 shows the clear relationship between stomatal conductance and pot moisture content. Although these relationships are highly significant, with the stomatal conductance of the driest pots being much lower than the average conductance of the wetter treatment, the variability probably reflects the actual variability in moisture content. The leaf temperatures recorded were converted into a temperature index using wet and dry reference surfaces. In these trials wet and dry Whatman filter paper disks in 9 mm Petri-dishes were used to provide reference surfaces and the calculation

$$T_i = \frac{(T_d - T_l)}{(T_l - T_w)} \qquad \textbf{(6-1)}$$

was used to generate temperature indices T_i (proportional to conductance) where T_d is the dry reference temperature, T_w is the wet reference temperature and T_l is the leaf temperature. These results are summarised in Figure 6.4.

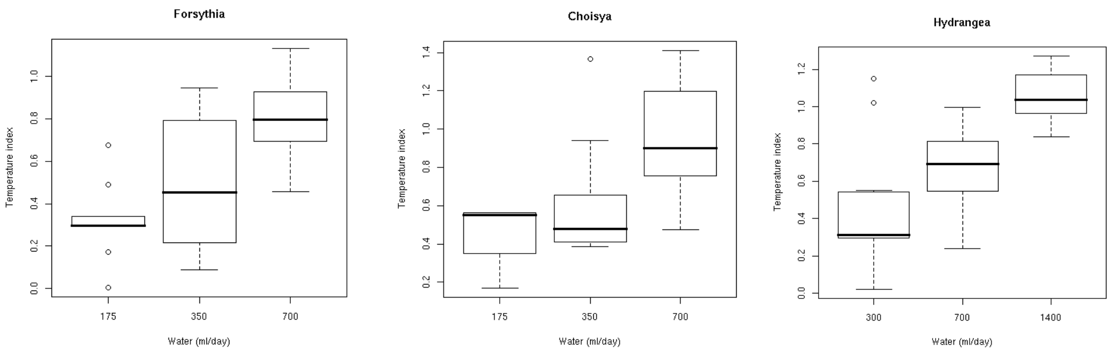

Figure 6.4. Temperature index against irrigation treatment.

Plotting temperature index against irrigation treatment again shows a clear relationship between T_i and irrigation treatment, with in all cases a clear difference between the well irrigated and the milder drought treatment. It is worth noting, however, that the two driest treatments were not statistically distinguishable for Choisya, probably as a result of the low stomatal conductances for this species (see previous report). In spite of these good results and highly significant relationships there was still substantial scatter in the relationship between temperature and either soil moisture (θ, Table 6.1) or stomatal conductance (g, Table 6.2).

Table 6.1. Regression of stomatal conductance to temperature index.

$\theta = A + Bt_i$	Intersect (A)	Slope (B)	Adjusted R^2
Forsythia	0.0535 (se=0.0393)	0.2265 (se=0.0637)	0.2553
Choisya	-0.0098 (se=0.0568)	0.3789 (se=0.0799)	0.3805
Hydrangea	0.0008 (se=0.0418)	0.3339 (se=0.0570)	0.4944

Table 6.2. Regression of pot moisture to temperature index.

$g = A + Bt_i$	Intersect (A)	Slope (B)	Adjusted R^2
Forsythia	25.91 (se=48.85)	330.58 (se=79.12)	0.3261
Choisya	-80.64 (se=27.97)	287.22 (se=39.37)	0.5987
Hydrangea	-43.38 (se=43.38)	359.84 (se=59.07)	0.5150

The weakest relationship was obtained with Forsythia; this probably results because this species grew in a much more linear fashion than Hydrangea and Choisya with shoots often over a metre long and the active transpiring leaves being out of view of the camera with our test set-up. Both Hydrangea and Choisya formed a fairly homogenous and connected canopy with a more or less solid circular appearance to the camera centred over the pot, with the leaves transpiring the greatest on the top and sides of the canopy. Stomatal conductances were measured for randomly selected leaves and in this case not just for leaves within the camera's field of view.

Plant performance: Developing a single non-destructive measure of growth from the data was not simple due to differing growth patterns between the species. The

Forsythia had a tendency in the high irrigation treatment to grow one or two very long shoots though in the low irrigation treatments it grew more, but shorter, shoots in a "bushier" form. The aim of using a measure of maximum diameter and height to generate and follow any increase in an approximately cylindrical volume was therefore not fully applicable to the Forsythia. In what follows we use approximate cylindrical volume as the size measure for the Hydrangea and Choisya and approximate total length of the shoots for the Forsythia.

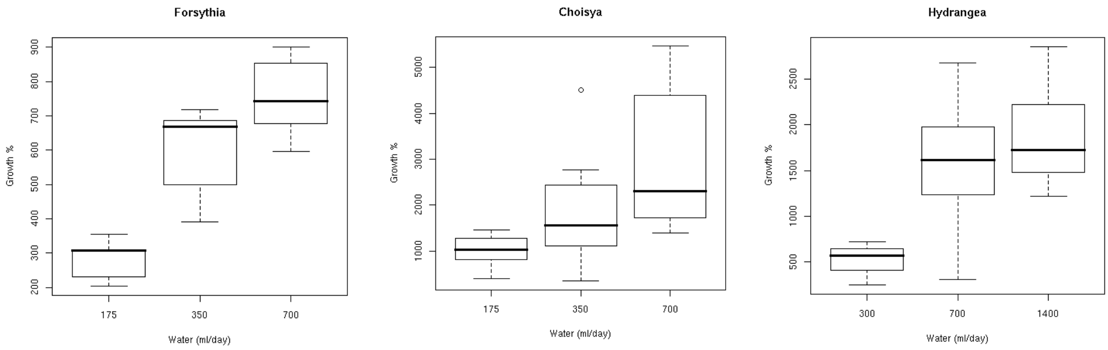

Figure 6.5. Percentage growth against irrigation treatment.

Figure 6.5 shows the growth measures across irrigation treatments for the three species, with the data presented against pot volumetric moisture content in Figure6.6.

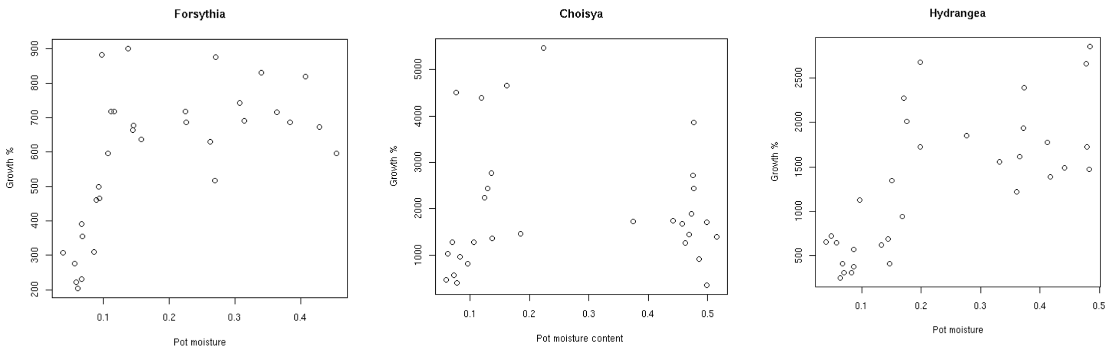

Figure 6.6. Percentage growth against average pot volumetric moisture content.

Although the droughted treatment was fairly extreme and clearly stunted growth across all species, for the Choisya there were some plants that did not grow even when well watered. When plotting percentage growth against average pot moisture content, it is clear that there is a region where pot moisture content strongly inhibits growth, though this differs, as expected, between species. Because the irrigation system used applied

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constant amounts of water to each species/treatment combination, some variation in soil moisture for and treatment built up over time as a result of differing sizes of plants. For Choisya this was particularly apparent with the smaller plants showing some evidence for waterlogging and consequent stomatal closure in the irrigated treatment.

Discussion

All the above work was done using the low resolution IRISYS imager and temperature differences between stressed and non-stressed plants were consistently in the range of 2 °C. We expect substantially better results using the higher thermal- and spatial-resolution cameras. Plant structure, in particular the straggly sparse nature of the Forsythia, can lead to a large influence of mixed thermal pixels that include background and leaf temperature when low resolution imagers. However this did not seem to cause much of a problem. A greater problem was caused by the field of view. The experiments were performed so that the pot was always place in the same place in the field of view, this caused problems with many of the strong growing Forsythia plants where transpiring leaves would be the ones at the ends of the shoots, no longer within the field of view.

There were noticeable growth pattern differences within the Forsythia, (data not presented here) where stressed plants maintained a more compact growth with more shorter shoots with smaller leaves, where as liberally watered plants tended to put out one or two long shoots with large leaves. This pattern was not as noticeable in the Choisya and Hydrangea although there was some suggestion of it by the end of the trial. Use of irrigation to control plant growth through RDI could assist in producing plants that are more marketable (as shown in WaterLink 1), but as well as understanding the relationship between stress and structure it will also be necessary to understand the relationship between structure and marketability or cost efficiency.

Much of the time the sun screens were in use in the glasshouse to prevent excessive IR reflectance flooding the low cost webcam used to acquire the visible and NearIR images that distinguish plant from background. It is possible that the use of sun screen also affected the growth of the plants as more light was therefore entering the glasshouse from the sides than from above. This needs further investigation.

Conclusions

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- Our automated thermal measurement system successfully distinguished irrigation treatments for all three species studied.

- The temperature index was well related both to soil moisture content of the different treatments and to stomatal conductance.

- Plant/canopy structure was found to be an important factor for successful application of the technique.

- The scatter in the data was largely related to varying environmental conditions (especially associated with time of day).

- The data for Choisya highlighted the possibility that overwatering can lead to stomatal closure and that this needs to be considered in the design of any automated irrigation system linked to stomatal responses.

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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

Pera joined the project as a Scientific Researcher to assist by studying the options for automated control of irrigation utilizing a system of sensors. We are collaborating with the Department of Applied computing at Dundee University in developing their digital imagery system to assess plant stress, by build test rigs to allow a preliminary evaluation of the practicalities and potential of this approach for industry application. Work Package 7 is being completed, work is continuing with design, development and testing of individual components in preparation for the construction of prototype irrigation rigs

Infra-red thermal detector (thermopile) System Testing

The month 12 report detailed the research that the team had done into the current systems on the market, the state of the art and how this applied to this project. It concluded that this system would be far more sophisticated than any of the current market systems and that it should use the thermal system on a moving gantry to determine the stress levels of individual plants and to be able to administer water to them.

Following this conclusion a test rig was built, incorporating thermopiles (actually infrared thermal detectors) mounted onto a boom and wired into a microcontroller transmitter circuit.

The purpose of these tests was to determine the relationship between Temperature and the output results of the Microcontroller receiver circuit. These results have enabled us to better understand the efficiency and operating parameters of the assembled parts.

Materials and methods

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The thermopiles are mounted onto a boom and wired into the microcontroller transmitter circuit also mounted on one end of the boom. The receiver is linked to a PC via a RS232 connection and the results taken from the circuit using the Hyper Terminal program. The system was then tested in an enclosed environment to determine that it was accurate.

The numbers shown in the results are raw numbers from the analogue to digital converters. Over the small range of temperatures tested these are representative of actual measured temperatures without the neccessity of calculating the actual temperature from the given polynomial.

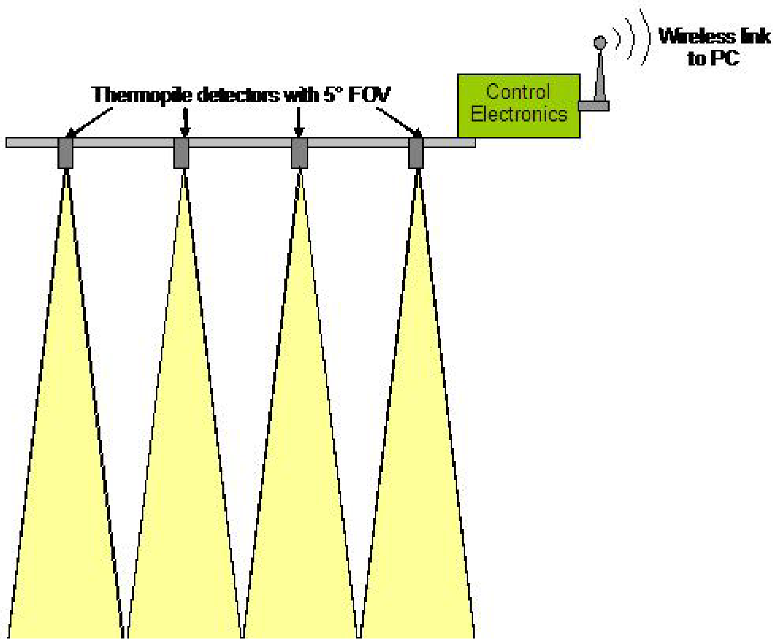

Figure 7.1. A schematic of the thermopile system.

Figure 7.2: Thermister under testing for uniformity.

Figure 7.3. The Gantry test rig with wireless connection.

Test 1

Methods

An object is placed under each sensor (3” distance). The temperature of the object and the time are recorded against the output results from the microcontroller receiver circuit.

Results and Discussion from Test 1

Temp °C	Sensor 1 (TP1)	Sensor 2 (TP2)	Sensor 3 (TP3)	Sensor 4 (TP4)
9	87	88	87	87
10	89	89	88	88
10.5	89	90	89	89
11.00	90	90	90	89
11.50	91	91	90	91
12.00	92	92	91	92
12.50	94	94	92	93
13.00	94	94	94	94
13.5	95	95	94	94
14	96	96	95	95
14.5	97	97	96	96
15	97	97	96	96
15.5	97	97	96	96
16	98	98	98	97
16.5	99	99	98	98
17	101	100	99	100
17.5	101	101	100	100
18	102	102	101	101
18.5	102	102	102	102
19	104	103	102	102
20	105	105	105	103
20.5	106	106	106	107
21	108	107	107	107
21.5	108	107	107	108
22	110	109	109	109
22.5	111	109	108	110
23	110	109	109	110
23.5	112	112	111	112
24	113	112	111	112
24.5	114	113	113	113
25	116	115	115	115
25.5	116	115	115	116
26	117	116	116	116
26.5	118	116	117	117
27	118	117	118	118

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Conclusions from Test 1

From the results we can see that the individual outputs are linear and when compared against each other they are well matched and evenly balanced.

Using these figures we will now be able to reference an approximate temperature to an output value (17.5°C=100, 14.0°C=95, etc).

Test 2

Methods

The boom is mounted 1 metre high. Objects of a fixed temperature are placed under **Sensor 4** at varying heights. The temperature of the object is recorded against the output results from the microcontroller receiver circuit.

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Results and Discussion – Test 2

Sensor 2 was used for this part of the test.

Temperature Measurements °C	Sensor1 (TP1)	Sensor 2 (TP2)	Sensor 3 (TP3)	Sensor 4 (TP4)	Test Conclusions
Temperature of Floor Area (Ambient) = 23.5°C (Approx)	112	111	111	111	The object is not present under sensor 2. Multiple readings are taken to show a steady ambient measurement. Comparing the output readings against temperature results taken in **test 1** we can approximate that 111=23/23.5°C
	112	112	111	112	
	111	112	112	110	
	112	111	112	111	
	111	111	111	111	
	112	111	112	112	
	111	112	111	110	
	112	111	112	111	
Object Temperature = 19/20°C (Approx)	112	105	111	110	The object is now present under sensor 2; it is slowly lowered to the floor. Several readings are taken to show a steady measurement. Comparing the output readings against temperature results taken in **test 1** we can approximate that 105=20/20.5°C
	111	105	110	110	
	111	106	111	110	
	112	105	111	111	
Object Temperature = 19/20°C (Approx)	112	106	111	110	As the object is lowered to the floor the output readings stay constant. The object is filling the thermopile field of view over 1 metre. Several readings are taken to show this measurement.
	111	106	111	110	
	112	105	111	110	
	112	105	110	110	

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Results and Conclusions-Test 2

The complete system appears to work well. Results are constant and steady. Consideration should be paid to the field of view during testing.

Temperature Measurements °C	Sensor1 (TP1)	Sensor 2 (TP2)	Sensor 3 (TP3)	Sensor 4 (TP4)	Test Conclusions
Temperature of Floor Area (Ambient) = 23.5°C (Approx)	112	111	111	111	The object is not present under sensor 4. Multiple readings are taken to show a steady ambient measurement. Comparing the output readings against temperature results taken in **test 1** we can approximate that 111=23/23.5°C
	112	111	111	111	
	112	112	111	111	
	112	111	112	111	
	112	111	111	111	
	112	111	112	111	
	112	111	111	111	
	112	111	112	111	
	112	111	111	111	
	112	111	111	112	
	112	112	112	111	
	112	111	111	112	
Object Temperature = 26.5°C (Approx)	112	111	111	117	The object is now present under sensor 4; it is slowly lowered to the floor. Several readings are taken to show a steady measurement. Comparing the output readings against temperature results taken in **test 1** we can approximate that 117=26.5/27°C
	111	111	111	117	
	112	111	111	118	
	111	111	111	117	
Object Temperature = 26.5°C (Approx)	111	110	111	116	As the object is lowered to the floor it appears that the temperature of the object is dropping. Several readings are taken to show this measurement. This drop is believed to happen because the size of the object as it is lowered allows the sensor to scan the surrounding floor area.
	111	110	111	116	
	111	110	111	116	
	111	110	111	116	

Test 3

Methods

The boom is mounted 2 metres high. Objects of a fixed temperature are placed under one of the sensors at varying heights. The temperature of the object is recorded against the output results from the microcontroller receiver circuit.

Results and Discussion – Test 3

Temperature Measurements °C	Sensor1 (TP1)	Sensor 2 (TP2)	Sensor 3 (TP3)	Sensor 4 (TP4)	Test Conclusions
Temperature of Floor Area (Ambient) = 23.5°C (Approx)	112	111	111	111	The object is not present under sensor 2. Multiple readings are taken to show a steady ambient measurement. Comparing the output readings against temperature results taken in **test 1** we can approximate that 111=23/23.5°C. Please note the sensor is out of its defined range.
	112	112	111	112	
	111	112	112	110	
	112	111	112	111	
	111	111	111	111	
	112	111	112	112	
	111	112	111	110	
	112	111	112	111	
Object Temperature = 19/20°C (Approx)	111	108	111	110	The object is now present on the floor. Several readings are taken to show a steady measurement. Comparing the output readings against temperature results taken in **test 1** we can approximate that 108=21/21.5°C. This is high because at 2 metres high the sensor is out of its defined range.
	112	108	110	110	
	112	108	111	111	
	111	108	110	110	
Object Temperature = 19/20°C (Approx)	112	105	111	110	As the object is raised from the floor the output readings lower to expected values. The object is filling the thermopile field of view inside the defined sensor range. Several readings are taken to show this measurement.
	112	105	110	110	
	112	106	111	110	
	112	105	111	111	

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As a final test a plant with wide tall foliage was placed under the sensor boom assembly while it was at the 2 metre level. The size of the plant should bring the foliage into the sensing range of the thermopiles.

The plant was positioned so that most of the foliage was under sensors 1, 2, and 3. Sensor 4 would just be seeing the outer plant leaves.

Sensor 1 (TP1)	Sensor 2 (TP2)	Sensor 3 (TP3)	Sensor 4 (TP4)
113	112	113	111
112	112	113	111
112	112	112	111
112	112	112	111
112	112	112	111
112	112	112	111
112	112	112	111
112	112	112	111

Conclusions-Test 3

At 2 metres high the output reading is higher than expected probably because the sensor is out of its defined range and it is also picking up the ambient area around the object. Even under these circumstances it can still be seen which sensor the object is under due to the difference in the output readings.

The plant test showed a noticeable difference in output values depending on how much foliage was seen but at this point the foliage temperature is an unknown value to compare against the ambient temperature and the output readings.

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Conclusions on Thermopile System Testing

Following these tests Pera has made some improvements to the thermopile scanning system. The transmission/reception distances have been greatly improved to facilitate testing of the measurement system in a representative agricultural environment, the transmission distance in recent greenhouse testing is now in excess of 50m at low power.

The wireless communications link has been greatly improved to allow the transmission and reception of data 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 should allow better thermal differentiation between healthy and stressed plants.

The PC software has been developed to take advantage of these improvements and also to monitor the batteries on the receiver transmitter and also monitor the signal strength of the received signal.

The system now needs to be field tested on a representative crop.

Representative Crop testing

Introduction

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

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Materials and methods

Figure 7.8. 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.

Results and Discussion – Test 1

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

Conclusions – Test 1

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.

Results and Discussion- Test 2

Figure 7.9. Two beds of plants - One side watered normally, the other watered 50%.

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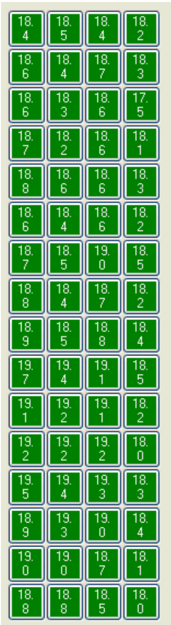
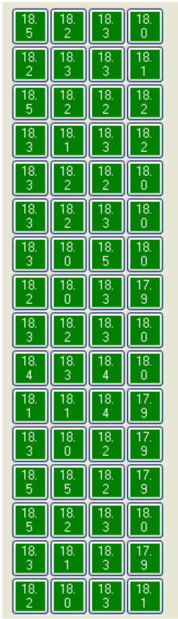
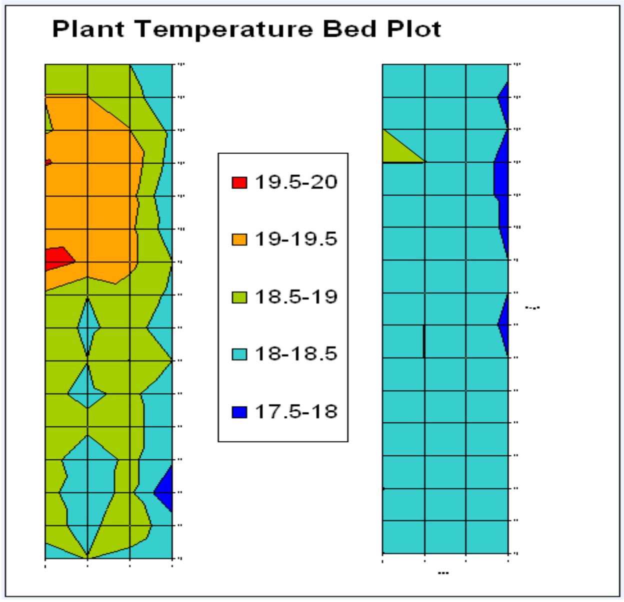






50% water 100% water 50% water 100% water

Conclusions – Test 2

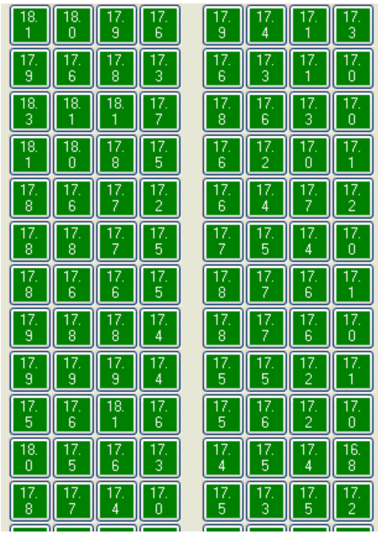
The thermopile system was able to determine a temperature difference between stressed and non stressed plants (the stressed plants having a higher temperature) while mounted on a moving gantry, with the readout from the system being wirelessly communicated.

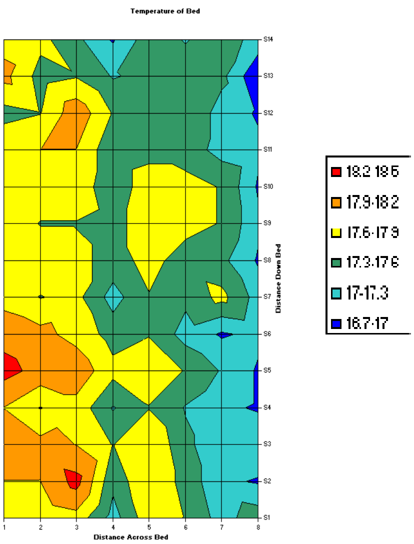
Test 3

Methods

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.

Results and Discussion – test 3





Conclusions – Test 3

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.

Conclusions from on nursery testing

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

The temperature measurement boom can be directly mounted on a watering boom and the processed data can be directly fed into the control of the watering gantries PLC 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.

Synthesising thermal images from a moving linear array of thermal sensors

Thermal sensors

University of Dundee produced a test system for evaluation of the concept of the use of an array of simple thermal sensors (spot sensors - sometimes called infrared thermocouples) for generating an image through movement. The basic instrument is illustrated in Figure 0. It consists of a set of five Calex thermal sensors arranged to generate a swath of 30°×6°. This particular arrangement was chosen to be compatible with a commercial active NDVI sensor which we are using for initial ‘concept testing’ as a means for estimating the amount of canopy cover in the ‘image’. We expect that any practical development of this concept will require NDVI sensors tailored to match the thermal sensors.

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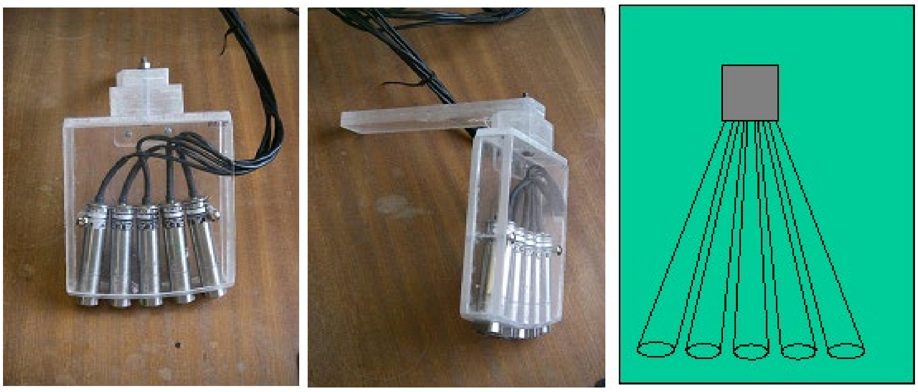

Figure 7.10. Arrangement of the mobile thermal scanner for generation of a 30°×6° 'image' which can then be used to generate a full temperature image as it moves over the crop.

The approach was tested by wheeling the Dundee thermal sensor at a steady rate over an area of grass and soil and thereby generating a thermal 'image' of the whole canopy by use of Excel software. The resulting image generated by the Dundee sensor is compared with a 'stitched' series of thermal images and a stitched series of visible images of the same view in Figure 11. Despite the very low effective spatial resolution of the Dundee sensor, the images correspond very well with the visible and high resolution thermal images.

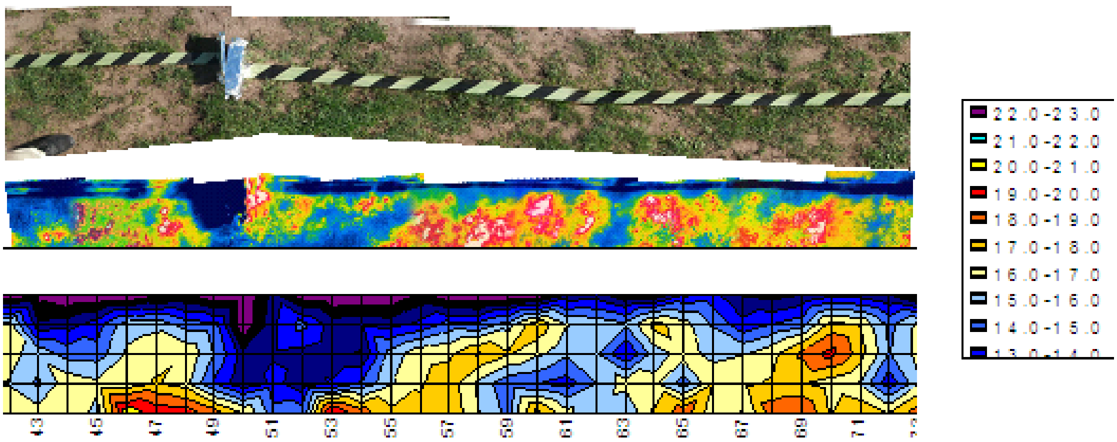

Figure 7.11. Typical example showing a comparison of a stitched visible image (top), a stitched thermal image (middle) and a thermal image synthesised from individual spot temperature readings.

<u>Camera based system</u>

Further developments have been made to the three image thermal camera system described in the first year report. The system can now be used interchangeably with either the high resolution FLIR P25 or the IRRISYS 1002. In addition, extra environmental sensors have been incorporated and improvements made to the software designed to facilitate the automated recording of both plant and reference surface temperatures in sequences of images, as shown in Figure 12.

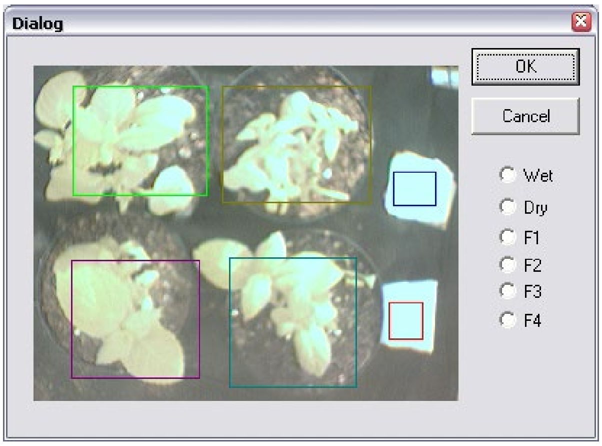

Figure 7.12. Screen view showing four areas from which the software extracts leaf temperatures and two areas from which it extracts reference surface temperatures. Note that the software uses the red and near infrared images to identify and ignore areas within the defined areas.

In particular there is an option to specify within the software preset areas within the view where the test plants are to be found and where reference surfaces are to be found. There is also now a facility to record and analyse a continuous time series. These additions enable us to specify 2 reference surfaces and up to 4 separate plant areas in the image. These could be areas or leaves on the same plant or 4 separate plants in view at the same time, as shown in Figure 12. Figure 13 shows a screenshot of the main application interface showing the calculation flow-path from the thermal, near-IR and visible light images (second column from the left) through to the segmented thermal images on the far right.

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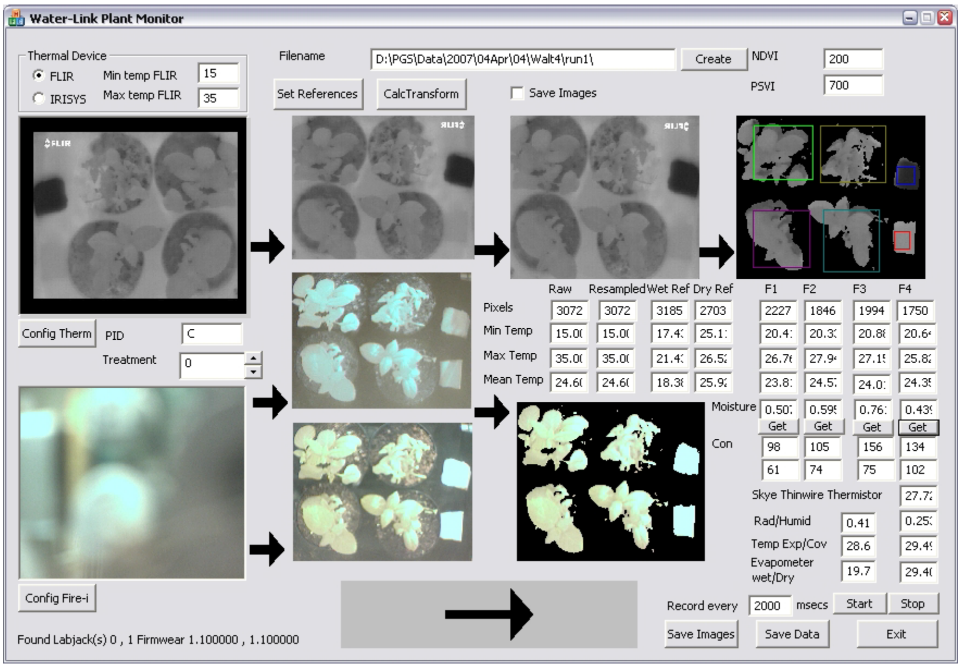

Figure 7.13. A screenshot showing the flow-path of calculations based on the three original images.

Due to the size and weight of the components of the thermal camera system and the delicacy of the alignment of the thermal and visible camera images, the thermal camera system is currently stationary and therefore not easily used for mass plant screening. It is envisaged at this point that the system being developed by PERA linked to the automated irrigation system is most likely to adopt a linear sensor array system.

Conclusions

We have successfully tested a moving thermal array sensor for synthesis of thermal 'images' as a potential low-cost replacement for a thermal camera in a moving sensor system. We have provided a simple way of representing the data using Excel and substantially improved the software for image extraction and analysis from our static thermal sensor test-bed which we use for calibration of control algorithms.

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Technology transfer

Presentations

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, 31st July 2007 (EMR).

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

Davies, W.J. (2007) Controlling water use under drought. Paper presented at Drought meeting in Adelaide Australia, October 2007 (Lancaster).

Visits

Visit by Olga Grant, Richard Harrison Murray, and Mike Davies to Palmstead Nurseries, March 2007, to discuss Palmstead's input into the project, and their irrigation issues generally (EMR).

Poster presentations

Sharp, R.G. (2007) 'East Malling Water Day': poster presented on the work of Lancaster University in this LINK project. East Malling Research, September 2007. (Lancaster).

Publications arising from the project

Wilkinson, S. and Davies, W.J. (2008) Manipulation of the apoplastic pH of intact plants mimics stomatal and growth responses to water availability and microclimatic variation. *Journal of Experimental Botany*. In the press, (Lancaster).

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

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