Project Title	Enhancing the quality of hardy nursery stock and sustainability of the industry through novel water-saving techniques
Project number:	Horticulture LINK HNS97b
Project leader:	Prof. Bill Davies, Lancaster University
Report:	1st Annual report, December 2006
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Location of project:	East Malling Research, East Malling, West Malling, Kent, ME19 6BJ. University of Dundee at the Scottish Crop Research Institute (SCRI) Invergowie, Dundee, DD1 4HN. Lancaster University, Bailrigg, Lancaster, LA1 4XQ Pera Innovation Ltd., Pera Innovation Park, Nottingham Road, Melton Mowbray, Leicestershire, LE13 0PB. Commercial holdings of hardy nursery stock producers forming part of the project consortium.
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Date project commenced:	1 October 2005
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Key words:	Hardy nursery stock, irrigation, deficit, infra-red sensing, automated, pH, quality

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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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CONTENTS

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Grower Summary

Headline

In the first year of this Horticulture LINK project, the researchers have examined the use of irrigation scheduling, chemical growth regulation and irrigation automation through the use of thermography, to identify ways of improving the efficiency of water use and evenness of application.

Background and expected deliverables

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

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

The project aims to develop novel ways to effectively apply appropriate quantities of water and nutrients to the crop. This will serve to:
a) Conserve diminishing water supplies

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b) Manipulate plant growth in order to increase the profitability and sustainability of the HNS industry.

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

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

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 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.

Objectives

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.

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

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

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

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

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

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Irrigation scheduling

Irrigation uniformity was measured on several overhead nursery systems using the HDC Irrigation Calculator procedure (Factsheet 16/05). Examples of inadequate uniformity were still evident even under glass where wind drift should not be a problem (Figure S1). Reasons for this included twisted overhead spraylines or sprinklers failing to irrigate bed edges adequately. Poor uniformity needs to be addressed before attempting to apply critical scheduling procedures or RDI techniques.

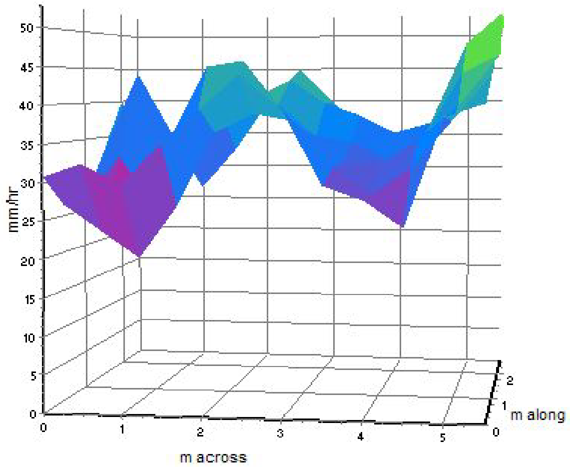

Figure S1. Example of irrigation output and uniformity measurement on a bed under Pinjet overhead irrigation at a commercial nursery.

Water uptake and run-through from containers on nursery beds was measured by pot weighing. This provides useful information on whether adequate or excess irrigation is being applied, the dynamics of water gain and loss, and uniformity of water status in the crop. These measurements indicated that between 7% and 38% of water could be taken up through the base of the pot. They also indicated that plant foliage could create a funnelling effect resulting in a significant increase in water entering the top of the pot.

Experiments examining the use of the evaposensors to measure crop water loss, indicated that it is possible to predict mathematical coefficients for use

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with an evaposensor from total leaf area measurements. It is now it is necessary to establish a rapid method for assessment of leaf area for use by growers on nurseries.

Variation in quantity of water received by plants under high precision overhead irrigation was greater than with high precision drip, but the effect of variation on plant growth was limited.

Growth and shape of plants can be controlled by deficit irrigation but scheduling for more than one species per bed is difficult under deficit irrigation (Figure S2).

Figure S2. Example of the appearance of *Lonicera periclymenum* 'Graham Thomas' after 7.5 weeks of overhead irrigation applied to replace different percentages of plant water loss.

The use of chemical treatments to control growth

Soil-drying stimulates an increase in the pH (alkalisation) of the xylem sap (the water moving through the plant from roots to shoots) in some (but not all) of the HNS species investigated in the first year of the project. The species

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that exhibited sap alkalisation showed the most effective control of their shoot water-status (avoidance of shoot water deficit) when water was withheld from the soil.

Conversely, plants that did not exhibit sap alkalization under drought stress, exhibited significant, potentially damaging, shoot dehydration.

Foliar sprays of alkaline buffers were shown to close stomata regardless of whether the particular species treated naturally undergoes sap alkalisation when soils dry. It is proposed that these sprays could be utilised by growers to control growth or reduce water requirements when demand for water peaks, midway through the growing season. As a result, frequency of irrigation could be reduced.

Soil drenches of alkaline buffers also showed potential for use on HNS as a means of controlling excessive vigour. When the soil pH was adjusted with different buffers, pH of the soil was inversely related to the degree of stem elongation achieved.

Development of an automated irrigation system using thermography

The project is investigating the possible automated use of thermography for detection of plant water status and hence a basis for irrigation scheduling. The approach is based on the principle that when plants are inadequately supplied with water, the stomata (pores on the leaf surface) tend to close. This reduces evaporative cooling and causes the leaves to warm up. This heating effect can be detected remotely using thermal imagery. The project is investigating ways in which this irrigation can be used to control irrigation for HNS plants. A system capable of detecting plant water stress from a thermal image requires two functional subcomponents:

1. It must automatically and accurately determine automatically the temperatures of the plants from the thermal image.

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2. It must use a mathematical model to predict the threshold temperature at which irrigation is required. This depends both on plant species and on the environmental conditions.

The work during the first year of the project has concentrated on:

a) Developing mathematical models for the estimation of stomatal conductance from leaf temperature
b) Developing a system for determining the aerodynamic properties of canopies for input into these models, and collecting data for contrasting nursery crops
c) Developing and testing a system for combining visible and thermal images of crops

Financial benefits

A recent estimate of farm-gate value for the HNS industry in England and Wales is around £379M per annum, with capacity for further growth if its competitive strength is enhanced by improved product quality and reduced production costs. Based on the cost of mains water, direct water savings may only be c.£1000/ha/ann. However, with the likely advent of water restrictions a water saving of 33% could allow 33% more production (equivalent to increased sales of 33% or c.£166,000/ha/ann). Financial benefit from more uniform and compact plant growth (reduced labour costs for pruning and order picking and reduced wastage) is likely to be an even more important driver.

Aside from any water saving, RDI and novel fertiliser treatments have the potential for greatly enhancing product quality and thus enhancing grower competitiveness against the best imported material. Precise monitoring of irrigation effectiveness will be essential to both improve crop uniformity and increase the effectiveness of RDI. Improved monitoring techniques will also reduce labour costs (c.35% of sales) for checking performance of irrigation systems. Increased crop uniformity and reduced necessity for pruning will

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also reduce labour costs. A 1% saving in labour equates to a saving of more than £1.3M in England and Wales.

At this stage in the project it is not appropriate to undertake a specific and detailed cost-benefit analysis.

Action points for growers

At this stage in the project (year 1 of 4), it is not yet pertinent to recommend any action points or changes to commercial irrigation practice.

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Science Section

INTRODUCTION

The aim of the project is to develop novel ways to apply more effectively appropriate quantities of water and nutrients to hardy ornamental nursery stock (NHS) to (a) conserve diminishing water supplies and (b) manipulate plant growth in order to increase the profitability and sustainability of the industry. The project aims to address problems of poor uniformity of application of irrigation to container-grown HNS and the practical application of deficit irrigation and novel chemical (fertiliser) treatments to control growth and water use. The project is evaluating thermal imaging as a means of sensing plant water status and comparing this with other means of monitoring and controlling irrigation on HNS nurseries (including the use of soil moisture and evaporation sensors, so called evaposensors). The project aims to assess the scope for high precision automated delivery of water to HNS in containers and build a test rig to evaluate the feasibility of regulating water application to individual plants.

Immediate benefits of the project will include improved operation of existing irrigation/fertigation systems while long term benefits include high precision automated systems capable of maximum savings of water and nutrients combined with reduced crop wastage and variability.

Legislative pressures, and the increasing cost of mains water, make it vital for the 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 5 times as a result of this variability and manual labour may also be considered as a diminishing resource within the industry. In addition, reductions of wastage by only one third can increase profitability by up to 300% (source: Hillier Nurseries).

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Non-uniformity of water application from the overhead irrigation systems used on most nurseries represents a barrier to reducing wastage and also to using 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.

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 (Cameron et al., 2002).

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 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

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protocols, while the novel fertiliser treatments emerging from recent studies are currently being evaluated at the practical level.

The project is guided by 9 key objectives:

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

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

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

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

7. To 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. To develop user-friendly guidelines for application of different methods of stress sensing and plant manipulation in nursery practice and

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produce ‘User Manuals’.

9. To 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.

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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.

Introduction

In the first year the project has provided training and advice to allow growers to undertake trial work on their nurseries. Some of this work included comparing irrigation systems, and on one nursery a gantry overhead irrigation system was compared with conventional overhead irrigation. Additionally, a desk-top study was undertaken to assess the variety and effectiveness of existing irrigation systems.

Materials and Methods

<u>Desk-based study</u>

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

<u>Data collection and trials on nurseries to test performance of systems</u>

At Hilliers Nurseries, Hampshire, water consumption and uniformity of water distribution from a Denton irrigation gantry was compared with that from volmatic pinjet sprayline irrigation. On the different nurseries, water distribution was measured. Additionally, drainage run-through during irrigation was measured by placing a second set of containers into slightly smaller pots lined with a polythene bag, i.e. 3 L crop pots supported in 2 L lined pots, to record drainage. This enabled only the surplus water which had drained from the pot to be collected, while an air gap above the drainage water prevented

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reabsorption by the growing medium. Comparison of net uptake between pots on the standing base and pots supported in smaller pots allowed the effect of uptake through the drainage holes in the base of the pots to be quantified, as well as the amount captured through the top. Finally, by recording the irrigation period, and the total quantity of water used over the area with a water meter, and the pot surface diameter, the net uptake and mean application rate could be expressed on a 'pot surface area basis' compared with an 'irrigated area' basis. This indicates the influence of the foliage canopy in 'funnelling' water into containers (resulting in a higher net uptake) or 'shedding' water away from containers (resulting in a lower net uptake).

Results and Discussion

Measurement of the uniformity of output from irrigation systems

At Hillier Nurseries, the gantry (Fig. 1a) gave good irrigation distribution with a Christiansen's co-efficient of uniformity (CU) of 87% and scheduling coefficient of 1.36 across the full bay width. The lower output in the middle coincided with the centre path, so the results over the bed would have been even better. The pattern from the left half of the pinjet bay is shown in Fig. 1b, with the highest irrigation under the central sprayline (right hand side of chart) which received overlap from the outside spraylines. Precipitation under the outside two spraylines was lower because there was no overlap irrigation from the adjacent bays during the experiment, but nevertheless uniformity overall was acceptable.

At Johnson's of Whixley, three glasshouse bays were converted from 'full house' irrigation pinjet sprinkler lines to inverted Dan nozzles with anti-mist devices. These were designed to give good uniformity across the bay into which they were installed, but with little overspill into adjacent bays. This meant that three adjacent bays could be scheduled independently, with minimal interference between treatments. The set-up across the 6.4 m wide bay irrigated with two lines 3.6 m apart gave acceptable uniformity (Fig. 1c). The depression in precipitation rate down the centre of the bay was due to the right-hand line being slightly twisted, but in this case was not too serious as it

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coincided with the central access pathway. The mean precipitation rate of 10.4 mm/h was much more gentle than the 36.4 mm/h rate measured at Hilliers.

Rather poor uniformity was measured at Wyevale (Fig. 1d) from impact sprinklers spaced 10 m apart down each side of the 8.7 m wide tunnel. Irrigation was lower along the edges, where problems would have been exacerbated by more exposed plants drying out faster. There was also a significant change in irrigation rate from along the 10 m section of tunnel measured.

<u>Irrigation uptake and run-through</u>

Results of tests carried out on the 3 L *Syringa* (Lilac) crop at Hilliers (5 September), the 3 L *Choisya* (Mexican Orange Blossom) crop at Wyevale (6 September), and the 7 L *Choisya* crop at Johnson's (16 August) are shown in Table 1. Mean run-through varied from 2% to 18%, and would have been influenced by the pot moisture content prior to irrigation, amount and application rate of irrigation dose, and structure of the growing medium. As a tool for checking the effectiveness and efficiency of irrigation scheduling, arguably a mean run through up to 15-20% would be acceptable.

A

B

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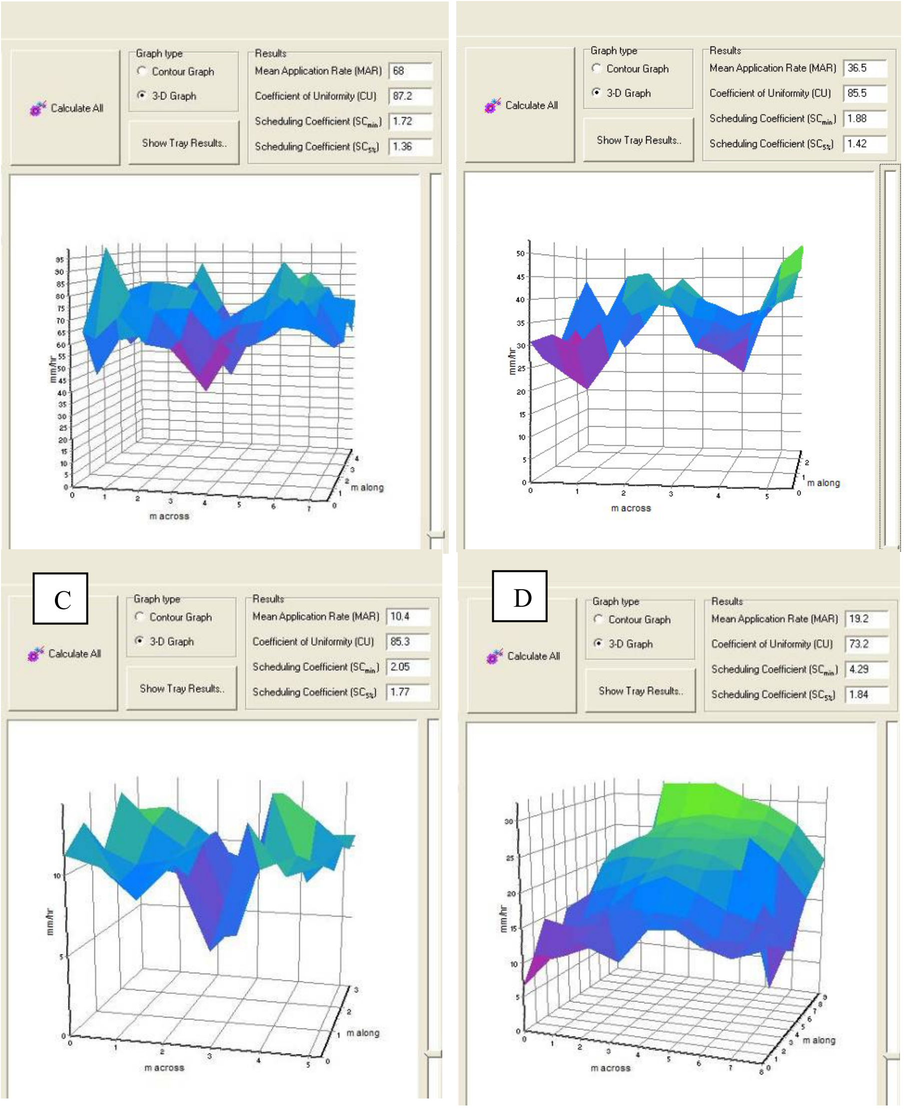

Figure 1. Examples of irrigation output and uniformity measurements under gantry (a) and Pinjet (b) overhead irrigation at Hillier, Dan sprinklers in glasshouse bay at Johnson's of Whixley (c) and Impact sprinklers down each side of a tunnel at Wyevale (d).

Table 1. Summary of water uptake and run-through tests

	Equivalent

Nursery	Run-through[1]	Basal Uptake[2]	Mean mm applied to bed (A)[3]	mm captured by pot based on pot surface area (B)[4]	Fact or B / A
Hillier – pinjet	18%	8%	4.6 mm	13.1 mm	2.9
Hillier – gantry	11%	18%	6.4 mm	11.6 mm	1.8
Wyevale	11%	7%	4.8 mm	7.3 mm	1.5
Johnson's	2%	38%	5.2 mm	7.4 mm	1.4

1 Drainage as % of total capture (pot uptake + drainage) by 'run-through' pots.

2 Difference in net water uptake by pots on standing base compared to 'run-through' pots as %.

3 Estimated mean irrigation dose applied to bed. For Hillier this was estimated using the recorded volume from a water meter / bed area. For Wyevale and Johnson's, this was based on the separate assessments of MAR using drip trays.

4 Total capture by 'run-through' pot expressed as mm based on pot surface area (mL water / pot area cm^2 x 10).

The proportion of water taken up through drainage holes in the base of the pot (and/or prevented from freely draining from the pot when in contact with the standing base) ranged from 7% - 38%. At Wyevale, the crop was standing on gravel, so zero basal uptake might be expected. However the gravel layer was not very deep and was sitting on rather poorly structured underlying soil, so it is possible that some puddling may have occurred during irrigation. At Johnson's, there was negligible drainage from the pot, but a large proportion of water was taken up through the base, and some puddling on the glasshouse floor was evident. The Hillier glasshouse beds were Mypex over polythene and sloped towards a drain along the central path. In this case puddling was not obvious, but during irrigation uptake of water from the bed surface would have been possible.

Comparison of columns A and B in Table 1 gives an indication of how the foliage canopy affects water capture via the top of the pot. Using the mean irrigation applied to the bed (A) as an estimate of what water would have entered the top of the pot in the absence of any plant foliage was subject to variation in water distribution from the pots assessed in (B). Water capture over the pot surface area was greater than the mean application over the bed by a factor of 1.4 to 2.9. This suggests that for these species, more funnelling, than shedding, of water by leaves and stems occurred. The large funnelling

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effects shown by the Hillier results probably relates to the canopy (*Spiraea*) being tall and dense at the time of the test.

Performance of complete irrigation systems

Water use of the Hilliers Gantry and Pinjet systems is summarised in Fig. 2. Some handwatering was applied to the Pinjet bay (about 8% of total water applied). The Gantry system consumed slightly more water, particularly early in the season, but initial inexperience in its use may have been partly responsible for this. Typically one or two passes were required at the slowest or medium speed to achieve an adequate irrigation dose. The nursery found it was helpful to be able to vary irrigation partway down the bay to cope with different water demand by the *Griselinia* (Privet) and *Spiraea*.

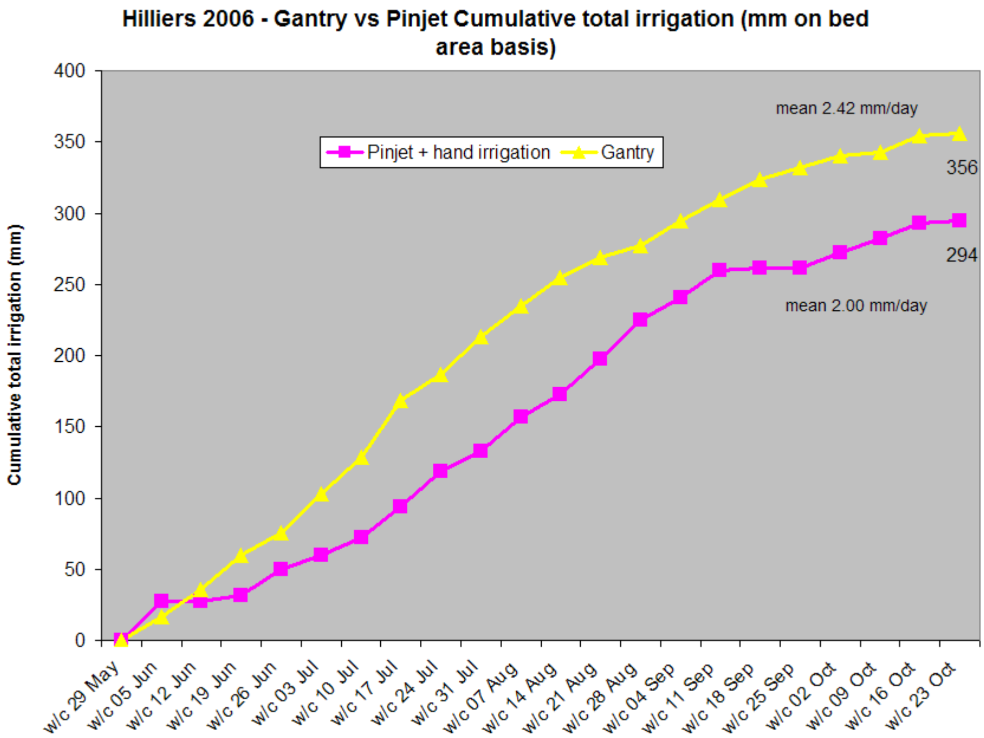

Figure 2. Cumulative water consumption for Pinjet and gantry systems from June to October 2006.

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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 were undertaken to determine the influence of factors such as canopy density on the relationship between plant water use and accumulated degree hours. 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. Experiments were also undertaken with deficit irrigation as well as full irrigation, and drip as well as overhead irrigation, to determine variation across beds in soil moisture under different irrigation conditions. Additionally, Evaposensors and soil moisture sensors were trialled on nurseries.

Materials and Methods

Scale of variation in Evaposensor readings depending on location

Five Evaposensors in different locations under a polytunnel – within a canopy, near the edge of the tunnel, at the centre of the tunnel etc. were logged continuously during September and October 2005, and from March to July 2006. Evaposensors were logged in different locations on and around an open bed of 3 L container plants. Additionally, from August to October 2006 evaposensors were set up in a polytunnel, all away from overhead irrigation but with one evaposensor in the centre of a bay on the Mypex bed, two near the edge of the tunnel on the Mypex, and one near the door of the tunnel on concrete pavement.

Predicting calibration coefficients for use with Evaposensors.

In July 2005, several HNS subjects were donated by Palmstead Nurseries Ltd and were grown in 2 or 3 L pots on gravel beds. One of these beds was

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covered in a polythene tunnel while another was unprotected. Two experiments were run, one with *Escallonia* 'Donard Radiance' and one with mixed species. Both experiments were split over the two gravel beds. Plants were arranged in groups of 9 (3 rows × 3 columns) and the central plant in each group was used for measurements of water use. When water use was being determined, these central plants were watered by hand, with the rest of the group still being watered by drip irrigation. Water use over 24 h was determined by weighing pots before and after watering. Fewer data were collected for outside plants than plants in the polytunnel, since rainfall on several dates meant that there was no loss of plant mass over 24 h. Plants were watered once a day (about 10 am). On either bed, Evaposensors with Evapometers were placed at the centre of either experiment, at approximately the height of the *Escallonia* canopy. The reservoirs were filled with deionised water to maintain the wick on the dry "leaf" sensor wet. The previous 24 h accumulated total of degree hours was read every day before weighing the plants, and the additional total of degree hours accumulating during the measurements was read at intervals during the measurements.

In the experiment with *Escallonia* 'Donard Radiance' there were two experimental factors, spacing and pruning. These factors each had two levels: pot thick ("narrow spacing") and with gaps between pots (25 cm between centres of neighbouring pots, i.e. 17 cm between edges; "widely spaced") in the case of spacing, and "severely pruned" (shoots were pruned to within the edges of the pot) and "lightly pruned" (shoots were pruned to within 10 cm over the edge of the pot) in the case of pruning. Each level of each factor was repeated in each of four blocks per bed.

In the experiment with mixed species, 20 species/cultivars were used on either bed. Plants were placed in groups of 9, as above, with the spacing between pots varying slightly according to the subject, but with on average 24 cm between pots. Groups were arranged in 4 columns × 5 rows, with the location of each species/cultivar being selected randomly.

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Percentage cover was determined for the area between the centres of the outside plants in the group by (a) estimating the percentage of that area covered in leaves, and (b) comparing, by eye, the area covered with that in images of known cover. These subjective assessments were undertaken separately by two people. Total leaf area was measured for representative plants by calculating leaf numbers and measuring the leaf area of a sub-sample. Light interception was determined using a linear PAR ceptometer with 80 PAR sensors at 1cm intervals (AccuPAR). Stomatal conductance was measured with a porometer (AP4, Delta-T).

A second experiment with a range of subjects with diverse canopies was set up in 2006. Fewer subjects were used than previously, so as to allow greater replication and more detailed data per subject. In early August 2006, HNS liners were purchased from New Place Nurseries Ltd and were potted into 100% peat in 2 L pots. Half the plants were placed on a Mypex bed outdoors; the other half were placed on Mypex in a polytunnel. Groups of plants were arranged in a randomised block design on either bed, with 4 blocks and one group of each subject per block. Each group consisted of 9 plants of one subject, as before, with 25 cm between pot centres. There were 6 subjects: *Choisya ternata* 'Sundance' (Mexican Orange Blossom), *Cornus alba* 'Elegantissima' (Dogwood), *Cornus alba* 'Gouchaulti' (Red-barked Dogwood), *Escallonia* 'Donard Radiance', and *Hydrangea macrophylla* 'Blue Wave', and *Lonicera × heckrotti* 'Gold Flame' (Honeysuckle).

Canopy measurements were made soon after the experiment started and were repeated monthly. Percentage cover was determined for the area around the central pots as before. Total leaf area was measured for each of the central plants with a portable leaf area meter (LI-3000A, Licor). Light interception was determined using a linear PAR ceptometer as before. Stomatal conductance of two leaves per plant was measured with a porometer (AP4, Delta-T).

Nursery trials of Evaposensors

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Notcutts, Johnsons of Whixley, and Wyevale compared scheduling of one treatment using an Evapometer with an alternative method (Table 2). This requires undertaking a two-stage calibration procedure firstly involving weighing a sample of, e.g., 10 pots over a one or two day period without irrigation, and correlating mean pot weight loss (evapotranspiration) to degree hours as measured by the Evapometer over the same period. The second stage involves measuring mean weight gain of the pot sample following a dose of irrigation applied over a known time. Thus, daily readings of degree hours ('Previous 24 hour value') can be directly converted into irrigation times required to replace water lost. A spreadsheet was made available for the nurseries to help with the calibration procedure and produce a 'look-up table' that could be printed out. This enabled daily Evapometer readings to be readily converted into irrigation times without having to use a calculator, and the irrigation manager can then adjust the irrigation control panel prior to the next irrigation event. Clearly the calibration was only directly applicable to one particular crop subject under one irrigation system, and it was expected that the calibration would need to be updated perhaps two or three times during the season to take account of relative changes in water use as the crop grew.

Table 2. Scheduling trials on nurseries using the Evapometer

	Notcutts	**Johnsons**	**Wyevale**
Crop	Herbaceous spp. mainly 2 litre	*Choisya* 7 L	*Choisya* 3 L
Bed location	Outdoors	Glasshouse	Tunnel
Irrigation type	Impact sprinklers	Dan micro sprinklers	Impact sprinklers
Scheduling comparison with …	Grower determined	(1) Grower determined (2) GP1 & SM200	Grower determined

<u>Regulated deficit irrigation</u>

An experiment was set up under a polytunnel on a bed of 5 m × 17 m, with both overhead irrigation and drip irrigation, and with crops watered at control irrigation and at crop water deficits. The Mypex bed was divided into 7 bays, each of 5 m × 2.4 m. The bays were separated by a vertical plastic sheet suspended 1.5 m above the ground from the cross bars of the polytunnel. The

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sheets were attached to plastic guttering on the floor. This sheeting prevented water from the overhead sprinklers from spreading into adjacent treatments and the guttering channelled the water away from the bay. Plants of *Lonicera periclymenum* ‘Graham Thomas’ and *Cornus alba* ‘Elegantissima’ (Red-barked Dogwood) purchased from New Place Nurseries Ltd were potted in 100% peat into 2 L pots and placed in the polytunnel, *Lonicera* (Honeysuckle) on one half of the bed and *Cornus* on the other.

Three experimental factors were applied: type of irrigation (drip vs. overhead), percentage of evapotranspiration (ET_p) applied (200% *vs* 50% *vs* 25%), and saucers (presence or absence under pots; this treatment was included to test whether the catchment area affected variation). Each combination of type of irrigation x percentage ET_p occupied an entire bay. Each bay contained 45 *Lonicera* (Honeysuckle) plants and 45 *Cornus* (Dogwood) plants, either subject arranged in 5 rows of 9 plants at a spacing of 25 cm between the centres of the pots. The outer rows and columns of plants were considered guard plants and not measured during the experiment. The experimental plants were paired into 10 replicates for each species, with one of the pair being placed into a 25 cm saucer (for 50% and 25% ET_p) and the other placed directly on the Mypex. For the 200% ET_p treatments upturned saucers were used instead. The Mypex surface of the bed covered gravel for the dripper treatments, but covered plastic for the overhead treatments. A number of tests to determine the overhead irrigation sprinkler arrangement that provided the most uniform water application were conducted. The optimal system for the bay size used was achieved with six 50 L per hour sprinklers (Eindor 861, Access Irrigation) per bay, running at a pressure of 2.3 bar. 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. This allowed a Christiansen’s coefficient of uniformity of 91%, a Scheduling Coefficient of 1.2, and a Mean Application Rate of 7.7 mm per hour (Fig. 3). Drip irrigation was applied using 2 L per hour drippers (C.N.L. Junior Dripper, Access Irrigation), one of which was placed into each pot. Dripper output was monitored and drippers were replaced as necessary to maximise uniformity,

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resulting in a Christiansen's coefficient of uniformity of 96-98% and a Scheduling Coefficient of 1.0 to 1.1.

A daily value of accumulated degree hours was obtained using an Evaposensor placed in one of the bays, and the amount of water applied to the plants was adjusted daily according to the estimated ET_p from the previous day. Evaposensor degree hours were calibrated against water use for *Lonicera* (Honeysuckle); a treatment of 25% ET_p therefore implies that both *Lonicera* (Honeysuckle) and *Cornus* (dogwood) were given sufficient water to replace 25% of the water lost by evapotranspiration in the *Lonicera* (Honeysuckle) plants. Treatments were applied from 8 August 2006.

Water delivery to pots was measured by determining weight gain during irrigation. Volumetric moisture of the compost was measured in every pot with a soil moisture sensor and meter (SM200 and HH2, Delta-T) twice weekly for the first 2 weeks and thereafter weekly. The height of every plant in the experiment was also measured weekly, as was the mass of five replicate pots in each treatment combination.

Additionally, volumetric soil moisture was measured in four locations per pot to obtain information about variability within pots. This was carried out once early in the experiment and again near the end of the experiment.

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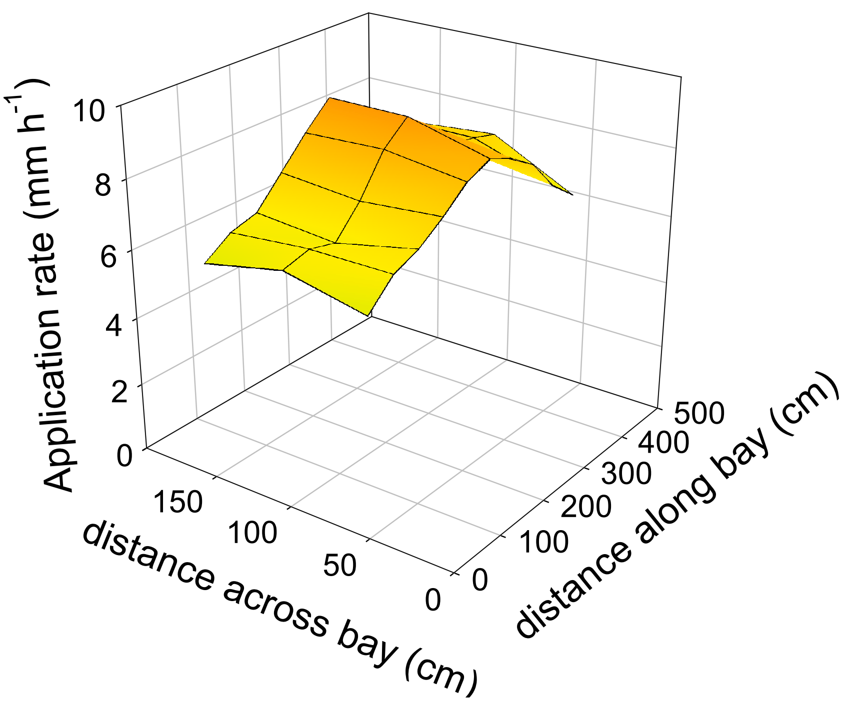

Figure 3. Distribution of water applied to a bed from 50 L per hour Eindoor sprinklers

Nursery trials of soil moisture sensors for irrigation scheduling

Soil moisture sensors (SM200, Delta-T) in conjunction with the GP1 irrigation scheduler (Delta-T) were trialled this year at Johnson's of Whixley, Notcutts, and Garden Centre Plants. The GP1 was used in comparison with Evaposensors on a drip irrigated tree crop (outdoors) at Notcutts and on a 7 L *Choisya* (Mexican Orange Blossom) (glasshouse crop at Johnsons of Whixley, as described above (Table 2). The GP1 was additionally assessed on sprinkler irrigated *Hibiscus* (until 8th August) and *Hydrangea* (from September) crops in a glasshouse at Notcutts, in comparison with grower-determined irrigation.

Results and Discussion

Scale of variation in Evaposensor readings depending on location

Some variation was seen between readings of Evaposensors in different locations across the polytunnel in 2005, with sensors close to or within canopies showing the least accumulation of degree hours. In the polytunnel in 2006, there was clearly some variation in the difference in temperature between the wet and dry sensors depending on location. Most notably the sensor on the pavement maintained a relatively large difference between wet and dry sensors at night, when the difference for the other sensors fell to close to zero.

On an outdoor bed in 2006, the evaposensor which occasionally received irrigation spray showed a tendency to show lower temperature differences than the sensor on a gravel bed. Similarly, there was substantial scatter in the correlation of temperature differences between the wicks of an evaposensor on the centre of a Mypex bed and one placed on wood away from the irrigation and at a lower height; the latter sensor showed a larger temperature difference between the wet and dry wick generally, and particularly did not show the very low temperature differences that occurred everywhere else. The precise location of the evaposensor does appear to have an influence on degree hours, but problems should be avoided by placing the sensor at a height similar to the plants, above a surface similar to that on which the plants are grown, and either consistently exposed to the same overhead irrigation as the plants or never exposed to any spray – the latter is preferable as frequent exposure to overhead irrigation can result in algae building up on the wick and eventually a change in the texture of the wick which prevents it from wetting up correctly.

Water use in relation to degree hours and canopy development

Escallonia

In general, the outside widely spaced plants showed the greatest loss of pot mass i.e. greatest transpiration, per degree hour. Severely pruned plants under the polytunnel showed the least transpiration per degree hour (Fig. 4a). For polytunnel plants, the greatest loss in mass per degree hour was for lightly

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pruned, widely spaced plants, and the least was for severely pruned, narrowly spaced plants. For outside plants, as under polythene, greater loss of mass per degree hour occurred in widely spaced than narrowly spaced plants (Fig. 4b), while narrowly spaced severely pruned *Escallonia* showed lower transpiration than any other group.

Mixed species, first experiment

The greatest water use per degree hour in the polytunnel was in *Cornus alba* (Red-barked dogwood) and *Ceanothus* Italian Skies (Lilac) (some examples in Fig. 5). This was followed by *Phlomis*, *Escallonia*, *Philadelphus* (Mock Orange), and *Physocarpus* Darts Gold (Ninebark). *Euonymus* and *Brachyglottis* (Senecio) showed very low water use per degree hour. The porometry readings showed high stomatal conductance in *Cornus alba* Elegantissima (Red-barked dogwood) and *Escallonia*. Stomatal conductance was low in *Ilex* (Holy), *Euonymus*, and *Nandina* (Heavenly bamboo).

Outside, the greatest water use per degree hour was by *Cornus alba,* (Red-barked dogwood), *Cornus sanguinea* (Common dogwood) *Escallonia*, and *Cornus alba* Elegantissima (Dogwood). *Physocarpus* Darts Gold (Ninebark) and *Phlomis* also used a lot of water. *Nandina* (Heavenly bamboo) used very little water. Stomatal conductance was highest in *Phlomis* and lowest in *Nandina*.

For *Cornus*, there was a similar order in water use per degree hour between the three types inside and outside, but they all show greater water use outside than under the polytunnel. The difference in water use between *Cornus alba* Elegantissima (Dogwood) and the other *Cornus* subjects was less marked outside than under the polytunnel. For *Ceanothus* (Lilac), on the other hand, there was little difference between the two varieties outside, despite a large difference under cover, and the water use of *Ceanothus* Italian Skies (Lilac) was much lower outside than under cover. For *Physocarpus* (Ninebark), the difference between the two cultivars was much greater on days of relatively high evaporative demand outside than inside, with outside Dart’s Gold using a lot more water than Diabolo. *Euonymus* showed much greater loss of water

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outside than under the polytunnel. Different responses of the same cultivar inside and outside, and in particular differences between individuals of one species when measured on different dates, suggests that it would be best to use several replicates of each subject, with fewer species overall.

Total leaf area and cover bore little relationship with average water use per degree hour per m^2 ground area. *Nandina*, for example, was estimated to have a dense canopy, and had a large total leaf area, but showed low water use. Estimates of cover and calculation of leaf area were carried out late in the season when several subjects had already lost many leaves. With regards to leaf area, an insufficient subsample of leaves may have been measured. Two people's estimates of canopy cover frequently differed, and an individual's estimate with and without the comparative pictures also sometimes differed substantially.

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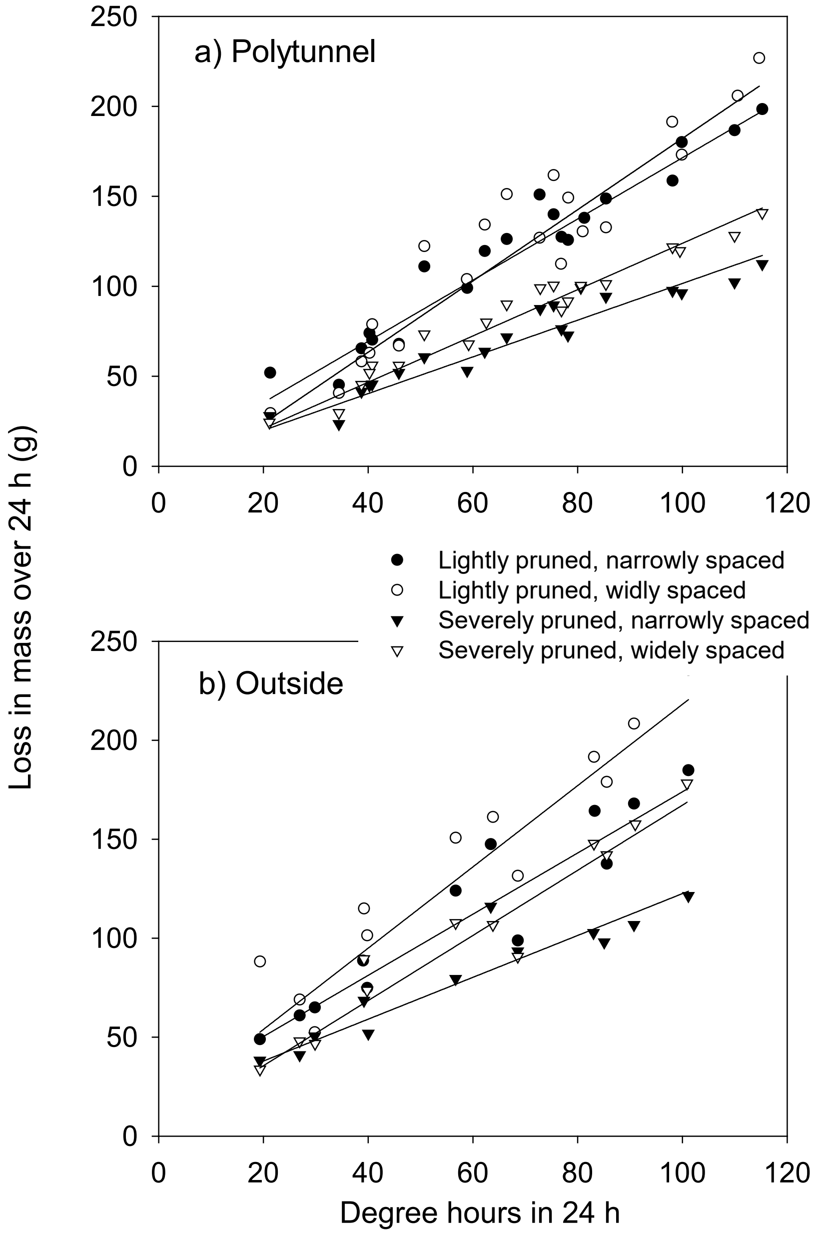

Figure 4. The loss in mass over 24 hour periods in relation to the Evaposensor degree hours accumulated over the same time of *Escallonia* 'Donard Radiance' plants kept (a) under a polytunnel and (b) on an outside bed, for lightly pruned (circles) or severely pruned (triangles) plants, at narrow spacing (filled symbols) or wide spacing (open symbols). Each point represents the mean for a treatment, n = 4. Lines demonstrate linear relationships between loss in mass and degree hours for each treatment.

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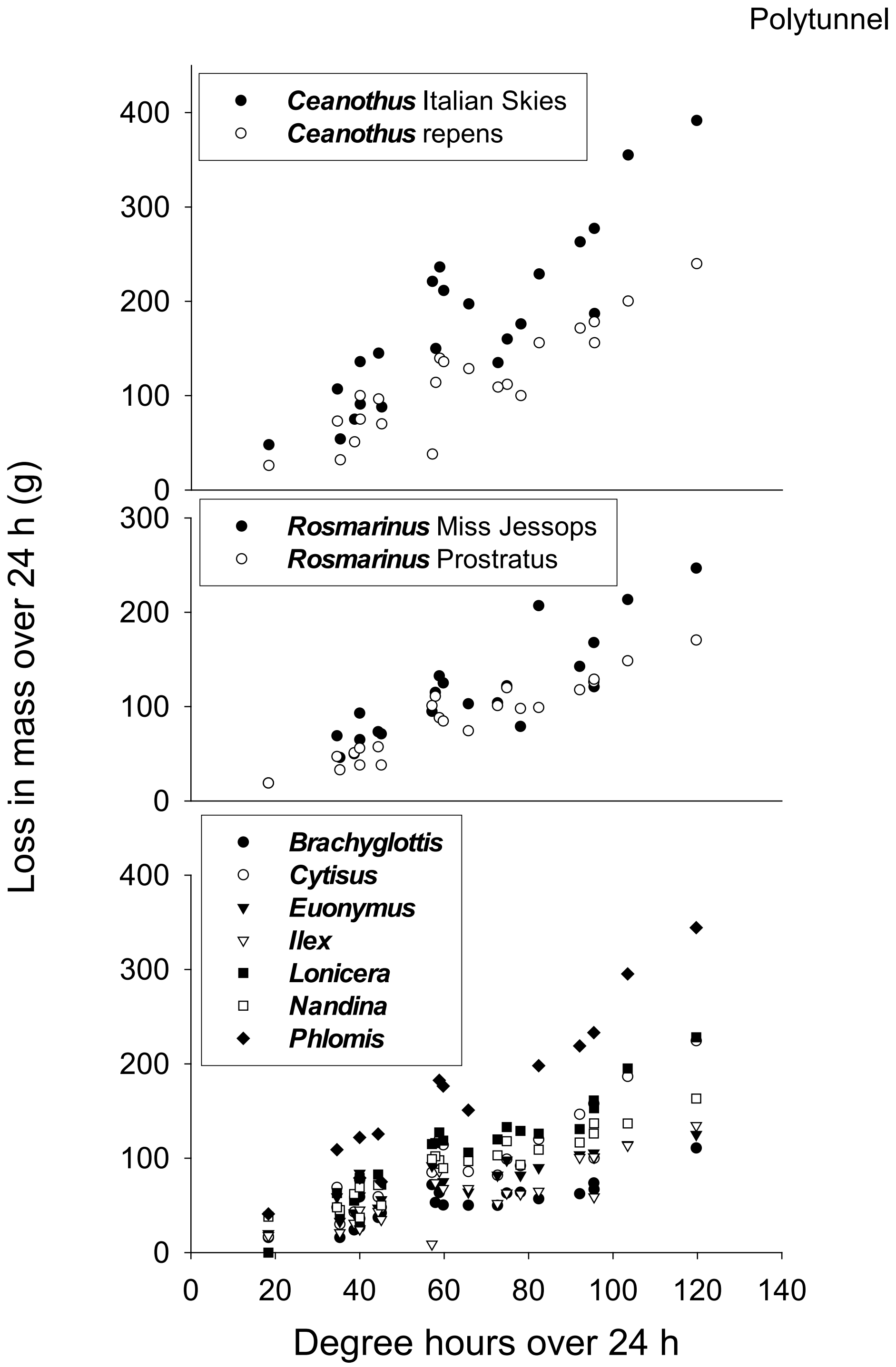

Figure 5. The loss in mass over 24 hour periods in relation to the Evaposensor degree hours accumulated over the same time of a selection of the plant species kept under a polytunnel. Each point represents an individual plant. Three different plants per species/cultivar were measured over the course of the experiment.

The average PAR over the whole of the ceptometer (80 cm), the average PAR measured along the ceptometer ± 25 cm from the centre of the group, the PAR measured at only the centre of the group, and the minimum PAR measured, were used as indications of canopy density. These measures correlated well with estimates of % cover for mixed subjects in the polytunnel but not those outside, and were not closely correlated with estimates of total leaf area in either case. While, as expected, greater water use per m^2 of ground area per degree h was found in subjects for which interception of PAR was greatest (i.e. the canopy was densest), correlations between these measures are poor, except in the case of *Escallonia* on the outside bed, for which the correlation between water use and, in particular, PAR at the centre of the group was high (R^2 = 0.83; Fig. 6). Outside, *Cornus alba* (Red-barked Dogwood) and *Cornus sanguinea* (Dogwood) were found to show a high water use per m^2 ground area per degree hour, despite having relatively sparse canopies. The data suggest that it is necessary to combine aspects of canopy density with physiological characteristics of different subjects in order to determine a generic system for estimating relating degree hours to water use in different crops.

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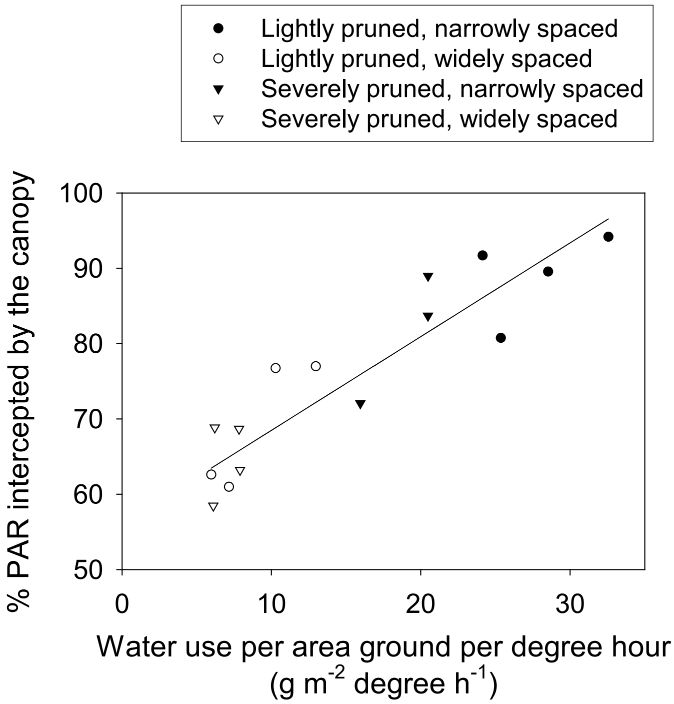

Figure 6. % PAR intercepted at the centre of *Escallonia* canopies on an outside bed, in relation to water use per area of ground per degree hour. The line represents a linear fit between % interception and water use

Mixed species, second experiment

The relationship between water use (measured as loss of mass over 24 h) and degree hours over the same interval in the second of these experiments indicated very little water use per degree hour for *Choisya* (Mexican Orange Blossom) either outside or under a polytunnel (Fig. 7). Water use was also quite low for *Lonicera*, and quite high for *Escallonia* and *Cornus alba* 'Elegantissima' (Dogwood). Water use per degree hour changed over time – for the plants outside the pattern was not very clear, although there appears to be an increase in water use per degree hour for *Cornus alba* 'Elegantissima' (Dogwood), and a decrease in water use per degree hour over time for *Choisya* (Mexican Orange Blossom). The seasonal trend is more noticeable for plants in the polytunnel. Water use per degree hour decreased in September in *Choisya* (Mexican Orange Blossom), but increased after about the first two weeks in the other subjects, and there was a notable increase in water use per degree hour mid-late September for *Cornus alba* 'Elegantissima' (Dogwood) and *Lonicera* (Honeysuckle). Thus a linear relationship between water use and degree hours is more evident when different stages in the growth of some of the subjects are shown separately (Fig. 8). A linear relationship was seen between average water use per degree hour and total leaf area (Fig. 9), both outside and in the polytunnel. This is encouraging as it means that some measure based on leaf area could be used as an alternative to frequent weighing of pots for calibration of plant water use against degree hours. However, an estimation of cover correlated well with water use per degree hour only for outside plants. Comparison of plant cover with images of known cover in this case was not very useful since all plants fell into only a few classes – images of a far wider range of percentage covers could, however, be generated. 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 – alternatively sampling for light interception may have been insufficient. Since total leaf area is very time-consuming to measure, some method for rapidly assessing leaf area needs to be devised for routine use on nurseries.

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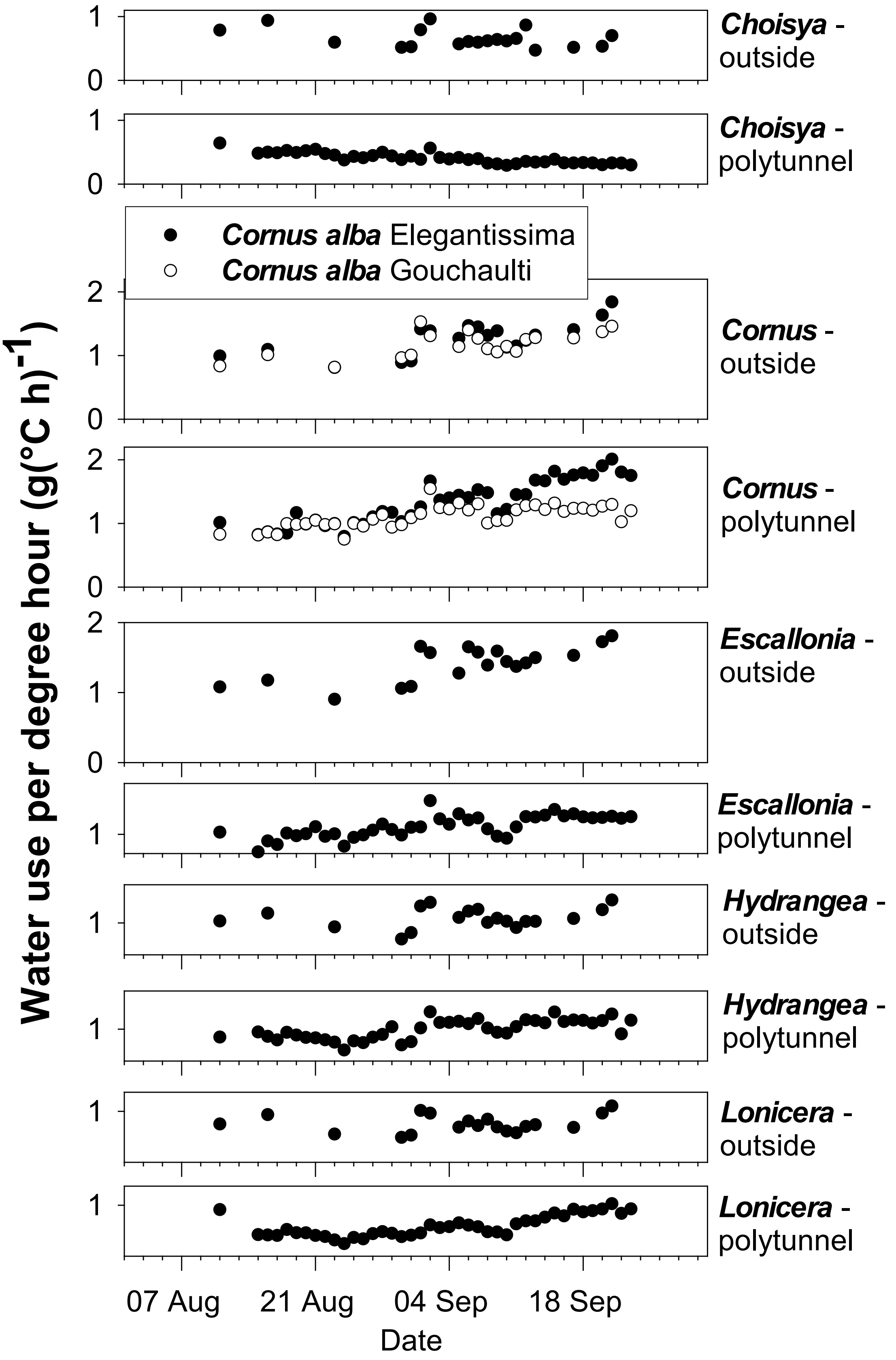

Figure 7. Changes in water use per degree hour over time, for a range of species/varieties, outside and in a polytunnel.

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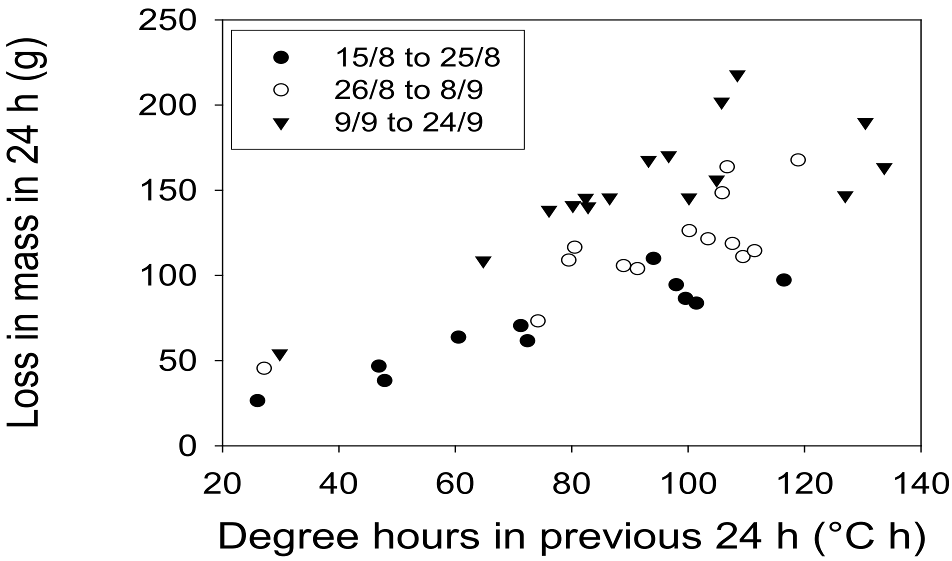

Figure 8. Daily water used measured as loss in mass over 24 h for different accumulated degree hours measured over the same interval during different stages in growth for *Cornus alba* 'Elegantissima' (Dogwood) in a polytunnel. Data points are the average for 4 plants.

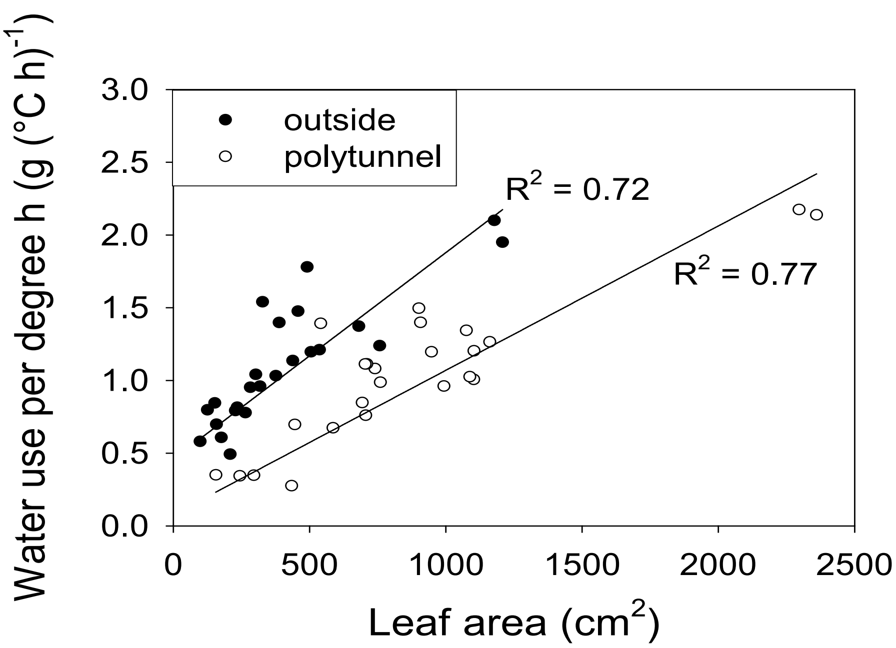

Figure 9. Relationship between average water use per degree hour and total leaf area. Daily values collected during the interval 9 Sept to 24 Sept were averaged for the average water use per degree hour, and total leaf area was measured on 14 Sept for outside plants and 21 Sept for plants in the polytunnel.

Nursery trials of Evaposensors

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

The Evapometer appears to have been successful in scheduling the Notcutts trial on an outdoor herbaceous crop, and resulted in similar or less water use than comparative beds on which irrigation was determined according to grower judgment (Fig. 10).

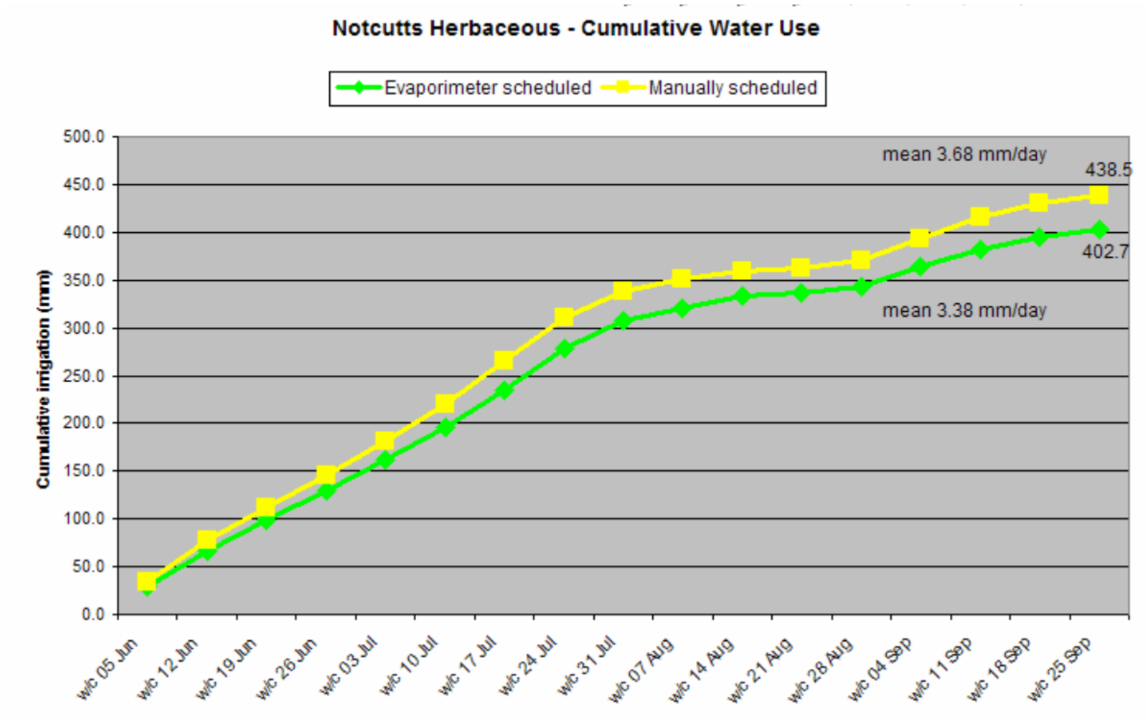

Figure 10. Cumulative water use in a scheduling experiment at Notcutts

Regulated deficit irrigation

Water delivery tests showed no consistent trend of either the overhead or drip irrigation resulting in more variation in the quantity of water acquired by the plants (measured as an increase in mass) during the irrigation; additionally, the different canopy structures of *Lonicera* (Honeysuckle) and *Cornus* (Dogwood) did not appear to lead to any difference in the quantity of water actually reaching the pot (but the plants were relatively small when the tests were carried out).

A general tendency was found for pot weight gain during irrigation to show more variation between pots under overhead irrigation than drip irrigation (Fig. 11). Variation between pots in volumetric compost moisture did not appear to be any greater under overhead irrigation than drip irrigation (Fig. 12) however. Similarly, while 25% deficit irrigation appeared to reduce variation in growth of *Lonicera* (Honeysuckle) overhead and drip irrigation both produced large variation in growth under 50% and 200% ET_p (Fig. 13).

Repeated measurements of compost moisture over the experiment (Fig. 14) showed a significant effect of the type of irrigation (overhead *vs* drip, $P = 0.01$, Repeated Measures Analysis of Variance), and of the % ET_p being replaced by irrigation ($P < 0.001$) for *Lonicera* (Honeysuckle). In addition, there was a significant interaction of irrigation and ET_p. For *Cornus* (Dogwood), however, while there was a significant effect of % ET_p and a significant interaction of irrigation type and % ET_p (both $P < 0.001$), there was no main effect of irrigation type.

The mass of both *Lonicera* (Honeysuckle) and *Cornus* (Dogwood) plants was significantly affected by both the irrigation type and % ET_p applied (all $P < 0.001$, Fig. 15). For *Cornus* (Dogwood), there was a significant interaction of % ETp applied and both irrigation type ($P < 0.001$) and whether or not the pots were standing in saucers ($P = 0.034$).

The % ET_p applied significantly affected growth of both *Lonicera* (Honeysuckle) and *Cornus* (Dogwood) ($P < 0.001$; Fig. 16). Growth of *Cornus*

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(Dogwood) was also affected by irrigation type ($P < 0.001$), and the interaction of irrigation and % ET_p applied ($P = 0.003$). Some examples of the effects of different treatments on plant growth and quality are presented in Fig. 17.

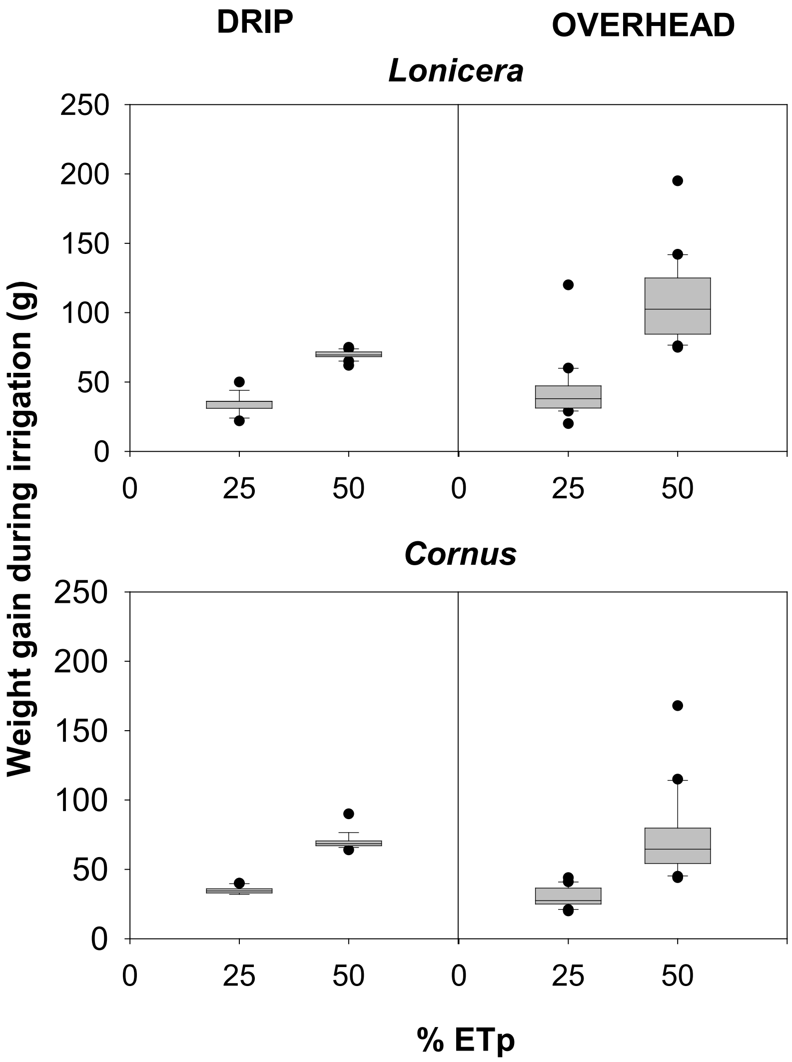

Figure 11. Water delivery measured as weight gain of pots of *Lonicera periclymenum* 'Graham Thomas' (Honeysuckle) and *Cornus alba* 'Elegantissima' (Dogwood) under drip irrigation and overhead irrigation. Application of 100% ETp on this date would have equaled 165 mL. Boxes indicate the 25th to 75th percentile range, whiskers extend another 15% either way, and outliers are represented by circles.

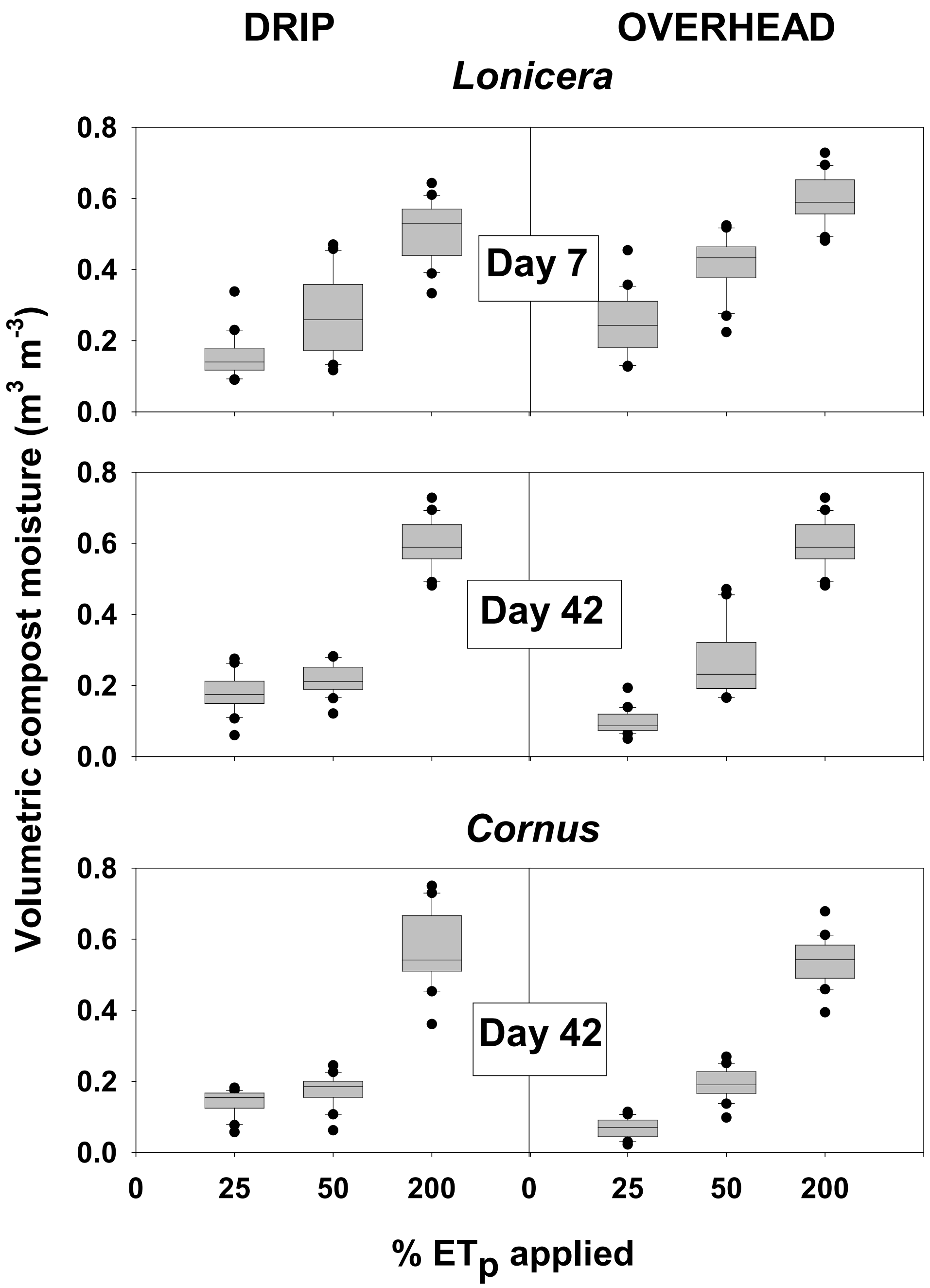

Figure 12. Volumetric compost moisture in pots of *Lonicera periclymenum* 'Graham Thomas' (Honeysuckle) and *Cornus alba* 'Elegantissima' (Dogwood) under drip irrigation and overhead irrigation. Boxes indicate the 25th to 75th percentile range, whiskers extend another 15% either way, and outliers are represented by circles.

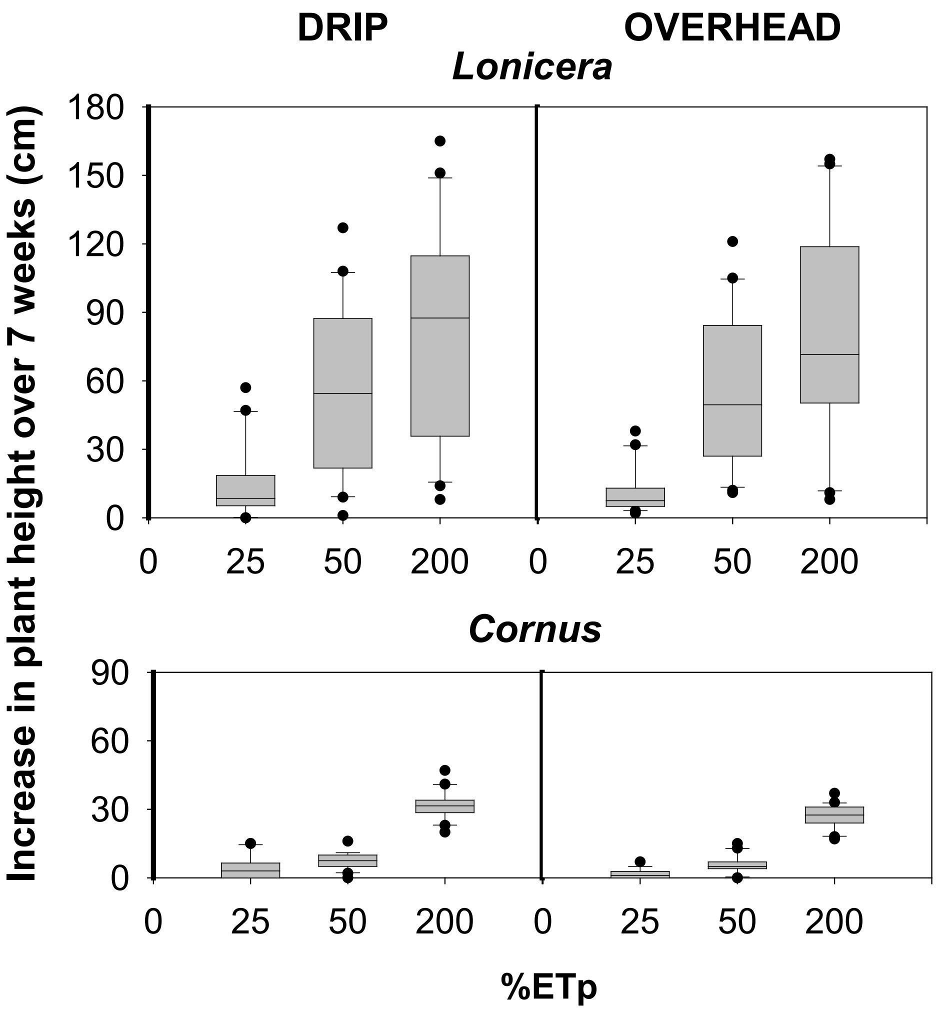

Figure 13. Increase in the height of *Lonicera periclymenum* 'Graham Thomas' (Honeysuckle) and *Cornus alba* 'Elegantissima' (Dogwood) over 7 weeks under drip irrigation and overhead irrigation. Boxes indicate the 25th to 75th percentile range, whiskers extend another 15% either way, and outliers are represented by circles.

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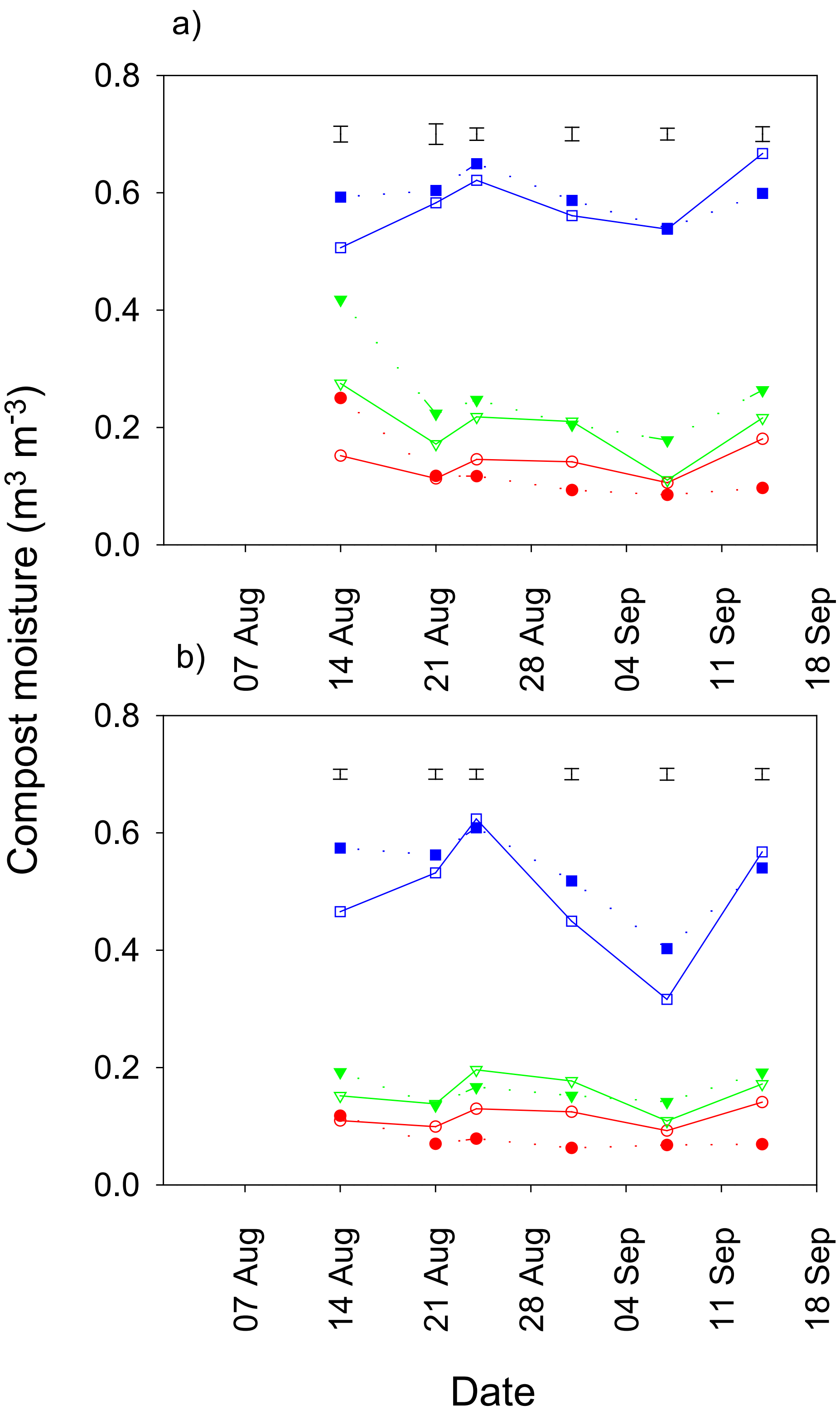

Figure 14. Volumetric compost moisture through an experiment in pots with two species, *Lonicera periclymenum* 'Graham Thomas' (Honeysuckle) (a) and *Cornus alba* 'Elegantissima' (Dogwood) (b) under overhead (closed symbols) or drip (open symbols) irrigation and with 25% (circles), 50% (trianges) or 200% (squares) of ET_p replaced with irrigation. Vertical bars represent standard errors of the difference between treatments (d.f. = 108)

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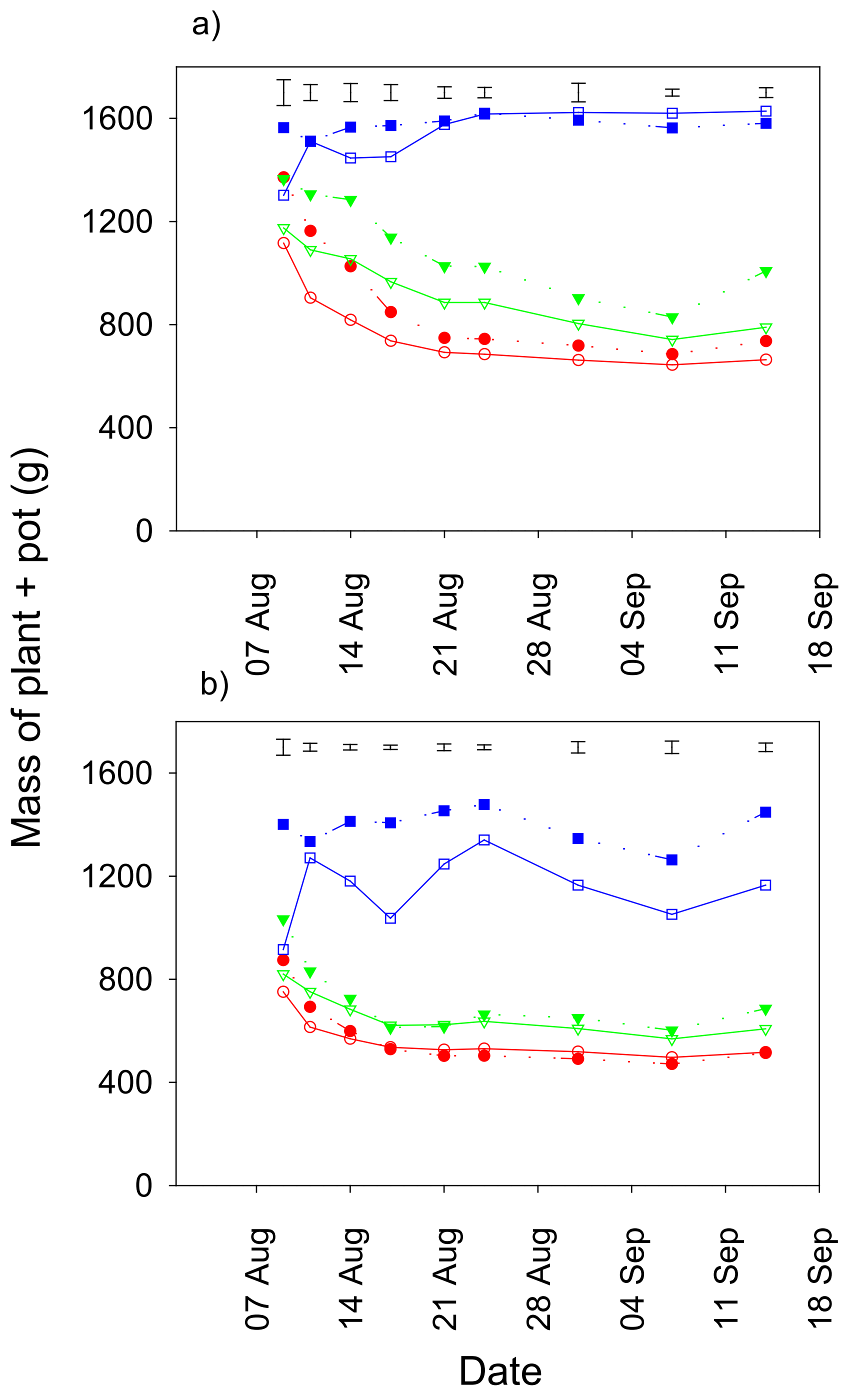

Figure 15. Mass of plants of *Lonicera periclymenum* ‘Graham Thomas’ (Honeysuckle) (a) and *Cornus alba* ‘Elegantissima’ (Dogwood) (b) and their pots. See Fig. 14 for key.

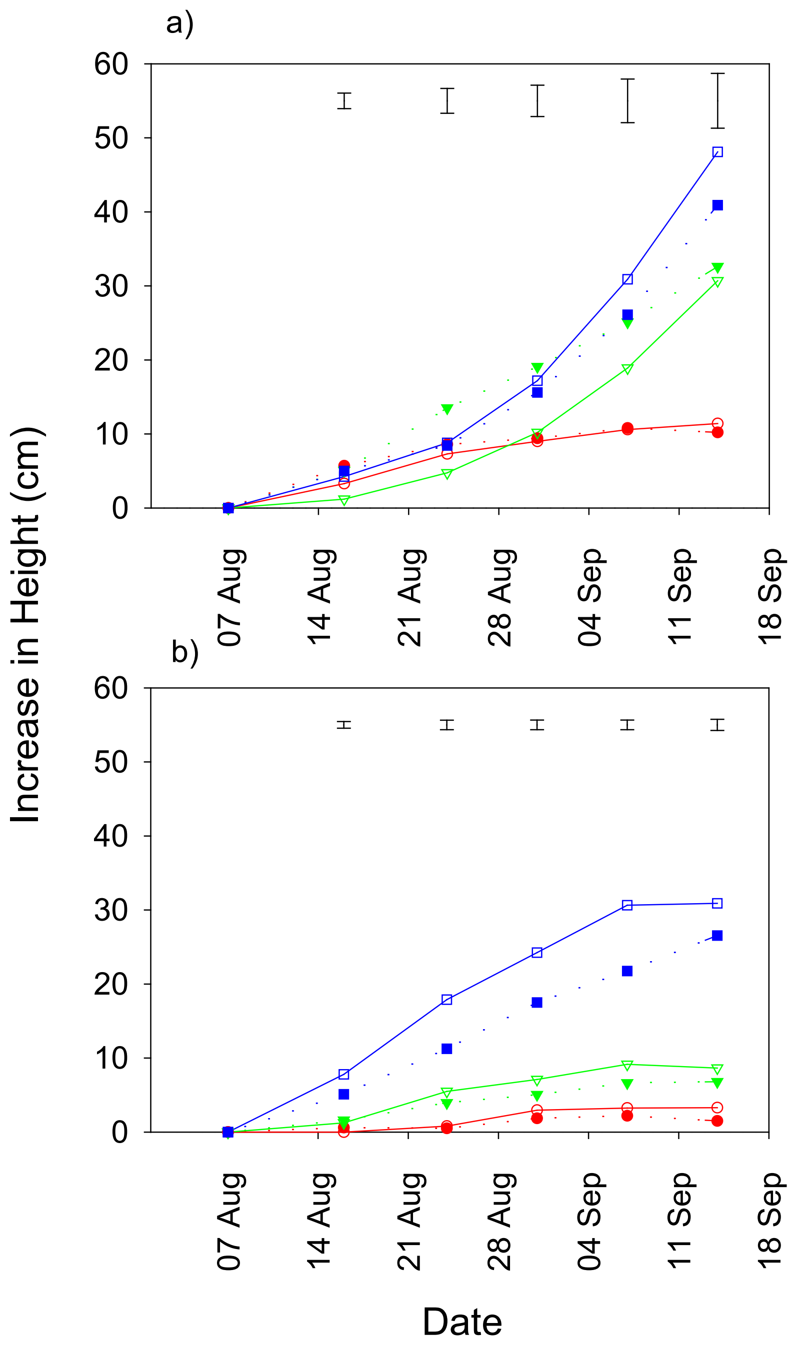

Figure 16. Change in plant height of *Lonicera periclymenum* 'Graham Thomas' (Honeysuckle) (a) and *Cornus alba* 'Elegantissima' (Dogwood) (b). See Fig. 14 for key.

200%

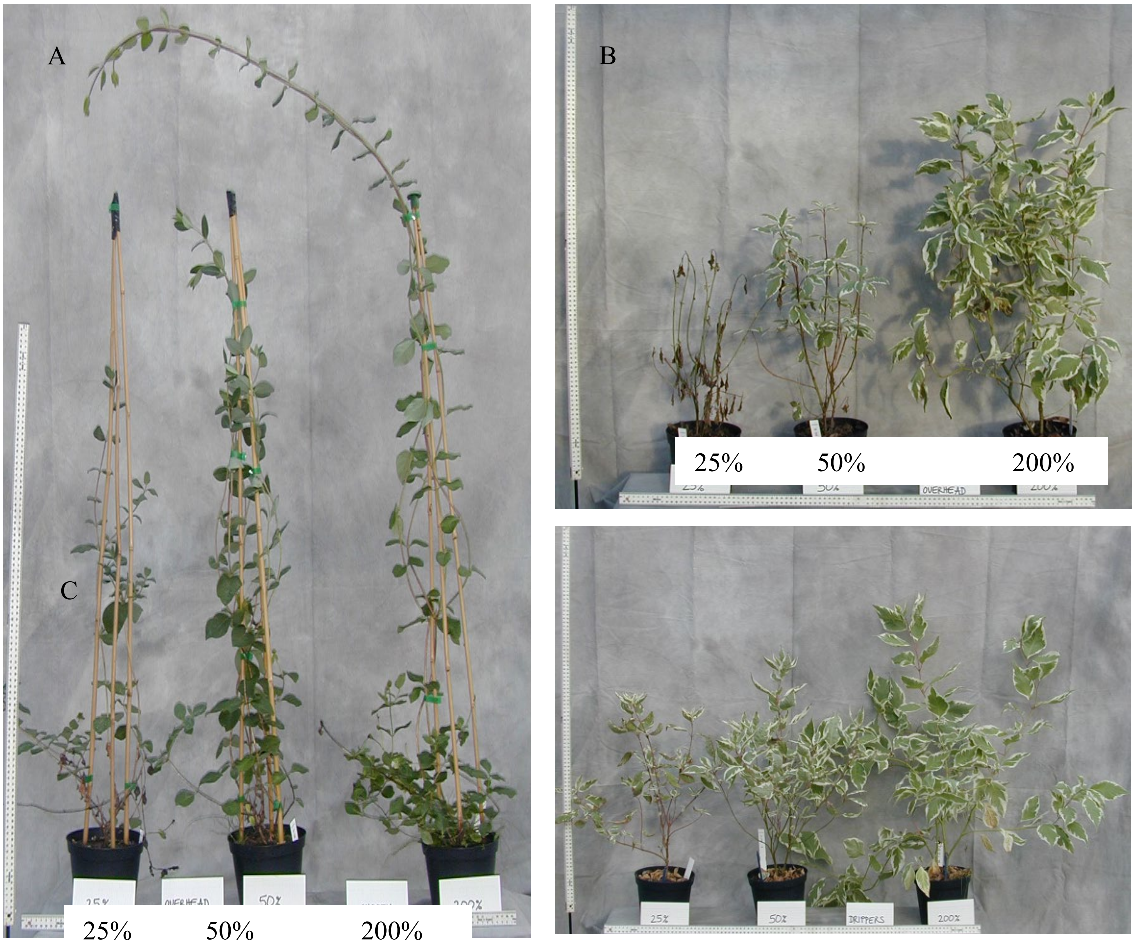

Figure 17. Examples of the appearance of *Lonicera periclymenum* 'Graham Thomas (Honeysuckle) (a) and *Cornus alba* 'Elegantissima'(Dogwood) (b) after 7.5 weeks of overhead (a, b) or drip (c) irrigation applied to replace different percentages of plant ET_p

Nursery trials of soil moisture sensors for irrigation scheduling

The GP1 and SM200 hardware and software appear to have been very reliable during the season, and there have been no reports of equipment breakdown or problems with batteries running out unexpectedly etc. There have been difficulties in proving the GP1's irrigation scheduling capabilities on some of the trials this year, but this has been due either to irrigation equipment failures (e.g. pump failures), or more typically insufficient irrigation timer program capacity to supply the water demanded by the GP1, so that the crop is not reaching sufficient moisture levels to switch off the irrigation.

Typically, the GP1 is retrofitted into an irrigation control panel – solenoid valve circuit. The GP1 can only control water supply to the crop while the control panel is providing a live supply to the circuit. During this time, the GP1 will switch the solenoid irrigation valve on and off according to moisture levels in the pot containing the SM200 sensor. The GP1 can also introduce on/off 'duty cycles' of irrigation pulsing while water is being called for. The main problem was often that an insufficient 'irrigation opportunity' period was set on the main control panel to the experimental block. This could be difficult to achieve if there was insufficient time for the controller to also supply irrigation to the other non-experimental blocks as well.

Problems with the tree crop were compounded because there were different species of trees within the trial block, which had different requirements.

In Fig. 18a, the control program was set to 35% on / 45% off according to Moisture probe 1 (red) with a 60% duty cycle every 3 mins (2 mins on / 1 min off). Moisture probe 2 (green) was monitoring levels in a second replicate tree pot. The solid blue band along the bottom shows that the relay was permanently cycling on and off calling for water, but that the moisture never reached the 45% level necessary to turn the irrigation off. More successful control was achieved with Johnsons *Choisya* (Mexican Orange Blossom) experiment (Fig. 18b) where Moisture probe 1 (blue) controller settings of 28% on/38% off were used with a 3 mins on/7 mins off sprayline pulse cycle. Moisture levels remained within the set points (except for 25 August when a

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manual irrigation dose was applied to the bay). Irrigation was required infrequently at this time with the slow growing *Choisya* (Mexican Orange Blossom) in 7 L pots.

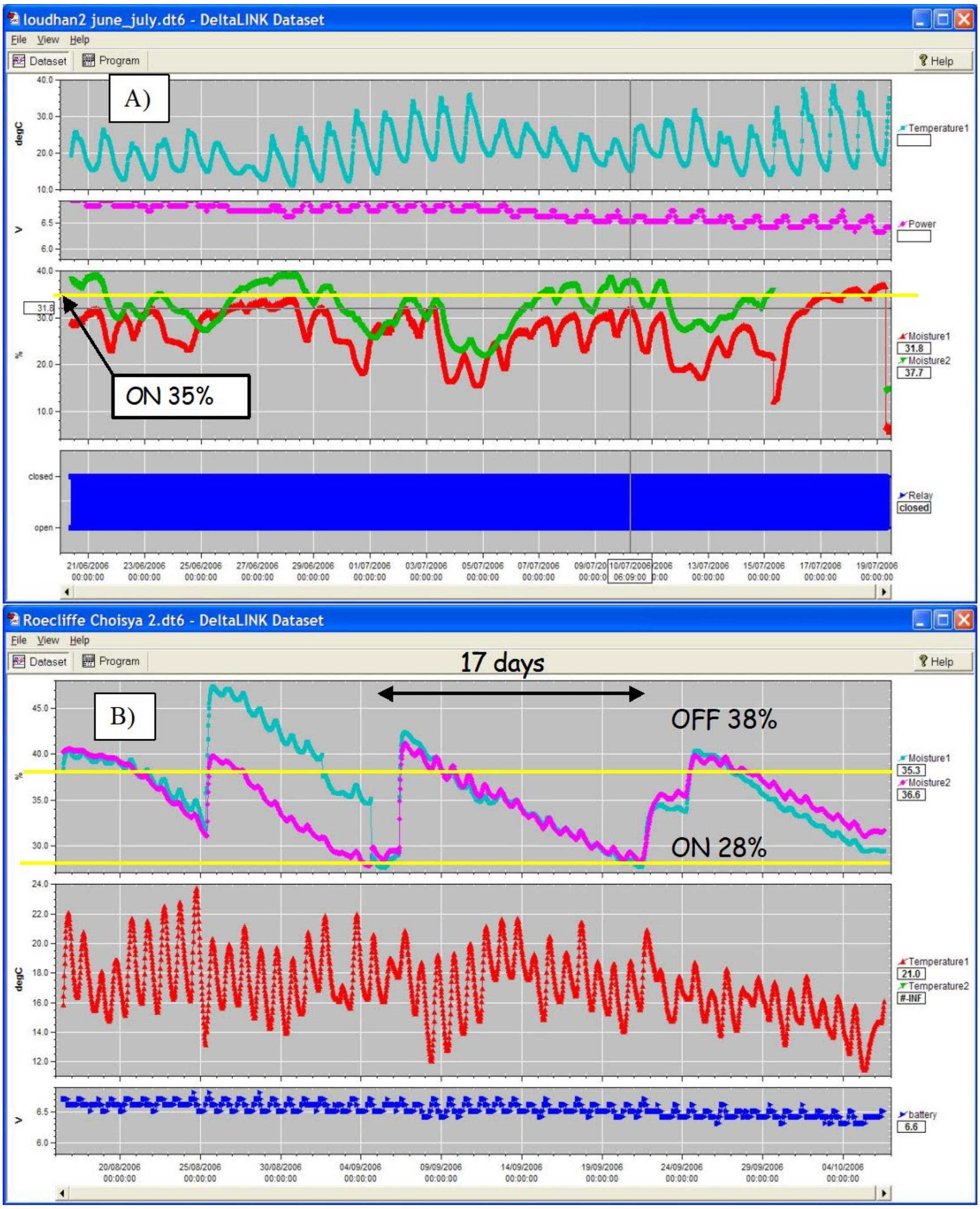

Figure 18. GP1 data from Notcutts Loudhan tree site 21 June – 19 July 2006 (a) and from Johnsons of Whixley's *Choisya* (Mexican Orange Blossom) experiment 12 May – 6 October (b). A control probe (red in a, blue in b) and a second monitoring probe (green) recorded soil moisture.

In a comparison of different scheduling methods at Johnson of Whixley's Roecliffe site, water use was relatively low under all of the scheduling systems, averaging only 0.5-0.7 mm per day. *Choisya* (Mexican Orange Blossom) is a fairly slow growing subject, and the experiment was run over 9 weeks in late summer, which might partly explain the low consumption. The GP1 controller worked very well, and consumed a similar amount of water as the grower determined control schedule. Scheduling using the Evapometer resulted in the highest mean water use. However, weekly data (not shown) indicates that irrigation on this bay did not, in fact, closely follow Evapometer readings, with excessive irrigation being given some weeks. The grower determined schedule to the pinjet irrigated bay used more water than the same treatment under the lower application rate Dan nozzles.

Conclusions

The results to date indicate that coefficients for use with evaposensors can be predicted from total leaf area. It is now necessary to establish a more rapid method for the assessment of leaf area for use on nurseries. Regarding precision drip irrigation versus high precision overhead irrigation, the variation within a bed in the quantity of water received by plants under overhead was greater than that under drip. This might indicate a risk associated with the use of overhead irrigation where a highly uniform crop is required – however, in our experiment variation in water delivery was *not* reflected by any greater variation in plant growth, or even soil moisture (point measurements), under overhead irrigation. Our experiment with deficit irrigation indicated that it can be used to control growth, but that too severe a deficit regime is detrimental to plant quality. Growers obtained familiarity with methods for scheduling and monitoring water use on the nursery this year – trials of different equipment and scheduling methods will be continued in the second year.

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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

The stomata of many plants close when they are under water deficit stress; this stomatal closure appears to be a sensitive indicator of water stress and hence of irrigation need. If a suitable method for monitoring for stomatal closure were available this could provide a sensitive tool for scheduling irrigation. Although direct measurement of stomatal conductance using a porometer is not thought to be feasible, the indirect effect of stomatal closure on raising leaf temperature appears to hold much promise. This part of the project therefore concentrates on the development of tools for using measurements of leaf or canopy temperature to aid the scheduling of irrigation for HNS crops.

The use of thermography is based on the reduction in evaporative cooling as stomata close under water stress, with the amount of consequent warming depending on the degree of stomatal closure. In practice, however, other factors influence the temperature of a plant's leaves, including the amount of sunlight falling on the plant, the air temperature, the air humidity and the wind speed. In order to use thermography to detect water stressed plants and hence to schedule or adjust irrigation it is necessary to calibrate the observed canopy temperature for the prevailing environmental conditions. It is essential to know if the plant is warmer than would be expected for a well watered plant in the same environmental conditions.

Under this objective the project has developed three lines of work during the first year of this project: (a) further development of the basic energy balance model to provide a tool to calculate expected canopy temperatures under any particular environmental conditions and to derive the expected sensitivity to

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changes in stomatal conductance, (b) devised and tested heated-leaf models for estimation of the critical boundary layer conductance that is required for solution of the energy balance and estimation of leaf temperature, and (c) initial tests of the “non-calibrated use” of hand-held thermal imagers for rapid monitoring of nurseries.

Materials and Methods

Experiments were run outside at the Johnson’s of Whixley head office site near York using a heated “leaf” system developed at Dundee University.

<u>Boundary layer resistance</u>

On the basis of previous work on the development of heated replica leaf systems to estimate boundary layer heat conductance (Leuning 1990; Brenner 1995; Stokes 2006) we have developed a simple heated leaf system to provide parameters for input into the model for estimation of leaf temperature. The energy input into the heated leaf is calculated from the voltage across the heating element and the resistance of the heating element. The temperature rise depends on the heat input and on heat loss through the boundary layer, with greater temperature rises reflecting large boundary layer resistances.

Artificial leaves of two sizes were created using commercially available silicone/polyamide heating mats. Small leaves used 50x25mm 1.25W mats, large leaves used 50x75mm 3.75W mats. Leaves were constructed in pairs (see Figure 19) with one heated and one unheated leaf. A thermocouple was created with two junctions in series to measure the temperature difference between the leaves. The leaves were covered in reflective material to minimise confounding effects of solar radiation. The two leaves were attached by plastic rod this joined the leaves but permitted movement.

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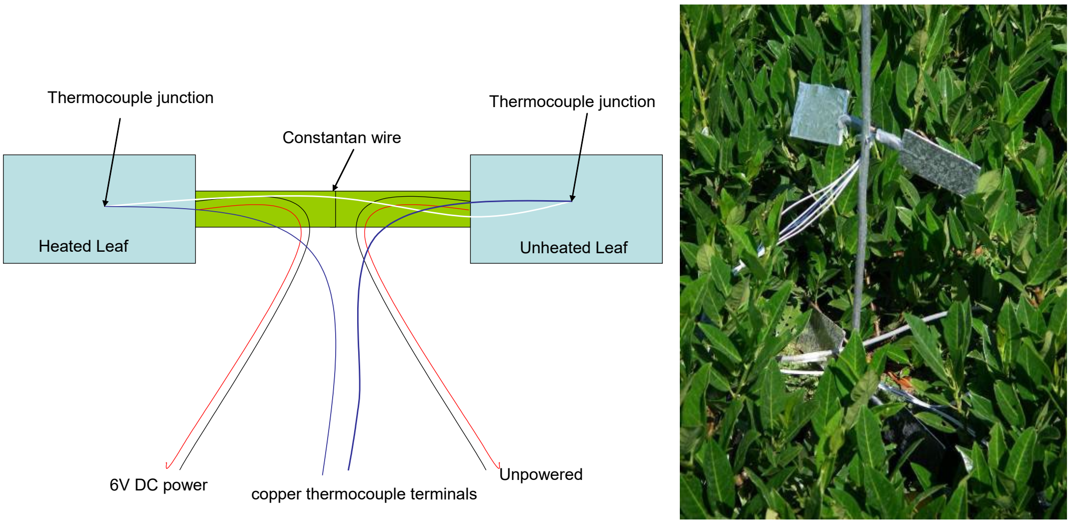

Figure 19. Heated leaf models and their installation in a canopy.

Two pairs of leaves were attached to aluminium rods creating paired pairs to enable measurements to be taken above and within the plant canopy at the same point. Six sets of such leaves were created three with small leaves and three with large leaves.

The artificial leaves were set up on the Johnson's of Whixley head office nursery site near York from 8th July to 8th September 2006 to investigate the effect of environmental conditions and canopy structure on the aerodynamic properties of different HNS canopies. Measures of the environmental conditions were monitored at the same intervals during the same period. Measurements were made for the first half of the period with the equipment setup in a stand of *Prunus laurocerasus* (Cherry Laurel) and *Weigelia* (Bristol Ruby) situated in an exposed position on top of a south west facing slope. The equipment was moved halfway through the period to a stand of *Ilex aquifolium* (Common Holy) in a sheltered location between wind breaks at the foot of the same slope.

<u>Canopy temperature</u>

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Individual spot canopy temperatures (cT) were continually recorded using a Calex infra-red thermometer (IRT). These readings were only for a small area of the canopy so varied quite rapidly as the solar exposure/shading changed and as cloud cover changed over the period of the experiment but provided a rough estimate of canopy temperature. Therefore the data from several individual IRT sensors were averaged to produce a measure of average canopy temperature.

<u>Hand-held monitoring of poor irrigation:</u>
A Thermacam P25 camera was used to survey a range of HNS nursery beds at Johnson's of Whixley to investigate the possibility of detecting poorly watered plants.

Results and Discussion

<u>Energy balance model for leaf temperature</u>
Work has been undertaken to devise a model, parameterisable from relatively few easily obtained environmental measurements, that can be used to predict expected temperature for a normally transpiring, well-watered plant, This model can then be used to detect "hot" plants by comparing the measured plant temperature with the expected plant temperature. The idea behind the use of thermography for scheduling irrigation involves the detection of plants that are hotter than they would be expected to be if they were transpiring normally in the given environmental conditions. However there are several factors that affect the temperature of a plant other than evapo-transpiration, the two of the main ones being the incident solar radiation and the wind speed. The approach was to reformulate the basic energy balance model (equation 1)

$$T_l - T_a = \frac{[r_{aH}(r_{aW} + r_{sW})\gamma R_n] - \rho c_a r_{aH} \delta e}{\rho c_a [\gamma (r_{aW} + r_{zW}) + s r_{aH}]} \qquad \text{Equation 1}$$

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

Given good estimates for the boundary layer resistances, equation 1 then permits us either to calculate the expected temperature difference between a leaf and the air for a well watered plant or to calculate the stomatal resistance given a measured temperature difference. We have therefore been working on developing ways of measuring boundary layer resistance to incorporate into the model.

Leaf boundary layer estimation

Even though the model leaves were manufactured from commercially available heating pads and attempts to were made to keep the leaves as standard as possible, a calibration test in a greenhouse showed there were significant differences in the thermal properties of the leaf pairs. It is possible this was also partly due to the differing lengths of cable runs to the leaves creating different voltages across the heating resistors, but this did not explain all the difference. Since the differences are most marked in the large leaves it is most likely it is due to variation in placement of the thermocouple terminal relative to the wires of the heating element.

To overcome this problem we developed a simple normalisation process to correct for differences between sensors. The procedure adopted was to apply a fixed voltage to twelve leaf-pairs in a shaded greenhouse with still air over a 15 minute period, the average difference in temperature $\overline{\delta t_i}$ for each leaf-pair

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$i \in 1..12$ and the average temperature difference for all leaf-pairs $\overline{\Delta T}$ were calculated and a correction factor for each leaf-pair calculated as:

$$cf_i = \frac{\overline{\delta t_i}}{\overline{\Delta T}}$$

The correction factor was tested on a further series of data collected for a heating and cooling cycle of the leaf-pairs. The effect of this correction is illustrated in figure 20.

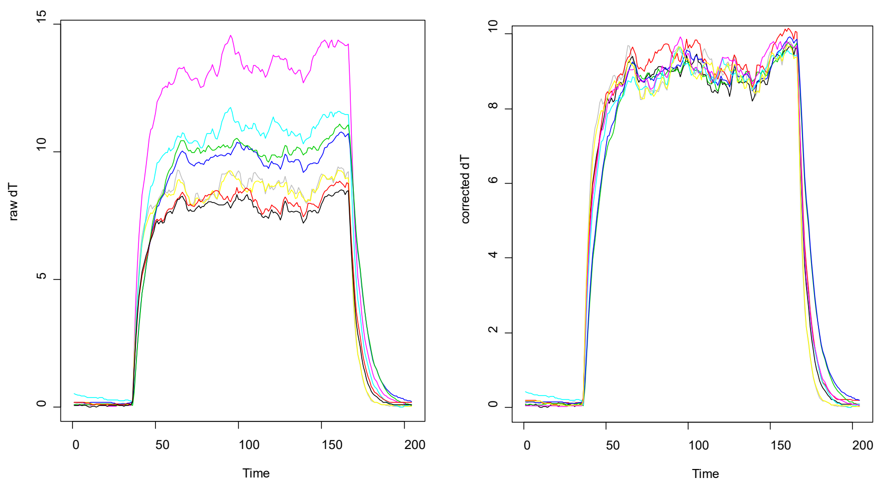

Figure 20. (a) Uncalibrated readings (b) calibrated readings

The effect of wind speed on the boundary layer resistance of plants grown outdoors was investigated using the heated leaf system. Data were collected for a variety of different crops in both exposed and sheltered locations. The following data which illustrate the general results obtained are for day-time hours (11:00-16:00) for two of the leaf-pairs.

The data were first checked for an expected correlation between the wind speed and the temperature difference (dT) between the heated and unheated

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leaves. A significant correlation was found, 87% of the variation in temperature difference could be explained by the variation in wind speed.

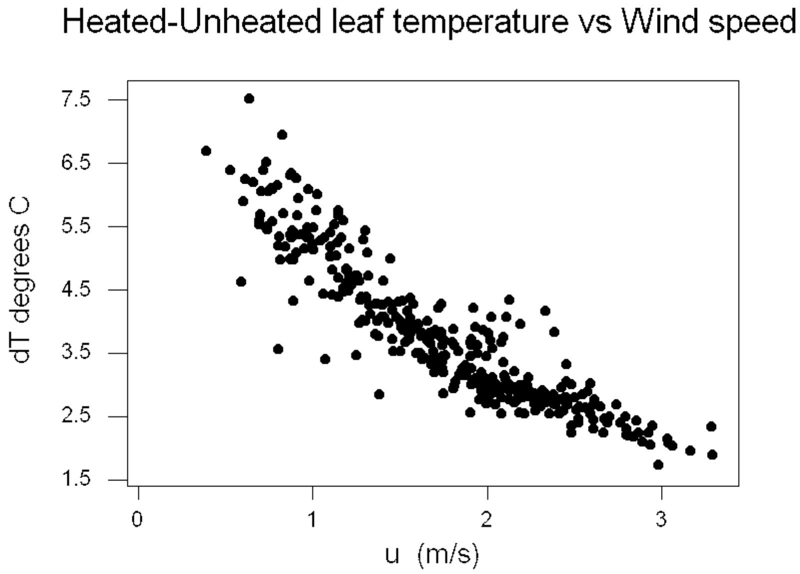

Figure 21. Heated and unheated leaf temperature difference with wind speed

Figure 21 shows the results of a regression of temperature difference dT against wind speed, suggesting that dT could be used to estimate wind speed. This correlation was not quite so clear, however, for a sensor placed within the canopy rather than at the top of the canopy where only 51% of the variation in temperature could be explained by variation in wind speed.

The relationship in figure 21 could be linearised by exponential transformation giving a straight line regression. Figure 22 show a comparison of the fitted regression lines for a within-canopy senor and an above-canopy sensor. The larger values for dT within the canopy at any given external wind speed reflect the fact that wind is slowed within the canopy, leading to less effective cooling (a higher boundary layer resistance) within the canopy.

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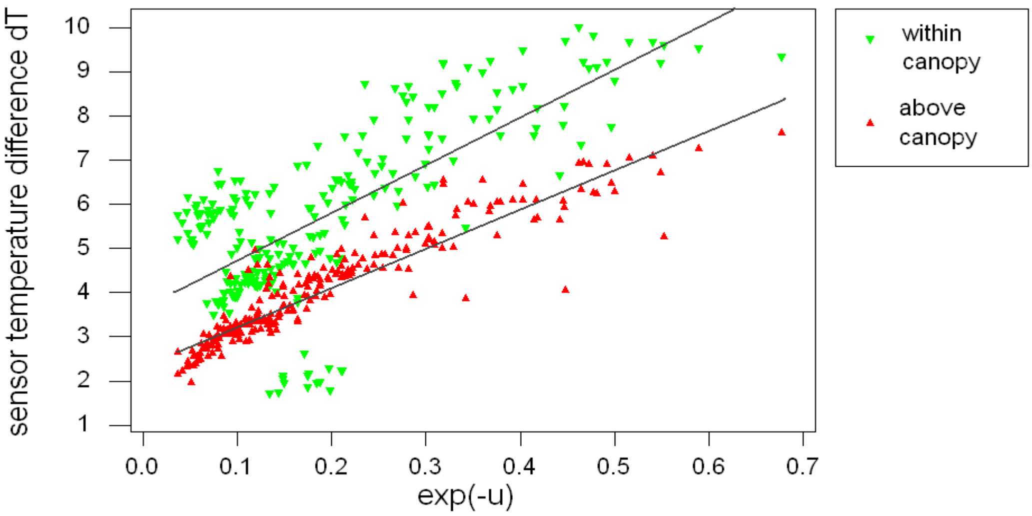

Figure 22. Regressions for within- and above- canopy temperature differences against external wind speed (measured at 2 m height)

<u>Canopy temperature</u>

The temperature of the leaf canopy is expected to be a function several factors including the incident radiation, the air temperature, the air humidity and the wind speed, as well as the transpiration rate of the leaves. The relationship between leaf-air temperature difference and the environmental factors was investigated using a multiple regression approach using the following environmental variables: air temperature, incident radiation, air humidity and boundary layer resistance (in the form of either wind speed of heated leaf sensor temperature difference).

The single most important factor effecting canopy temperature was found to be incident radiation with 39% of the variation in recorded canopy temperatures being explained by variation in radiation. The models of canopy temperature were incrementally extended by adding in the extra factors in a step-wise manner.

Table 3. Comparison of models of canopy temperature cT as functions of radiation (r), wind speed (u), leaf-pair temperature difference (dT), ambient air temperature above the canopy (aT) and air humidity above the canopy (aH). The value of R^2(adj) is a measure of hoe much of the variation in the data is explained by the given model.

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

These models are shown in table 3, where it can be seen that the final model explains 84% of the variation in canopy temperature. It can also be seen that use of heated leaf sensor temperature rather than raw wind speed figures gave a consistently better fit.

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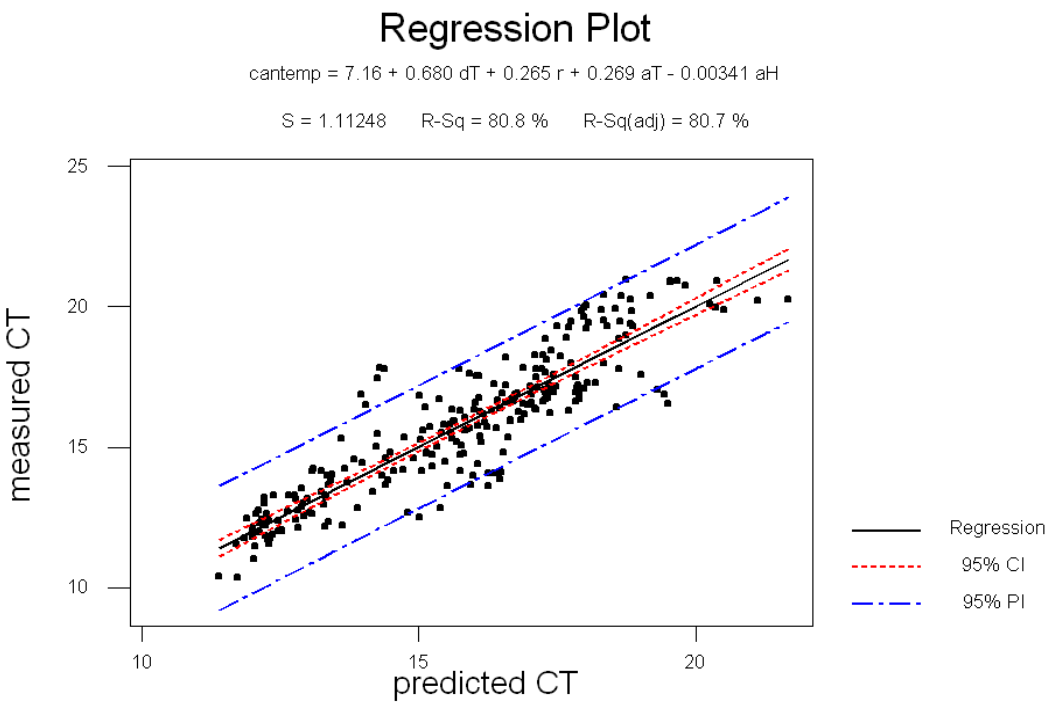

Figure 23. The regression plot for the four factor model

Monitoring of canopies for poor watering

Preliminary tests of the concept of using thermal imaging for *ad hoc* monitoring of irrigation status of HNS crops on commercial nurseries were conducted at Johnson's of Whixley. An example where an area of poor watering could be detected is shown in figure 24.

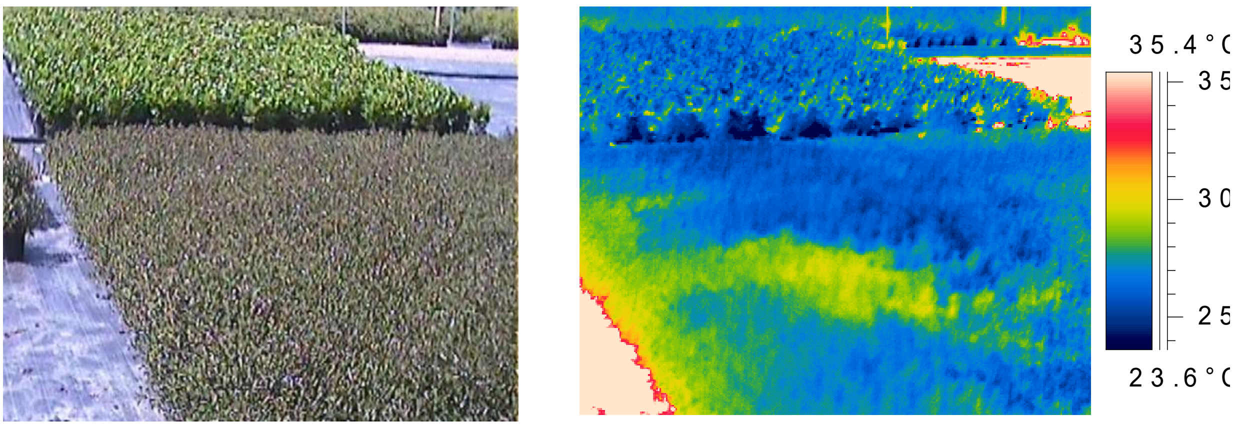

Figure 24. Irrigation failure detected by thermography

The image on the left is a conventional visible light image of a nursery bed of *Hebe* (Mrs Winder), while the image on the right shows the same scene but using a thermal camera. The picture can be artificially coloured to enhance the image for a human observer. The light green/yellow area of plants amongst the darker blue indicates an area where the plants are a few degrees warmer than the surrounding plants. On closer inspection it was found that the containers of these plants were dry due to a failure of the irrigation system to cover the bed evenly.

Conclusions

The energy balance model has been re-expressed in a convenient form for estimation of stomatal conductance from leaf temperature data and spreadsheets are now available to investigate the environmental sensitivity of the temperature difference.

Initial trials of a simple heated-leaf system show promise providing an estimation of boundary layer resistance for incorporation in the energy balance models. However further investigation is needed to investigate whether the heated-leaf system can be sensitive enough to distinguish different boundary layer resistance in different species with canopy structures. Recent work with more sophisticated replica-leaves that mimic the behaviour of the focal plant species more accurately has indicated that this is possible (Stokes 2006).

Preliminary tests have shown that areas of poor irrigation can be detected using a hand-held thermal camera.

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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

Plants have evolved strategies to protect themselves from catastrophic dehydration in times of drought. This can be beneficial for growers who through force of circumstance (and particularly under environmental change) may be limited in the amount of water available for irrigation. If it is possible to manipulate the plant's drought protection mechanisms then it may then be possible to use water more effectively on the nursery while minimising plant damage and losses. This kind of manipulation requires an understanding of the biology of the plant's drought stress responses.

The plant's first line of defense against drought is closure of stomata (pores in the leaf surface through which water is lost and carbon dioxide (CO_2) for photosynthesis is taken up). In addition, leaf growth rates are reduced when the soil dries, thereby limiting the transpiring leaf area. Stem extension rates are also reduced so that plants become more compact and low growing and thereby experience lower evaporative demand. These changes occur in response to signals, either hydraulic or chemical, sent from roots in contact with drying soil. By actively withholding water from plants, we can induce the generation of such signals and trigger the responses described above in a controlled manner. An understanding of signalling processes will inform the development of a wide variety of practical techniques (e.g soil treatments or leaf sprays) to conserve water and regulate growth.

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Soil drying under controlled irrigation has been shown to impact on ABA and ethylene delivery to shoots and the acidity (pH) of the xylem sap. ABA and ethylene are two plant hormones that are well-known as inhibitors of growth and stomatal opening. These chemical changes resulting from soil drying will impact on leaf growth and functioning (e.g. Davies, 2006). Roles for these compounds in inducing increases in water use efficiency (by closing stomata) and in producing more compact plants (by inducing slower growth rates) are investigated here.

Once the chemical signalling pathways used by HONS to control stomatal aperture and growth have been elucidated, this science can be exploited to the benefit of growers. There is evidence in the literature that acidification of the xylem and the shoot apoplast (cell walls) can enhance the effectiveness of other stomatal and growth-active compounds produced by plants (Wilkinson and Davies, 2002; Jia and Davies, 2007). Changing the pH of the soil is one way to close stomata and reduce water use via an effect on ABA distribution in the plant (Peuke et al. 1994). It is also possible that leaf apoplastic pH can be controlled with foliar sprays (Final report for Water Link 1). If changes in sap pH and/or ABA concentration can be induced independently of environmental conditions, it may be possible to produce plants that use less water and require less frequent pruning without compromising shoot water status. This approach therefore holds out the possibility of saving water and labour on commercial nurseries.

Materials and Methods

Experiments were conducted in the glasshouse or controlled-environment facilities 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

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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.

pH signalling in HONS species

A number of experiments were set up to study pH signalling in plants in drying soils. Initial experiments were unsuccessful in that we were unable to find apoplastic alkalisation when water deficits were imposed on the plants studied. This was either due to the sampling times missing the timeframe when alkalisation occurs or that in the species sampled apoplastic alkalisation is not a response associated with soil drying. Significant changes in apoplastic pH in *Choisya* (Mexican Orange Blossom) and *Forsythia* have yet to be found, however *Hydrangea* did significantly lower apoplastic pH. Because of these inconsistencies it was decided to use a quick test for analysing apoplastic pH responses to water deficits. The aim was to determine: a) whether pH responses were linked to "isohydric" (regulation of shoot water status) or "anisohydric" (dehydration of shoots as rooting medium dried) behaviour of shoots, and b) whether pH responses are only seen in certain evolutionary groups of plants.

Twenty two HONS species donated by Notcutts Nurseries were selected because they are popular HONS species and because they represent a diverse spread across the plant kingdom. Plants were grown in a greenhouse for five weeks to establish roots and sufficient foliage for experimentation. Once enough foliage had developed for destructive sampling plants were transferred to a controlled environment room for the imposition of treatments. Six plants of each species were watered such that containers were filled to capacity daily, and for six plants water was withheld until soil dielectric measurements measured with a Theta probe reached <300mV (severe stress) and another six plants were watered minimally daily until the soil dielectric reached ≤500mV (mild stress). The soil dielectric of well-watered plants was always >900mV. Leaf temperatures were then measured on two leaves per plants using a Thermacam SC2000 infra-red camera. Leaves with higher temperatures were considered to have lower stomatal apertures due to a reduction in the evaporative loss of heat. The two largest stems were then

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cut 50 mm from the apex and placed in a pressure bomb. Compressed air was progressively added to the chamber until xylem sap could be seen to be exuding from the cut end. The pressure at which exudation started was deemed to be equal but opposite of the stem water potential (an indication of plant water status). The cut stem was then dried with blotting paper and the pressure increased by 0.2 MPa. A micro pH probe was then applied directly to the exudates to measure xylem sap pH. If the volume of sap exuded was too small for analysis then the sap was collected and added to sap from a number of stems from the same plant and placed on ice for later pH analysis. A few species were found to be unsuited to the experimental design, for example; the morphology of *Yucca gloriosa* meant it would not fit into the pressure bomb, while the exudation of latex from *Trachelospermum jasminoides* (Jasmine) prevented accurate determination of water potentials and xylem sap collection.

pH buffer treatments

Both foliar and root-drench buffer treatments were utilised to determine the effects of xylem/apoplastic pH on physiological processes and growth. Root drench treatments were applied to *Forsythia* plants in 3 litre containers. Phosphate buffers at pH 5, 6, 7 and 8 (KH_2PO_4/K_2HPO_4) were prepared at 50mM and 100ml was applied as a root drench twice weekly along with a control treatment of water, plus a regulated deficit irrigation (RDI) treatment. Stem elongation, stomatal conductance and xylem sap pH were measured regularly for the duration of the treatments. The experiment ran from 03/05/06 until 04/07/06.

Foliar spray experiments were conducted on *Buddleja* (Butterfly bush), *Physocarpus* (Ninebark) and *Lonicera* (Honeysuckle); as they respectively showed xylem sap alkalisation, xylem sap acidification, and no change in pH in response to soil water deficit treatment. Phosphate buffer (20mM) at pH6 and pH8, as well as a water control were sprayed onto six well-watered plants for each treatment and then left to dry. After two hours, leaf temperature was measured on two leaves on each plant and mean leaf temperatures were calculated.

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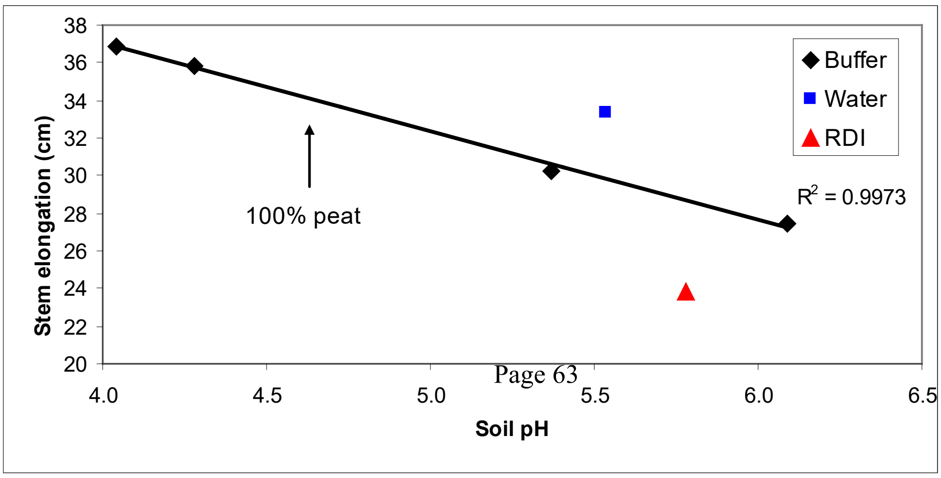
An experiment has just begun to determine what reductions in plant water use can be achieved by applying alkaline buffer foliar sprays to HONS species. 20mM phosphate buffers at pH5 and pH8 as well as a water control are being sprayed onto ten plants of each of three species twice weekly. A number of different water-use and plant-performance parameters are also being measured regularly on the same three HONS species. This experiment will also investigate what effects buffer sprays have on xylem sap pH over the course of a treatment. *Pieris* (Lilley of the valley bush), *Fatsia* (Japanese aralia) and *Euonomys* were chosen for this study because these plants are considered to have particularly high irrigation demands (Pers. Comm. from Trevor Connor at Garden Centre Plants, who donated the plants). The experiment is being conducted in a heated glasshouse with supplementary lighting applied to provide warm long days to stimulate the plants into a flush of growth. The experiment is planned to run until spring 2007.

Results and Discussion

<u>pH buffer treatments</u>

Alkaline buffers reduced stem lengths to below those of plants treated with just water or with neutral/acid drenches (figure 25). The degree of reduction was not as severe as the impact of a deficit irrigation treatment. It is possible that the effects of root drench treatments may be due to the action of the altered soil (media) pH on nutrient availability. However, as soil pH didn't rise above 6.09, which is well within the optimum for *Forsythia*, this is unlikely. Stem elongation showed strong inverse proportionality to the soil pH values once it had been treated with a buffer. Unfortunately no significant differences in stomatal conductance or xylem sap pH could be detected between the



‘water only’ control plants and those treated with buffer drenches (data not shown).

Figure 25. The degree of stem elongation in *Forsythia* can be controlled by manipulating the soil’s pH. Values are compared to a “well-watered” control treatment, plus a regulated deficit irrigation (RDI) treatment. The pH value for 100% peat is given for comparison.

Alkaline buffer foliar sprays increased mean leaf temperature regardless of whether the species naturally increases xylem sap pH in response to soil water deficits (Table 4). This shows that stomatal closure due to alkalisation is a general plant response, regardless of whether it is associated with soil drying. pH5 had no significant effect on leaf temperature compared to water sprayed plants. Therefore, it seems likely that the effect of pH is a specific response of stomata to apoplastic pH rather than a general response to a change in leaf ion levels or osmotic effects of the buffer.

Table 4. The change in leaf temperature after treatment with foliar sprays adjusted to pH 6 and 8 with 20 mM phosphate buffer and water controls. Least significant differences (LSD) were calculated from means of 12 readings at P= 0.05.

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

This work highlights the potential that buffer sprays have to control stomatal aperture. Follow-up experiments will determine whether this can be translated into significant reductions in plant water use or improved plant architecture of HONS species.

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pH signalling in HONS species

If a plant controls water status and cell turgor by closing it's stomata and preventing water loss as soon as water deficits are detected, it is deemed to be "isohydric". Conversely if the species allows significant losses in water and reductions in shoot water status before it closes it's stomata, it is deemed to be "anisohydric". Plants that exhibited significant increases in leaf temperature under water deficits but had no change in water potential were deemed to be acting isohydrically. Those where there was little or no response of leaf temperature to water deficits but had significantly reduced water potentials were deemed to be acting anisohydrically. The responses of species were often not as clear cut, with degrees of responses ranging between the two extremes. It is important to know what types of plants respond in each way, as it would govern how any buffer treatment or irrigation set-up should be arranged on a nursery. It is envisaged that it would be best to group plants with similar responses together as they will respond to treatments in a predictable manner.

Not all species exhibited an increase in xylem sap pH in drying soils (Table 5). However, it is of note that the three species that demonstrated the greatest isohydric control of water status, *Buddleja* (Butterfly bush) *Penstemon* and *Dicksonia*, also demonstrated alkalisation of xylem sap in the deficit treatments. *Cortaderia* had the greatest anisohydric response and this was associated with an extremely stable xylem pH of 5.8 in all treatments. These findings suggest that anisohydric responses and alkalisation of apoplastic pH are in someway linked and further experiments will investigate this. The fact that the evolutionarily primitive species *Dicksonia antarctica* (Soft Tree Fern) was strongly isohydric and responded to water deficits by raising apoplastic pH suggests that these responses did not evolve as plants gained greater ability to control internal water status.

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Table 5. The effect of mild and severe water deficit treatments on 21 hardy ornamental nursery stock species. Those species that exhibited either a significant increase or decrease in xylem pH in deficit treatments are indicated by a corresponding arrow in the far right column. Values are means of 10 replicates per treatment. Least significant differences (LSD) were calculated at P=0.05. Missing values represent where plant morphology and physiology prevented the measurement of that variable.

	Leaf temperature / °C				**Water potential / MPa**				**Xylem pH**				
Genus	WW	Mild	Severe	LSD	WW	Mild	Severe	LSD	WW	Mild	Severe	LSD	
Eleagnus	32.72	32.71	**34.45**	1.18	*	*	*	*	*	*	*	*	
Abies	28.59	**29.62**	**30.40**	0.55	-1.27	-1.17	**-1.77**	-0.35	5.31	5.34	5.16	0.22	
Laurus	31.46	**33.78**	**33.83**	1.33	-1.70	-1.88	-2.07	-0.54	5.84	5.87	5.76	0.10	
Trachelospermum	35.20	34.98	35.78	0.72	*	*	*	*	*	*	*	*	
Buddleja	26.70	27.14	**29.09**	0.85	-0.28	-0.30	-0.38	-0.12	7.84	8.17	**9.25**	1.19	↑
Physocarpus	26.80	**28.27**	**28.91**	0.86	-0.42	-0.52	**-1.43**	-0.18	8.25	7.30	**6.32**	1.23	↓
Penstemon	24.82	**25.93**	**26.39**	0.61	-0.20	-0.19	-0.19	-0.08	7.53	7.53	**8.90**	1.32	↑
Dicksonia	30.46	**32.13**	**33.05**	1.36	-0.30	-0.34	-0.49	-0.23	5.90	6.37	**6.86**	0.83	↑
Lonicera	24.65	**25.80**	**26.00**	0.34	-0.21	**-0.41**	**-0.52**	-0.20	5.67	6.08	5.67	0.54	
Perovskia	25.66	**27.23**	**27.08**	0.99	-0.29	-0.39	**-0.66**	-0.19	7.15	7.35	6.32	1.50	
Spiraea	24.11	**26.18**	**25.98**	0.81	-0.57	-0.72	**-1.21**	-0.22	6.11	6.04	**5.94**	0.16	↓
Hypericum	24.72	**25.43**	**26.43**	0.54	-0.22	-0.31	**-0.35**	-0.15	5.08	4.90	4.89	0.28	
Philadelphus	24.67	**25.29**	**25.69**	0.54	-0.49	-0.60	**-2.15**	-0.56	6.26	6.18	6.12	0.17	
Abelia	27.03	27.38	**27.82**	0.37	-0.43	-0.35	-0.34	-0.22	5.85	5.67	5.70	0.19	
Cortaderia	26.11	26.04	**27.22**	0.49	-0.29	-0.45	**-1.48**	-0.22	5.84	5.82	5.81	0.07	
Hydrangea	32.81	34.24	34.11	1.59	-0.40	-0.36	-0.41	-0.06	6.00	5.95	**5.92**	0.06	↓
Forsythia	29.73	**32.93**	**32.79**	2.21	-0.74	**-1.24**	**-1.96**	-0.16	*	*	*	*	
Incarvillea	26.63	**27.55**	**27.56**	0.4468	-0.37	**-0.96**	-0.50	-0.46	5.68	5.56	5.78	0.16	
Escallonia	25.86	**26.63**	**27.20**	0.50	-0.81	**-1.23**	**-2.05**	-0.35	5.51	5.41	5.40	0.15	
Euonymus	29.06	**29.87**	**29.67**	0.54	-0.41	-0.52	**-0.60**	-0.17	6.20	6.05	6.09	1.61	
Yucca	28.70	**30.43**	**30.84**	0.59	-0.33	-0.38	**-0.54**	-0.10	5.57	5.48	5.50	0.26	

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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

There are two main tasks relating to this objective: (1) Establishment of irrigation trials; and (2) Measurement of temperature, conductance and growth within these trials.

Establishment of controlled irrigation trials

We have obtained plant material for initial trials at Dundee. After conferring with Russell Sharp at Lancaster University and Paul Masters at Nottcutts we identified three plant species for initial experiments in Dundee. These are *Hydrangea macrophylla* var Endless Summer, *Choisya ternata* (Mexican Orange Blossom) and *Forsythia* cv. 'Lynwood'. We have been given 100 plants of each by Nottcutts and these were established in greenhouses at the Scottish Crop Research Institute in Dundee and used for our initial trials as described below under Objective 7. These initial trials were be used to test and calibrate the thermal imaging technology and to determine the plant responses to different soil moisture regimes.

Measurement of temperature, conductance and growth.

A substantial part of our work over the first year has related to the development of thermal imaging approaches for the discrimination of leaves and background for the extraction of leaf temperature data from thermal imagery. This is an essential prerequisite to achieving both objective 6 and objective 7. Further details of this work are provided under objective 7.

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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

During the first year progress has been made in developing hardware and software for the production of a automated system for measuring plant temperatures using a combination of visible-light, infra-red and thermal radiation. A review of previous published uses of thermal approaches for the estimation of plant stress was undertaken. The information on models for relating temperature to water status is contained in Jones (2004). We have reviewed recent work by other groups in Australia, US, Portugal, Germany, Belgium, Canada and Israel working on thermal imaging for use in scheduling irrigation, most of this work uses either, remote sensing techniques with aircraft borne imagers for whole field imaging or is in highly controlled laboratory environments. In most of the protocols developed by these groups there is a degree of human intervention in the image processing, for manual co-registration, alignments, of images or plant detection, which is inappropriate for a fully automated irrigation control system.

A prototype two-camera three-image system was developed at Dundee that enabled the use of two different thermal sensors to compare performance and assess the necessary resolution. Data has been collected to ascertain the necessary spatial and thermal resolution of the thermal imager. This work is still in progress with the data still being analysed so only a summary of the results are presented here. Collaboration with PERA has started to improve the design by substitution of the moving mirrors and filters of the existing system with a beam splitting design with three fixed cameras.

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Materials and Methods

Development of imaging system

For an adult human with normal vision it is relatively easy to detect plants in a full spectrum visible light photograph. We have a wealth of knowledge of plant shapes and colours to draw from to aid us. It is different however when we are confronted by an image with reduced information (e.g. figure 26, right): for example identifying the plants in the image on the right is much harder because the colour information has been removed and telling if the rock is surrounded by gravel or grass becomes more difficult. Thermal images pose a similar problem to monochrome visible light images. In high resolution images there maybe sufficient detail for a human to recognise shapes in the image however there are no other clues as to what each pixel is associated with plant and which with background.

Figure 26. Visible and grey-scale images of a scene with different components

To get round this difficulty we have borrowed a technique from remote sensing. That is to use the Normalised Difference Vegetative Index (NDVI) of a pixel to estimate if it is plant or non-plant. This uses two images of the same scene one in the visible light spectrum and one in the near infra-red (IR), and the property that plant material reflects near-IR light more efficiently than most other material. Pixels whose intensity difference between the visible and near IR images is large are assumed to be plant material.

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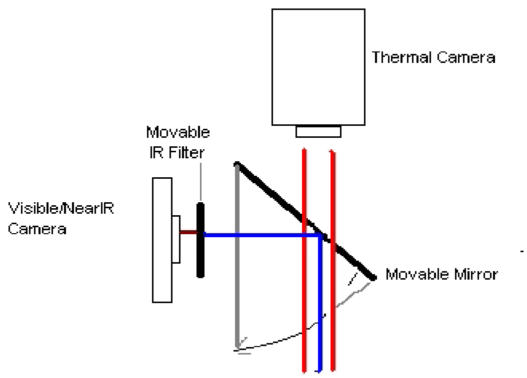

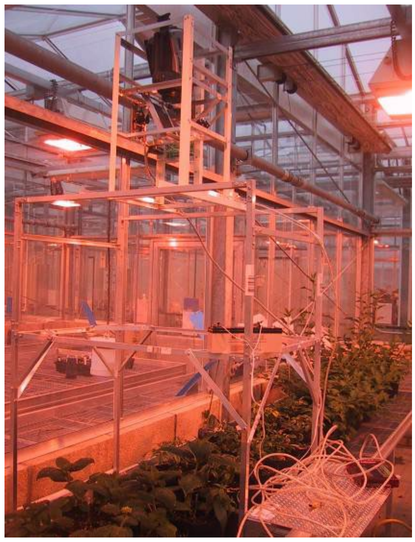

Figure 27. Diagrammatic and actual image of the beam splitting device trialled in the first year.

A test-bed has been devised, constructed and tested that allows us to overlay images from a thermal camera and a visible/near-IR camera using a moveable mirror as a beam splitter. The system is illustrated in figure 27. The standard digital camera image was enhanced by obtaining an image in the red wavebands and one in the near-IR using a movable filter. The system was tested in two versions, firstly using an IRISYS 1002 multipoint radiometer (IRISYS) as the thermal imager, secondly using a FLIR P25 Thermacam as the thermal imager. The IRISYS 1002 has a 16x16 pixel resolution and the FLIR has a 320x240 pixel resolution. The visible light camera used was a 640x480 resolution Fire-i webcam from Unibrain. In order to match information from the visible and near –IR images on which pixels represent plants in the thermal image it is therefore necessary to resample the thermal image to the same resolution as the visible image The FLIR camera provides this resampling as part of its internal software, The IRISYS images were resampled by a simple linear interpolation algorithm.

The performance of this system was tested in a greenhouse using small leaved (Forsythia) and large leaved (Hydrangea) plants. Trials were also going to be undertaken using Choisya however the plants were infected by a

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pathogen and insufficient plants of high enough quality were available for the trials.

Plants were split into 3 treatment groups, well watered, watered regularly everyday, regularly watered, watered every third day, and droughted, watered only when appearing to wilt. The camera system was setup on a bench in the greenhouse and plants placed under it individually. The plant temperature was taken with the automated system and in the case of the system using the IRISYS radiometer an additional thermal image was taken with the FLIR camera. Three measurements were made of the thermal conductance using a Delta-T AP4 porometer, the ambient air temperature and air humidity were recorded and the incident radiation.

<u>Development of prototype gantry</u>

A state of the art study has been carried out using a range of data bases and web searches on current gantry watering systems, their construction and levels of sophistication; sensor systems related to gantry control and environmental conditions; thermal imaging systems and cameras and optical sensors; and the communication and transfer of data .

Visits to growers and Denton Automation, and a watering gantry manufacturer, were made to gather additional information and discuss ideas.

In order to meet the project's requirement - for the new watering system to have the ability to supply additional water to a single plant which is showing signs of stress - two outline concepts of a spray bar have been designed; one with multiple spray heads individually controlled; and the second with additional moving spray heads, were produced for consideration by the partners on Solidworks, a computer aided design package.

Sensor systems

A range of sensors have been considered for both automation and the environmental monitoring of the watering system. Equipment from preferred suppliers will be interfaced to the watering system as the prototype trials develop.

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Thermal imaging systems

The system is currently at the development stage and we are exploring ways to adapt the technology into a usable commercial system. The design of the imaging unit will be made on a number of factors: (1) It's overall performance; (2) the number of units required to cover a required area; (3) the cameras' position within a structure; (4) the size of the working area observable at the required resolution; (6) the need for the camera to traverse along the structure; (7) the speed at which the structure will be required to travel; (8) image data gathering of site independent of watering structure.

Communication and control

Transfer of data from imaging system, gantry control and remote sensors can be processed remotely from the gantry itself by wireless communication. Frequencies would need to be identified for data and video.

Results and Discussion

<u>Development of Imaging System</u>

Together with constructing and testing the multi-camera mounting for acquisition of leaf temperature data we have devised a simple, easy to use computer control interface that allows one to collect the necessary visible, near-IR and thermal images semi-automatically and to automate the necessary image manipulation. A screen-shot of the interface is shown in Figure 9. The left-hand column of images shows at the top the original (real-time) thermal image from the IRISYS camera, and the bottom image shows either the visible or near-IR image (depending on the position of the filter. The second column of images shows (from the top) the resampled thermal image, the near-IR image and the visible image. The next column shows the thresholded NDVI image which is then used to isolate the leaf from the thermal image as indicated in the rightmost image. The NDVI system can be seen to be working very well for identifying plant material from background. In these images the pots were standing on black sheeting similar to that used in many nurseries for surfacing plant beds.

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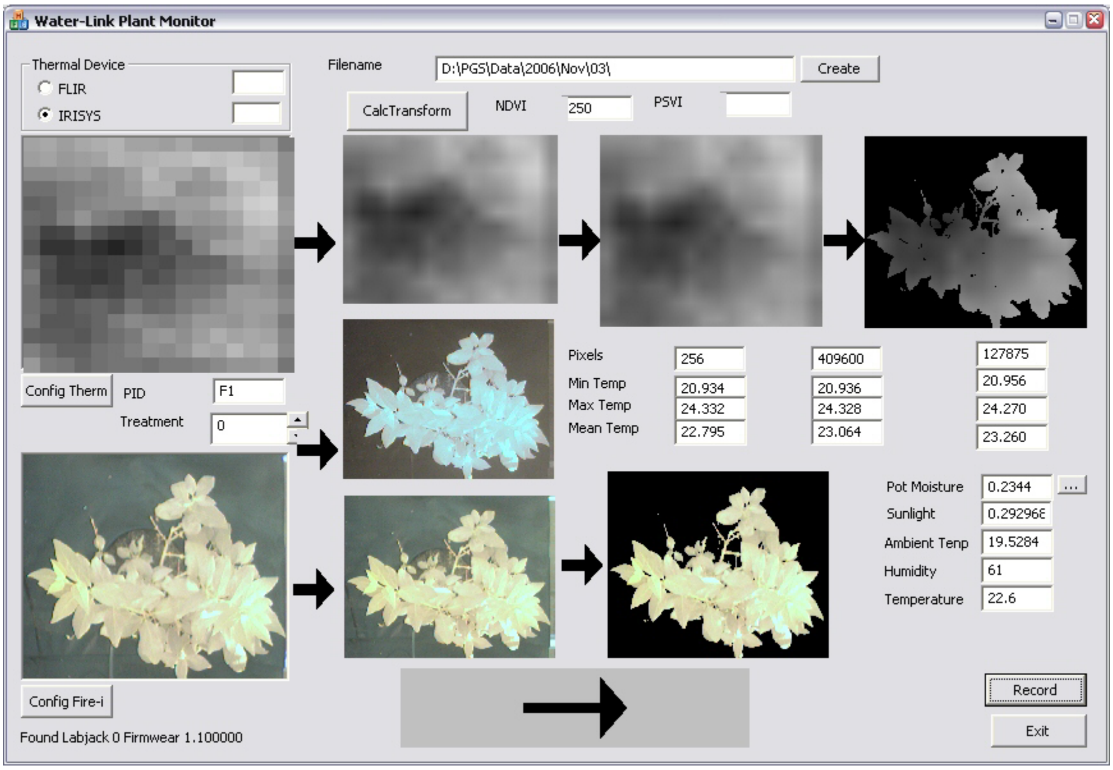

Figure 28. Screenshot from the computer controlling image acquisition and analysis, showing the various stages from the raw images on the left to the final image of the leaf temperatures on the right. A full explanation of this image is given in the text.

The histograms in figure 29 of the pixel intensity corresponding to images similar to those in figure 28 show the black sheeting to be at a higher temperature to the plant. The histograms on the left are for the whole image and the histograms on the right represent just pixels identified as plant.

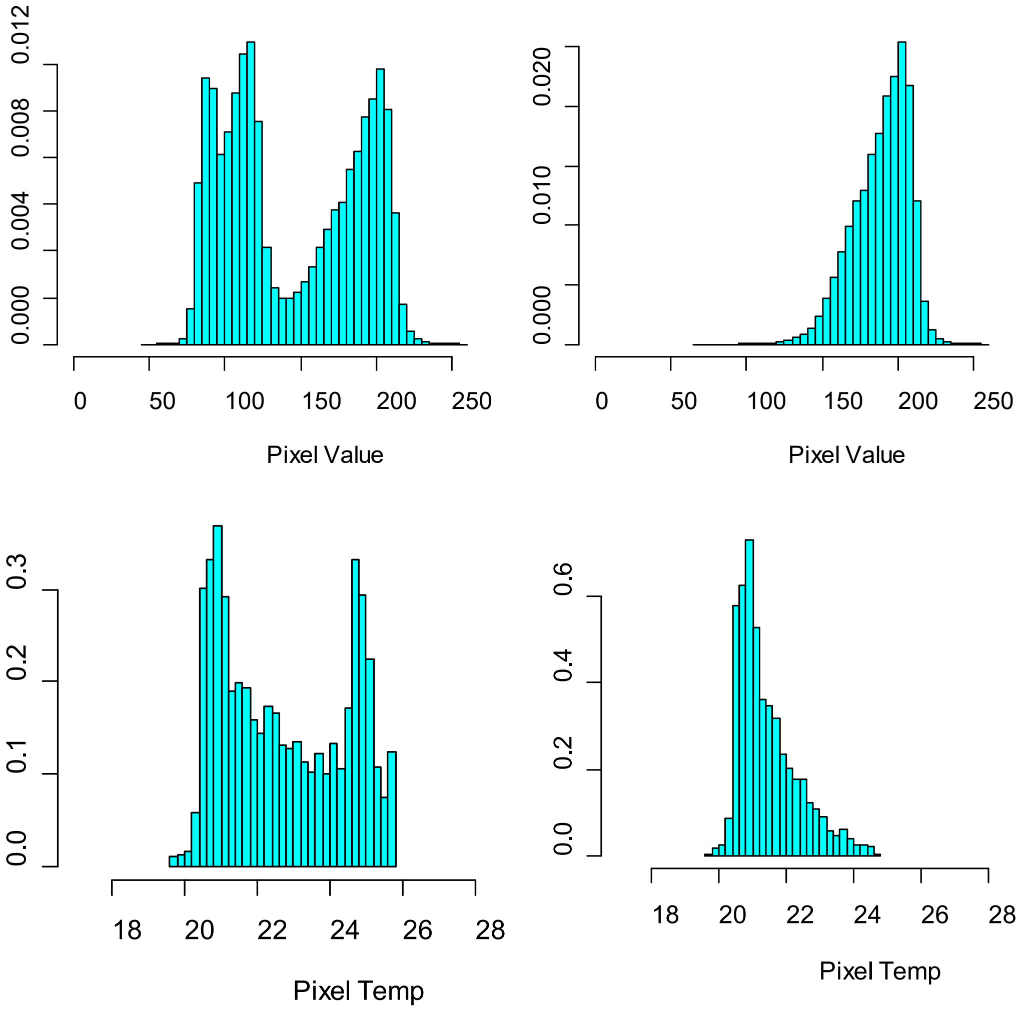

Figure 29. The top row shows the frequencies of different pixel intensity in the visible, with values for the whole image shown left and values for the plant area only (i.e. the brighter pixels) shown at the right. The lower two panels show the frequencies of relative temperatures, with again values for the whole image on the left and for the plant on the right. In this case the lower temperature peak corresponds with the leaves and the higher temperature with the background.

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Development of prototype gantry

Gantry systems

From the study of gantry watering systems that are currently available, the units surveyed ranged from very little control to semi intelligent in their operation. Currently none appear to possess the level of sophistication the project will bring to plant watering.

To carry out trials we will use a small watering gantry from Denton Automation, which has a programmable capability, acting as a test bed for the equipment under development. The trial area, which is to be a small poly tunnel on the Pera site, will also be fully instrumented.

Of the 2 new concepts of gantry spray bar proposed, the moving spray head design, which can be positioned above the plant requiring additional watering, was selected. The variation in pot size and pattern would make any fixed point spray head very complex to target an individual plant. A trial unit is being designed to fit on the test gantry.

Systems Sensors

The laser measurement system has been selected as the preferred method for positioning the water gantry. The laser has an accuracy of +/- 3mm at a distance of 100 metres, which is non accumulative. This will give the level of precision required to identify a single plant. A unit has been identified which has an industrial specification and is suitable for both covered and outdoor use; data can be transferred by wireless communication making it is easy to install; the unit is maintenance free as there are no moving parts.

Laboratory tests have been carried out to ascertain the maximum speed that a thermal camera can move and still provide images of a usable quality. A Raytec thermal camera was used for the tests and a speed of 8 metres per minute is still useable, this speed is possibly the maximum speed that would be used with a watering gantry.

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Communication and control

All processing of data for imaging system, gantry control and remote sensors can be processed remotely by wireless communication. The signal transmission bands used will be the current government specified free use unlicensed bands of 433Mhz for data and 2.4Ghz for video. Equipment for these frequencies is readily available and not expensive. Open use channel steps may be required in order to stop interference. This method of communication and control can eliminate the need for long cables to be laid between sensor and control units.

Conclusions

Equipment and associated software for extracting only the leaf temperature from thermal images has been constructed and tested. This has successfully demonstrated the principle of identifying plants and extracting their temperatures by use of a combination of visible and thermal images.

At this stage it is still unclear as to whether the IRISYS 1002 will provide the necessary resolution required particularly for small leaved crops or sparse canopies as there are many mixed pixels. We are currently comparing the data from this with the much higher resolution FLIR Thermacam P25, and we may in the future investigate the possibility of using a new IRISYS camera with higher spatial resolution.

We are currently also investigating alternative resampling algorithms to improve the handling of mixed pixels. Dundee University are also collaborating with PERA to investigate options for a system with improved alignment of the thermal and the visible images.

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TECHNOLOGY TRANSFER

Oral and Poster Presentations

Atkinson, C. (2006). East Malling Water Centre and Controlling height and improving shelf life of Poinsettia. Waterlink Day. Wellesbourne, July 2006.

Davies, W.J. (2006) Soil:plant signalling networks: manipulations to limit water use and sustain plant productivity during soil drying. Joint meeting of Spanish/Portuguese Plant Biologists. Tenerife, Sept 2006.

Davies, W.J. (2006) Soil:plant signaling and transpiration. ASPB Discussion Meeting on Transpiration. Snowbird, Utah, Oct 2006.

Davies, W.J. (2006) Sustainable water use in agriculture: pH and the control of stomatal function. Presentation to UN Soil, water and nutrients programme. Vienna, June 2006.

Schofield, P.G. & Jones, H.G. (2006). Combined thermal and visible imaging to detect water stress". Workshop on "Imaging plant stress" held at the Society for Experimental Biology Annual meeting. Canterbury, April 2006.

Jones, H.G. and Ilkka Leinonen, I. (2006). Dynamic thermal imaging for estimating leaf and boundary layer conductances and Towards automated analysis of thermal images, at the Society for Experimental Biology Annual Meeting. Canterbury, April 2006.

Jones, H.G. (2006). The use of thermal imagery to schedule irrigation of hardy nursery stock. Waterlink day. Wellesbourne on 20th July

Schofield, P.G. & Jones, H.G. (2006). Automated detection of water stress by thermography. WaterLink Day. Wellesbourne, July 2006.

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Sharp, R.G. (2006) ‘Water Day: presented the proposed goals of the latest LINK project and the findings of the first Water-LINK project. WaterLink Day. Wellesbourne, July 2006.

Sharp, R.G. (2006) International Plant Propagators’ Society Conference, “Sustainable Plant Production”: Presentation given about the scope of the latest Water-LINK project and the technology being utilised. Grobbendonk, Belgium, September 2006.

<u>Publications</u>

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

Davies, W.J. (2006) Responses of Plant Growth and Functioning to Changes in Water Supply in a Changing Climate. In JIL Morison and M Morecroft. (Eds) Plant Growth and Climate Change. Blackwells, Oxford. 96-117.

Jia,. W. and Davies, W.J. (2007) Modification of leaf apoplastic pH in relation to stomatal sensitivity to root sourced ABA signals. *Plant Physiology* (in the Press).

Morison, J.I.L., Baker, N.R., Mullineaux, P.M. and Davies, W.J. (2007) Improving water use in crop production. *Phil. Trans. Royal Soc.* Special Issue on Sustainable Agriculture (In the Press).

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REFERENCES

Brenner, A. J., Jarvis, P.G. (1995). A heated leaf replica technique for determination of leaf boundary layer conductance in the field. *Agricultural and Forest Meteorology* 72: 261-275.

Cameron, R.W.F., Wilkinson, S., Davies, W.J., Harrison-Murray, R.S., Dunstan, D. and Burgess, C. (2003) Regulation of Plant Growth in Container-Grown Ornamentals through the use of Controlled Irrigation. *Acta Horticulturae* 630, 305-312

Davies, W.J., Wilkinson, S. and Loveys, B.R. (2002) Stomatal control by chemical signalling and the exploitation of this mechanism to increase water use efficiency in agriculture. *New Phytologist* 153: 449-460.

Davies, W.J. (2006) Responses of Plant Growth and Functioning to Changes in Water Supply in a Changing Climate. In JIL Morison and M Morecroft. (Eds) Plant Growth and Climate Change. Blackwells, Oxford. 96-117.

Jia, W. and Davies, W.J. (2007) Modification of leaf apoplastic pH in relation to stomatal sensitivity to root sourced ABA signals. *Plant Physiology* (in the Press)

Jones, H.G., Aikman, D. and McBurney, T.A. (1997). Improvements to infra-red thermometry for irrigation scheduling in humid climates. *Acta Horticulturae* 449: 259-266.

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

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Leuning, R., Foster, I.J. (1990). Estimation of transpiration by single trees: comparison of a ventilated chamber, leaf energy budgets and a combination equation. *Agricultural and Forest Meteorology* 51:: 63-86.

Peuke AD, Jeschke WD and Hartung W (1994). The uptake and flow of C, N and ions between roots and shoots in *Ricinus communis* L. III. Long distance transport of abscisic acid depending on nitrogen nutrition and salt stress. *Journal of Experimental Botany* 45: 741-747.

R Development Core Team (2005). R: A language and environment for statistical computing. Vienna, Austria., R Foundation for Statistical Computing.

Ryan, B. F., Joiner, Brian L., Cryer, Jonathon D. (2005). MINITAB Handbook, Thomson

Stokes, V. J., Morecroft, Michael D., Morison, James I.L. (2006). Boundary layer conductance for contrasting leaf shapes in deciduous broadleaved forest canopy. *Agricultural and Forest Meteorology* 139: 40-54.

Wilkinson, S., Davies, W.J. (2002). ABA-based chemical signalling: the co-ordination of responses to stress in plants. *Plant, Cell and Environment* 25: 195-210.

Wilkinson, S. and Davies, W.J. (2002) ABA-based chemical signalling: the co-ordination of responses to stress in plants. *Plant Cell and Environment* 25: 195-210.

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