Improving the control and efficiency of water use in container-grown hardy ornamental nursery stock

Final Report on HortLINK Project HORT 201 / HNS 97

Project title:	**Improving the control and efficiency of water use in container-grown hardy ornamental nursery stock**
Project number	**HDC project HNS 97** **Horticulture LINK project 201**
Government Sponsor	**Defra (project HL0132LHN)**
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Final report	**April, 2003**
Previous reports	**March 2000, March 2001, March 2003**
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Location of project:	**HRI (East Malling and Efford), Lancaster University, CEH, WRc, and commercial nurseries (Notcutts, Hillier, Wyevale, Orchard Close Nursery [Hugh Nunn], Johnsons of Whixley)**
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Date project commenced:	**1 April, 1999**
Date completion due:	**30 March, 2003**
Key words:	**hardy nursery stock, HNS, water, irrigation, evapotranspiration, evaporation, transpiration, drought, stress, water deficit, regulated deficit, RDI, partial root drying, PRD, soil moisture, sensor, signalling, ABA, xylem pH, apoplast, pH, containers, drip, capillary, Forsythia, Cotinus, Hydrangea, Lavandula, Lonicera, Cornus, Choisya, sensors, tensiometer, atmometer, evaposensor, ThetaProbe, EvapoMeter**

Members of the consortium	**Science partners:** **Horticulture Research International (HRI)** **Lancaster University** **Centre for Ecology and Hydrology (CEH)** **Water Research Centre plc (WRc)** **Industry partners:** **Horticultural Development Council (HDC)** **Horticultural Trades Association (HTA)** **Skye Instruments Ltd** **Delta-T Devices Ltd** **Hillier Nurseries Ltd** **Notcutts Ltd** **Johnsons of Whixley** **Hugh Nunn Nurseryman** **Oakover Nurseries Ltd** **Wyevale Nurseries Ltd**

The results and conclusions in this report are based on an investigation conducted over four years. The conditions under which the experiments were carried out and the results obtained have been reported with detail and 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.

Intellectual Property Rights are invested in Horticulture Research International on behalf of the Consortium members for LINK project number HORT 201. The following are members of the Consortium for LINK project HORT 201:

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Sponsor's Executive Summary

This project explored the potential to save water and improve quality of hardy ornamental nursery stock (HONS) by better regulation of the amount of irrigation applied. Equipment was developed to help growers regulate irrigation more accurately.

Beneficial effects of controlled drought

Regulated deficit irrigation (RDI) was shown to have potential as a means of manipulating growth of HONS, in addition to the obvious benefit of saving water. Plants in the RDI treatments were irrigated daily but received 20-80% less water than a well-watered plant would use. The plants adapted to RDI by gradually reducing their water use until it matched the water applied. The benefit of RDI was that it restricted shoot growth so that plants maintained a more compact and well balanced appearance than well watered plants. These results were obtained using high precision drip-irrigation under protection. Before this work can be taken up by the industry, further work is required to develop less expensive means of achieving the required precision of irrigation.

Manipulating the plants' chemical signalling system

Part of the response to drought depends on chemical signals produced in roots exposed to drying soil. Evidence was obtained that, in HONS, the plant hormone ABA is an important signal, and that its concentration at sites of action can be modulated by evaporative demand operating via the acidity (pH) of the xylem sap. If these signals can be induced by treatments other than drought it should be possible to control growth and reduce water use without the implicit dangers of RDI. Experiments with ammonium chloride (reported to increase ABA) and pH buffers gave promising results with *Forsythia* but further work is required to assess the commercial potential of this approach.

Irrigation control

In current industry practice, a combination of intuition and experience is used to set irrigation time-clocks. Two approaches to more accurate regulation were developed: (i) based on evaporative demand of the atmosphere measured with a novel evaposensor (Skye Instruments EvapoSensor and EvapoMeter); (ii) a controller which switches irrigation on and off on the basis of a moisture sensor (Delta-T Devices ThetaProbe) inserted into the centre a representative pot. Both performed well but require further development before they are ready for widespread use by growers.

Economic benefit

Measurements of water use on nurseries and the results of trials suggest that most beds are over-irrigated, usually by 30% to 300%. This is only partly attributable to misjudgement of irrigation need because measurements showed that as much as 200% over-irrigation is often necessary to compensate for the uneven distribution of overhead irrigation. Further improvement of irrigation efficiency, as well as the potential to benefit from RDI, depends on improving the uniformity of overhead irrigation or on finding an economically attractive alternative. If these practical problems can be overcome, it should be possible to reduce water use by up to 75% of current levels.

Cost benefit analysis showed that, for nurseries using mains water, the value of water savings alone will often be enough to justify investment in better control equipment. For other nurseries and for larger investments (e.g. in drip irrigation), improvement in plant quality, reduction in labour costs and limits on water supply will be more important drivers.

GROWER SUMMARY

Headline

Water use can be cut by up to 75% and the need for pruning reduced or eliminated by precisely controlled drought or, possibly, by triggering plant defences against drought with novel fertigation treatments

Background and expected deliverables

Drivers for change

Irrigation is essential for HONS production in containers and investment in overhead irrigation systems has been fundamental to the growth of the industry. However, there is a widespread perception that overhead sprinklers are inherently wasteful and that nurseries generally overwater, largely because the effects of overwatering are subtle whereas wilting is obvious. There is pressure to conserve water from many directions: rising costs of mains water, limitations on water supplies, legislation (e.g. the draft Water Bill) and regulations (e.g. abstraction licences). Water shortages have become common and are predicted to become more so as a result of global warming. There is a pressing need for nurseries to have the means to ensure that the irrigation applied matches the needs of the crops.

Basic concepts - ETp, and g_s

The amount of water used by a well watered crop, including evaporation from top of the pot, is known as the potential evapotranspiration (ETp). It is determined by a combination of the environmental and crop factors (e.g. humidity and leaf area). Transpiration from leaves occurs through tiny pores called stomata, the size of which is under complex control within the plant. By reducing stomatal apertures, plants can reduce transpiration and thereby adapt to water shortage.

We measured changes in stomatal aperture with a porometer, an instrument which measures how easily water vapour escapes from a leaf. This quantity is known as ‘stomatal conductance’, or g_s for short.

Plant responses to drought - RDI and PRD

When plants are generously irrigated, their ability to adapt is not exploited and they use water and grow at the maximum possible rate. Complete absence of water shortage is rather unnatural and, in HONS, it contributes to excessively vigorous and ‘leggy’ growth. It follows that there may be benefits from intentionally applying somewhat less water than the plants are capable of using (i.e., < ETp) so that a water deficit develops which triggers the plants' adaptive processes. This is known as Regulated Deficit Irrigation (RDI) and is widely used to restrict excessive vegetative growth in crops, such as grapevines, where too much leaf and shoot growth is recognised to reduced fruit quality. A major aim of this project was to explore the potential of RDI in HONS production.

As well as the direct effects of water shortage on stomata, there is good evidence that chemicals are produced by roots in dry soil which are transported to the shoots where they act as signals, causing stomata to start closing *before* the plant runs short of water. These chemical signals also slow the growth of shoots and leaves. It is believed that they help plants to avoid lethal water shortage by starting to conserve water before soil water reserves have been exhausted.

Partial root-zone drying (PRD) is a technique which attempts to exploit these root signals. Its origins lie in an experimental technique known as a split-pot in which the root system is split between two pots so that half the root system can be kept moist while the other half dries out. However, a similar effect can be achieved if irrigation is localised to one side of the plant, particularly if the total amount of water applied is somewhat less than ETp. PRD offers the potential to control excessive growth and reduce water use without exposing the plant to the risk of damage from excessive water shortage (e.g. leaf scorch or leaf drop).

The plant hormone abscisic acid (ABA) is thought to be the main chemical signal but other factors may also be involved. For example, the acidity of the sap that carries the hormone to the leaves ('xylem sap') influences how much of the ABA is removed from the sap into the cells surrounding the pipe-work (xylem) before it reaches the stomata.

Expected deliverables

1. Knowledge and understanding of the way that HONS respond to drought.
2. Evaluation of the potential to improve quality or reduce pruning costs by carefully controlled water deficit (RDI and/or PRD) or by other techniques that exploit the plant's drought defence mechanisms.
3. Development of equipment to enable HONS growers to match irrigation to plant requirements.
4. An economic model for cost benefit analysis of investment in water-saving measures.

The work was intended to identify opportunities, not to provide fully developed solutions ready for immediate application.

Summary of the project and main conclusions

Effects of controlled water deficits on plant growth and development (Unit 1)

Experiments were conducted in polythene tunnels and mainly using drip irrigation for high precision. In most experiments, ETp was estimated by weighing a sample of well watered 'reference' plants every day. The main experimental subjects were *Forsythia x intermedia* cv. Lynwood, *Cotinus coggygria* cv. Royal Purple, and *Hydrangea macrophylla* cv. Blue Wave. Additional subjects were *Choisya ternata* cv. Sundance, *Cornus alba* cv. Elegantissima, *Lavandula angustifolia* cv. Munstead, and *Lonicera periclymenum* cv. Belgica. The main conclusions are summarised below:

Plant adaptation to RDI and PRD

- All species reduced their water loss to match the irrigation applied under RDI regimes ranging from 20 to 80% of ETp
- Adaptation generally took about 2 weeks, after which soil water content stabilised at 20 - 30% (v/v), compared with 50 - 60 % in well-watered controls.
- Transient wilting occurred in many species but 'little and often' irrigation protected against permanent wilting (i.e. all plants received some water every day). Extending the interval between irrigations caused more severe stress than smaller daily applications.
- In PRD treatments, roots in the moist zone protected shoots from damagingly low water status while chemical signals from drier roots induced reductions in water use and shoot extension.
- When RDI is imposed using drip irrigation, a relatively moist zone forms under the dripper, giving some of the advantages of PRD.

- Adaptation to RDI was more effective if the water deficit developed slowly so that plants had time to adapt.
- Previous exposure to RDI increased resistance to a subsequent sudden water shortage. Some of the adaptive changes induced by RDI are likely to last many weeks, at least.

Effects of RDI and PRD on growth and quality

- Even the mildest RDI tested (80% ETp), reduced shoot extension by 30% (Figure 1).
- More severe RDI, applied for the whole season, reduced shoot growth by up to 80%
- Leaf scorch or other visible damage was confined to severe RDI (50% ETp or less) and to *Forsythia*.
- When RDI was severe, even using drip irrigation, much of the reduction in growth was attributable to the direct effect of the water deficit in the shoots.
- The extent of wilting and reduction of growth did not reflect tolerance of drought under natural conditions: for example, Lavender was severely affected.
- If full irrigation is restored after a short period of RDI, growth is sometimes *faster* than normal, partially cancelling out the initial growth reduction.
- In most species, RDI reduced shoot growth more than root growth so that root:shoot ratio increased.

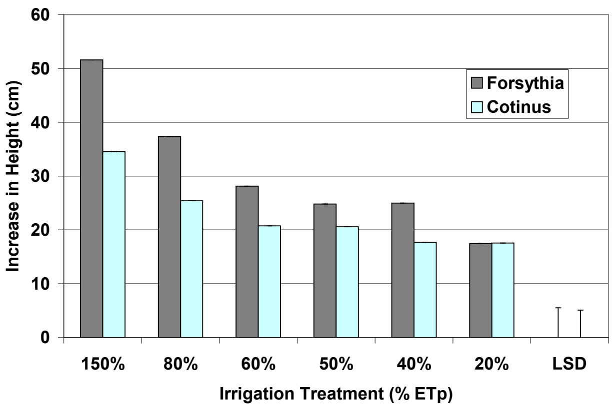


Figure 1. Effect of RDI on growth of *Forsythia* (solid) and *Cotinus* (shaded)

Potential benefits to the industry

- Well-shaped plants without the labour costs of repeated summer pruning
- Ability to hold back plants to meet scheduling targets.
- In some species, better quality than can be achieved by pruning (e.g. by shortening internodes of climbers which tend to be ungainly and difficult to manage) (Figure 2)
- 'Pre-hardened' plants, better able to tolerate water shortages during retailing and during establishment in the garden or amenity planting.

Figure 2 Effects of RDI on *Lonicera* and *Cotinus*, 4 weeks after the start of treatment

Practical limitations

- For effective growth control by RDI, each plant must receive the same amount of water. Most overhead irrigation is not sufficiently uniform. The use of capillary matting to even out variation was not successful.
- On outdoor beds, rainfall limits the severity and consistency of RDI treatments but helps counteract the non-uniformity of overhead irrigation. In preliminary experiments, 50% ETp produced satisfactory crops but the degree of growth reduction was modest.

Root derived signals and the potential to manipulate them. (Unit 2)

Any attempt to restrict growth and water use by deficit irrigation inevitably carries some risk that the crop will accidentally be exposed to a damaging level of water stress (e.g. if a fault develops in the irrigation system, there will be less time to fix the problem before the plants come under damaging levels of stress). Studies of the plant signals regulating growth and stomata led us to novel ways to obtain the benefits of RDI and PRD with much reduced risk.

What signals are involved in drought responses of HONS species?

- In *Forsythia*, reduction of g_s and leaf growth were associated with higher concentrations of ABA and a more acid pH in the xylem sap.
- Solutions of pure ABA fed to *Forsythia* shoots reduced leaf growth and g_s, supporting the suggestion that ABA acts as a signal produced by roots in dry soil that is transported to the shoots where it reduces growth and water use.
- Results from *Hydrangea* and *Cotinus* were less clear.

Some unexpected results

- The change of pH in *Forsythia* in response to drying soil was in the opposite direction to that seen in most other plants (i.e. more acid rather than more alkaline) and is unlikely to be involved in root-shoot signalling.
- Instead, the evidence indicated that sap pH may act as a local signal within the leaf, sap becoming more alkaline and stomata tending to close when evaporative demand was high (i.e. when light levels were high and humidity is low) (Figure 3).

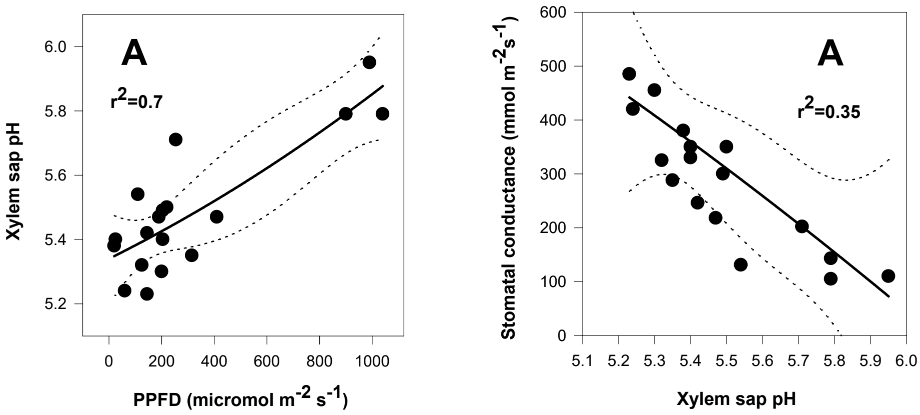


Figure 3 Evidence that sap pH has a role in stomatal response to light (PPFD) in *Forsythia*

Exciting practical developments

- These unexpected findings led us to test the effect of spraying buffer solutions directly onto the foliage of *Forsythia*. Spraying well watered *Forsythia* with a buffer solution at pH 6.7 (i.e. relatively alkaline), substantially reduced g_s and leaf extension rate.
- Adding ammonium chloride to the irrigation water, which was expected to reduce sap pH and increase sap ABA level, had the effect of reducing growth and g_s in *Forsythia.*
- These novel techniques have the potential to reduce water use and control growth without the difficulties or danger of deficit irrigation. However, further work is required before they can be recommended to the industry.

Instruments for estimating irrigation needs of container-grown HONS (Unit 3)

Based on a thorough search of the literature, patents and other sources, the project focused on a simple instrument for estimating ETp and two soil moisture sensors.

An evapotranspiration sensor

Invented at HRI East Malling, the 'evaposensor' represents a simple and inexpensive alternative to an automatic weather station for estimating ETp. Skye Instruments now sell an EvapoSensor and have adapted their Helios datalogger to produce the EvapoMeter, which monitors an EvapoSensor and displays accumulated totals (Figure 4). The EvapoMeter can be used by growers to decide whether to irrigate and/or how much to apply.

The evaposensor was shown to correlate closely with established methods based on meteorological data. In common with other methods of estimating evaporative demand, some calibration for specific crops is required.

Soil moisture sensors: ThetaProbe and Mini-tensiometers

Of the many types of soil moisture sensor, two were considered small and robust enough for use on commercial container beds:

(i) Small tensiometers with electronic pressure measurement
(ii) Small capacitance sensors

Tensiometers measure soil water tension (i.e. how tightly the water is held rather than the amount of water) independent of the type of medium. The Skye Instruments Mini-tensiometer is small, robust and needed relatively little maintenance.

Capacitance sensors measure the amount of water in soil by its effect on dielectric properties. A water release curve is needed to convert water content to water tension. The Delta-T ThetaProbe is a robust instrument measuring the water content of the soil between four stainless steel prongs (60mm long) (Figure 5). It can be used for spot measurements in the surface of pots but was selected in this project as the most suitable instrument for automatic control because it requires no maintenance or calibration.

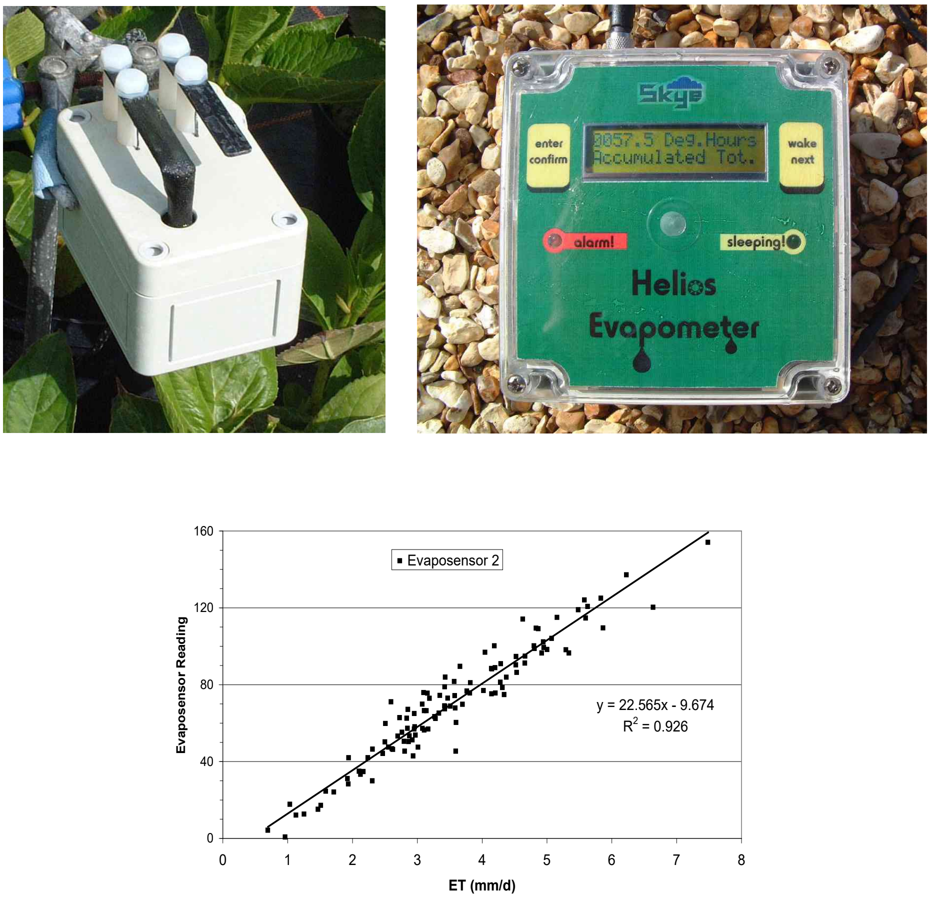


Figure 4 The Skye evaposensor (left), EvapoMeter (right), and its close correlation to a well established method of estimating ETp (Penman-Montieth equation, bottom).

Development of practical means to regulate irrigation according to plant requirements (Unit 4)

Development work was mainly on semi-commercial scale outside beds consisting of overhead sprinkler irrigation and a standing base of well drained gravel or sand. Over four years, the method used to estimate irrigation requirement progressed from weighing a sample of plants through to a prototype fully automatic system.

Evaposensor control

- The Skye EvapoMeter was used successfully to schedule irrigation, determining either the duration of irrigation to apply on a daily basis and / or when to apply a fixed dose.
- A single EvapoMeter can be used to monitor ETp across many cropping areas on the nursery provided they are in a similar environment (e.g. outdoor beds with no shade). This adjustment is then applied to all beds. On some modern irrigation control panels (e.g. the Heron MC96) a percentage adjustment is available which makes the adjustment to all beds simultaneously.

- Growers did not like the need to calibrate for specific crops and irrigation systems. However, the calibration factor depended mainly on the percentage of ground cover so it is likely to be possible to develop simple tables from which approximate calibration factors can be drawn. These could then be adjusted in the light of experience.
- It would be possible to develop automatic control based on the evaposensor but there are no plans to do so at present.

ThetaProbe control

- An advantage of soil moisture sensors is that, as well as detecting the need for irrigation, they also provide feedback to the controller about the effect of the irrigation applied.
- Automatic irrigation control (100% ETp) using the output from a single ThetaProbe in a representative container worked extremely well.
- Set points may need to be adjusted to allow for changes in the properties of the medium over the course of the season.
- A prototype ThetaProbe irrigation control unit (Figure 5), which runs on the 24 V supply to the irrigation solenoid, was developed by Delta-T Devices. Its performance at Efford and on two nurseries was very promising, achieving water savings of 30 to 40 %.

Further development work is needed on both these systems, including their applicability to different irrigation systems, different sizes of container and to control of RDI regimes. Delta-T has plans for a cheaper version of the ThetaProbe and collaboration with an irrigation control company to develop a commercially viable product.

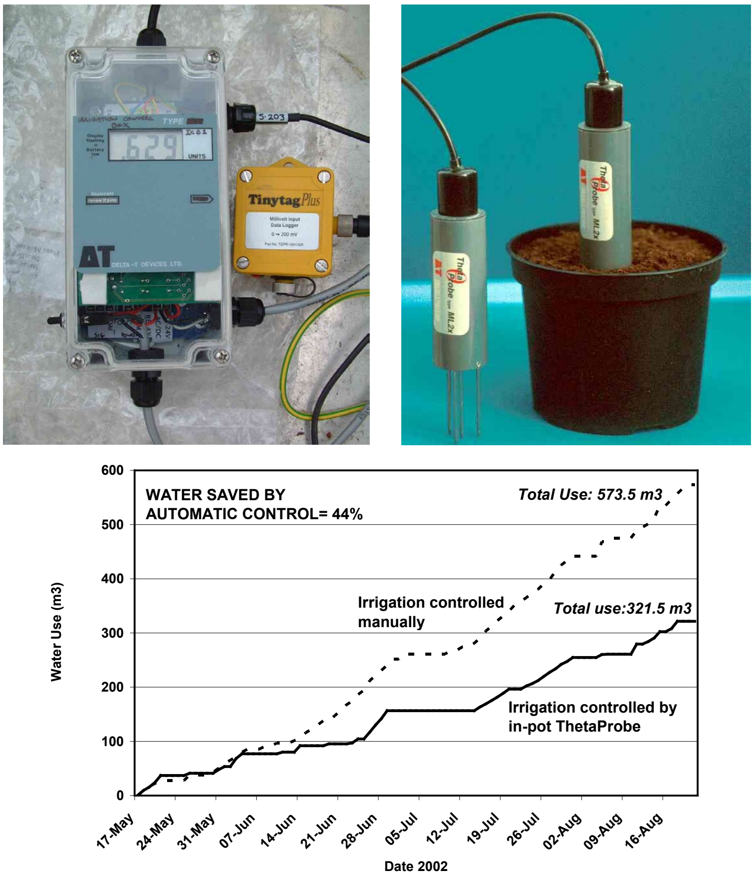


Figure 5 Prototype Delta-T control unit (left) for automatic irrigation based on a single ThetaProbe (right) and the water savings achieved in a nursery trial.

Uneven water application and other practical issues

This work exposed many practical difficulties in matching irrigation to plant requirements, irrespective of the method used to estimate the irrigation needs. These are outlined below:

- The type of standing base affects both drainage of surplus water and the opportunity for water falling between pots to be taken up through the base. Unexpectedly, water use efficiency was no greater on a drained sand bed than on gravel.
- Overhead irrigation is often so uneven that, to provide enough water in the driest areas, most plants must receive 3 to 4 times what they need (e.g. Figure 6). Supplementary irrigation of dry spots reduces the problem but is imprecise and labour intensive.
- High application rate (>15 mm/h) is wasteful because water runs through the larger pores in the medium before it can be absorbed into the smaller pores.

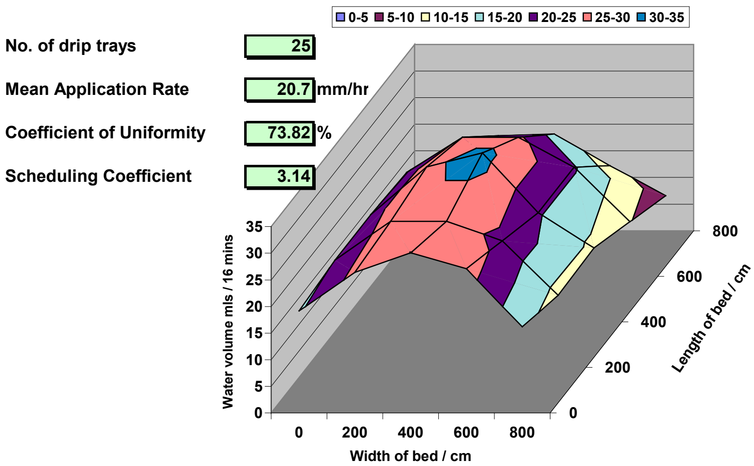


Figure 6. Water distribution across a bed with 2 lines of Rotoframe sprinklers, as presented in the 'Water Distribution Calculator' spreadsheet.

Economic evaluation of the costs and benefits of reducing water use (Unit 5)

Scope for saving water

- Improved regulation of existing systems can cut current water use by 30-40 % (Figure 5)
- Improving the distribution of irrigation could bring additional large savings of water (Figure 6).

- Where water distribution is made sufficiently uniform for RDI to be used, then total water savings of 75% are a realistic goal.

Cost benefit model

An economic model was developed, in a spreadsheet format, which was then simplified to provide a basis for cost benefit analysis of investments in irrigation technology.

A number of example analyses were run, which indicate that:

- costs tend to be dominated by the equipment
- water savings have relatively low financial impact
- saving in labour or increase in crop value have a large impact
- for nurseries using mains water, the value of water savings alone will often be enough to justify investment in equipment such as the ThetaProbe controller

The value of the cost benefit model is currently limited by lack of data for key inputs, e.g. how much labour is saved by automatic irrigation or by RDI.

Financial benefits

This project has opened up many opportunities for the industry to benefit financially:

- reduced losses from overwatering damage
- reduced labour costs, especially for pruning and for managing climbers
- improved quality through more balanced shape
- meeting standards for water saving and minimising environmental impact
- greater production potential within limits of existing water supplies
- reduced water costs

As mentioned above, data is not yet available to allow firm prediction of cost benefits from investment in the sort of equipment and techniques that have emerged from this project. However, it is likely that improved precision and automation of irrigation will be fundamental to the future growth and profitability of the industry. This project has provided a foundation for that improvement and identified areas for future R&D.

Action points for growers

Most of the exciting opportunities revealed by this project need more development before they can be recommended to growers. Some of the equipment is not yet available commercially. However, many of the practical techniques applied and developed in the project can safely be adopted and these are listed below:

- As well as estimating the moisture content of pots by eye and by feel, consider simple quantitative methods, such as spot readings with the ThetaProbe or weighing pots *in situ* with a spring balance. Use such records to help decide on irrigation settings and to develop protocols that allow beds to be run a little drier with confidence.
- Measure the water distribution (page 87) and determine the ‘scheduling coefficient’ (SC), a measure of how much water is being wasted keeping plants in the drier areas well watered. Take advice or experiment on ways to reduce SC.
- The same approach can be used to find out how much of the irrigation is being 'captured' by the plants. For example, the weight gain of pots placed on inverted saucers compared to those directly on the bed will indicate how much of the water falling between the pots

is captured by uptake through the base. On clean gravel it is likely to be small but on a Mypex covered soil it can be surprisingly high.

- Arranging irrigation risers near the edge of beds can bring large improvements in uniformity which may more than compensate for any practical difficulties with such arrangements (e.g. tractor access).
- The Skye EvapoMeter is commercially available and can be used as a management tool to assist in adjusting irrigation time-clocks.
- If your irrigation controller is set in steps of 5 min. or more, consider replacement with an electronic controller which can be set in 1-second steps and incorporates a percentage adjustment facility (e.g. the Heron MC96). This feature greatly simplifies day to day adjustment in line with evaporative demand.

For the more adventurous grower interested in trying out experimental techniques on their own crops (and at their own risk):

- Use RDI to achieve well-shaped plants with minimal pruning, to hold back plants for scheduling purposes, to make climbers more manageable, or to harden up plants prior to selling. This will only be possible if the crop is under protection and the irrigation is relatively uniformly (e.g. a good quality drip or flood-and-drain system). (Contact Richard Harrison-Murray at HRI East Malling for detailed guidance)
- Achieve well-shaped plants and save water by adding buffer solution to overhead irrigation systems. This is a much less thoroughly tested technique than RDI or PRD but would be very easy to test on a small sample of plants. (Contact Sally Wilkinson at Lancaster University for detailed guidance)

SCIENCE SECTION

Introduction

Production of HONS in containers depends on irrigation, because rainfall alone is never sufficient to maintain an adequate water supply during summer months. Compared to field grown material, the root volume is restricted and much of rain is lost in the spaces between the pots. Growth of the industry has relied heavily on overhead irrigation because it is relatively cheap and flexible compared to more water efficient systems such as capillary sand beds.

Water shortages are becoming more frequent, and forecasts predict that over the next 50 years rainfall will decrease and become more erratic, especially in southern Britain (Davies, 1997). Nurseries are finding it increasingly difficult to obtain new licences to abstract water from boreholes or rivers. This has focused attention on the need to improve efficiency of water use throughout this sector of horticulture, and in particular, to find ways to make overhead application more efficient. The industry currently relies on intuitive assessment of irrigation requirement based on inspection of crops, experience, and weather forecasts. Inevitably, there is a tendency to apply too much rather than too little because the effects of water shortage are evident much sooner than the effects of persistent overwatering. A major objective of the project was to identify the most appropriate method to regulate irrigation for container nursery stock and to develop equipment that would match water applied to the needs of the plants. Substantial progress has been made and is reported in Units 3 and 4.

A survey of water use was conducted to provide a measure of the scale of over-irrigation in the industry today. This survey, combined with various other sources of information, provided the foundation for an economic analysis of potential returns on investment in irrigation techniques emerging from the project, which is report in Unit 5.

Apart from saving water, another reason for interest in reducing irrigation is to improve plant quality. Not only can excessive irrigation lead to transient waterlogging and plant death, but also it promotes vigorous growth, thereby increasing the need for frequent pruning to achieve a well shaped plant. In their natural environment, most plants experience water shortage from time to time and are able to adapt to it. The project therefore explored the potential to exploit this adaptive ability to control plant growth in ways that produce high quality plants with less water and less labour for pruning. We also sought to understand more about the mechanisms whereby plants adapt to water deficit, particularly the chemical signalling systems used to co-ordinate the adaptive responses, with the aim of controlling plant behaviour as effectively as possible. The results of all this work, including evidence that it may be possible to trigger the adaptive responses without exposing plants to the risk of damage from water stress, are presented in Units 1 and 2.

General materials and methods

Most methods were specific to particular experiments and are outlined with the results to which they relate.

Standard growing medium

100% peat (medium/coarse sphagnum peat)

6.0 kg/m^3	controlled release fertiliser (Osmocote Plus Spring [15+9+11+2MgO+trace elements], 12-14 months)
1.5 kg/m^3	Magnesian limestone
0.75 kg/m^3	SuSCon Green

In 2001 & 2002, a wetting agent, Aquamix G at a rate of 0.5 kg/m^3, was added for the experiments at Efford (Experiments 4.2 and 4.3).

Radio-immunoassay (RIA) for ABA.

Leaf tissue and xylem sap was immediately frozen in liquid nitrogen. Frozen leaf tissue was freeze-dried for 48h, finely ground and extracted overnight at 5ºC with distilled deionised water using an extraction ratio of 1:50 (g dry wt:ml water). The ABA concentration of the extract, or of xylem sap, was determined using a radio-immunoassay (RIA) following the protocol of Quarrie et al. (1988), using [G-^{3}H] (±)-ABA at a specific activity of 2.0 TBq mmol^{-1} (Amersham International, Bucks., UK), and the monoclonal antibody AFRC MAC 252 which is specific for (+)-ABA. The premise behind the assay is that the tritiated ABA binds to the antibody, which can be precipitated out of solution and counted as a measure of radioactivity. Any ABA present in the tissue extract/xylem sap inhibits the binding of the tritiated ABA to the antibody, therefore the lower the count in the resuspended precipitate, the greater the [ABA] in the tissue extract/xylem sap aliquot. This concentration is quantified using a series of standards of known non-radioactive [ABA] in the assay such that sample counts can be calibrated from the resultant standard curve.

However, compounds with a similar structure to ABA but without ABA activity may contaminate the tissue extract, or even the less complex xylem sap. Every species must be tested for such interfering compounds, using what is known as a 'spike dilution' test. This involves testing a set of ABA standards in the presence of an increasing dilution of tissue extract. If the resulting standard curves ([ABA] added v. [ABA] detected) at each dilution remain parallel, then the only compound present in the tissue extract that binds to the antibody is endogenous ABA itself.

Spike tests on extracts of leaf tissue from *Forsythia* and *Hydrangea* (Appendix 1) showed no interference. However leaf tissue extracts from *Cotinus* could not be tested for [ABA] in the RIA due to the presence of highly coloured compounds (assumed to be anthocyanins) which interfered with the assay. All readings were uniformly excessively high. Gas Chromatography-Mass Spectrometry (GC-MS) measurement of leaf extract [ABA] from all 3 species was carried out at HRI East Malling, confirming the validity of the readings obtained using the RIA at Lancaster in *Forsythia* and *Hydrangea* (results not shown).

Unit 1: Growth and developmental responses to controlled water deficits (Objectives 1, 2, & 7)

This Unit combines work towards the following closely related scientific objectives:

Objective 1 Test the hypothesis that woody ornamentals can readily adapt to water stress and that transpiration can be reduced by at least 50% in a range of species without loss of horticultural quality.

Objective 2. Test the hypothesis that carefully-timed and directed supply of reduced quantities of irrigation water can act as an alternative to pruning, or application of growth regulators, for controlling the plant shape and size.

Objective 7. Develop strategies for implementing regulated deficit irrigation (RDI) or root signalling techniques over a wider range of ornamental species (i.e. *Choisya*, *Lavandula*, *Cornus*, *Lonicera*) and assess effects on plant quality, water use and agrochemical leaching.

Background

For agricultural crops, any shortage of water usually reduces crop growth and that is frequently reflected in a reduction in growth of the harvested part of the plant and hence reduction in economic yield. For HONS, which is grown for its appearance rather than its mass, the effects of a shortage of water may sometimes be beneficial. Whilst size is an important determinant of value in HONS, very vigorous growth rarely produces aesthetically pleasing plants and pruning is frequently required to create a dense head.

A major component of this project was to explore the response of HONS to carefully regulated water deficit to determine whether there is a potential to improve quality and/or reduce pruning costs in this way. The idea of purposely imposing moderate water deficit stress to achieve a beneficial effect on a crop has been termed regulated deficit irrigation (RDI) (Behboudian and Mills, 1997). When the irrigation is applied in a way that causes the soil around part of the root system to become much drier than the remainder, the term partial root zone drying (PRD) applies. Both techniques are increasingly being used for fruit production in dry climates. In this Unit, we report on responses to both RDI and PRD and preliminary trials at imposing RDI on overhead irrigated nursery beds.

Experiment 1.1 Response to severity of RDI

Materials and Methods

Plant material

Cotinus coggygria cv. Royal Purple
Forsythia x intermedia cv. Lynwood
Hydrangea macrophylla cv. Blue Wave.

One-year-old plants were potted into the standard growing medium in February 1999 and grown on in a polythene tunnel. In mid July, they were graded and any excessively long shoots were pruned back, before random allocation to treatments on 28 July.

Irrigation treatments

Plants were irrigated to the following percentages of potential evapotranspiration (ETp): 150%, 80%, 60%, 50%, 40%, and 20%. Of these treatments, from 80% to 20% ETp represent RDI of increasing severity, while 150% represents the well watered control.

Till the start of the experiment on 4 August, all plants were well watered and the treatments were then maintained for 8 weeks.

A daily estimate of ETp for each species was made gravimetrically, i.e. from the weight loss of 6 additional well watered plants (reference plants). Each day, after the weight loss had been measured, water was added to the reference plants to restore their original well-watered weight.

Irrigation was applied daily from one nozzle per pot (2 L/h, Netafim PCJ CNL, from Aquaplast Irrigation, Skelmersdale). These drippers incorporate a non-return / shut off valve (indicated by CNL in the product code number) which ensures that water is held in the pipework between irrigations. This feature was found to be essential to achieving closely matching application to each plant (i.e. coefficient of variation < 3%). To ensure that plants in the RDI regimes had access to all the water applied, saucers were placed under the pots so that any 'run through' was reabsorbed into the pot.

Irrigation times were set on a Heron MC96 irrigation controller. This has a resolution of 1 s and incorporates a 'percentage adjustment' feature which facilitated adjustment in line with daily variation in ETp.

Measurements and experimental design

Soil water content was monitored with a single ThetaProbe pushed into the surface of the medium and read using the 'organic soil' calibration setting of a ThetaMeter HH1. In each pot, one measurement was taken adjacent to the dripper and one on the opposite side of the pot.

In addition to standard measurements of growth and water relations, at the end of the experiment, root distribution was assessed. The pot was removed and the percentage of the exposed surface covered by roots was estimated in each of 12 zones (3 depths x 4 quadrants).

The experimental design was a randomised complete block with 3 blocks. There were 9 plants per plot, 5 of which were used for non-destructive growth measurements. Each species was treated as a separate experiment.

Results and discussion

Pot weight and volumetric water content.

Water content of the growing medium decreased rapidly in all except the 150% ETp treatment (Figure 1.1) for about 2 weeks, but thereafter showed no consistent decline. This indicates that, where water applied was less than ETp (i.e. all except the150% treatment) actual evapotranspiration (ETa) decreased until it matched the irrigation applied. This represents the process of adaptation to drought conditions

Pot weights showed very similar trends to the measurements of water content from the ThetaProbe but reached more stable equilibrium values (Figure 1.2), probably because they are insensitive to local variations in water content within the pot.

Plant water relations

Once soil water content had stabilised, indicating that plants had adapted to the drought treatment, stomatal conductance (g_s), leaf water potential (LWP) and leaf relative water content (RWC) were measured in a subset of the treatments. Data were collected over two consecutive days with contrasting weather. The results in Table 1.1 show that g_s decreased broadly in proportion to irrigation applied (ignoring the 50% excess inherent in the 150% ETp well-watered control treatment). This suggests that stomatal closure was the main process whereby the plants adapted to the drought conditions. This in turn suggests that the effects of smaller leaf area (due to reduced growth) and the development of a dry 'mulch' on the surface of the medium were relatively small.

Despite the reduction of g_s with increasing irrigation deficit (i.e. severity of RDI), LWP decreased (i.e. became more negative) significantly (Table 1.1). There was a parallel decrease in RWC as the irrigation deficit increased. These results indicate that adaptation to RDI was not sufficient to prevent desiccation stress completely. This conclusion is consistent with the occurrence of wilting, which was observed occasionally in all three species but was particularly prevalent in *Forsythia* at 20% ETp.

There were few distinct leaf lesions associated with the RDI treatments but some discoloration and abscission of *Hydrangea* leaves at ≤ 40% ETp and permanent wilting of a few shoot tips among *Cotinus* at 20% ETp.

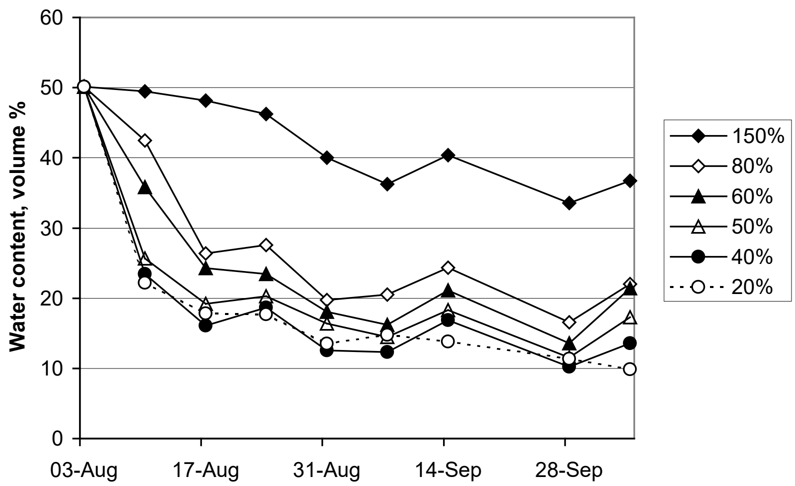


Figure 1.1 Changes in the water content of the growing medium from the start of the irrigation treatments (different percentages of ETp). Plotted values are means of ThetaProbe readings in pots of *Forsythia* (n=6 pots).

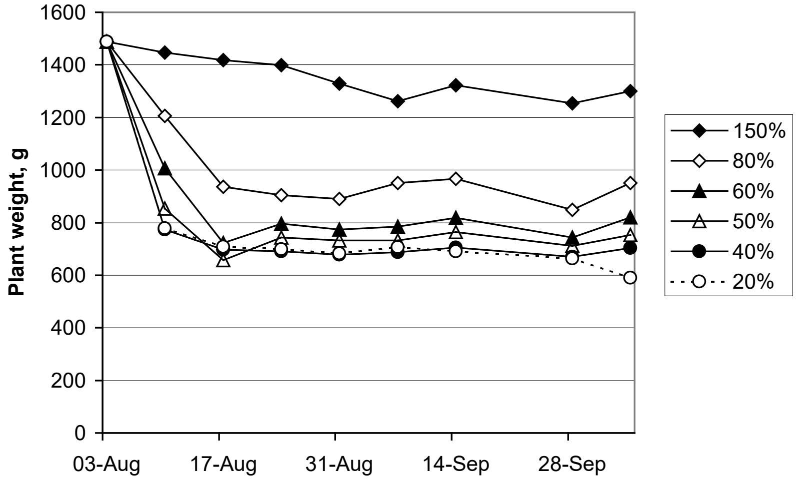


Figure 1.2 Changes in the weight of *Forsythia* pots (i.e. pot + medium + plant) from the start of the irrigation treatments (different percentages of ETp). Plotted values are means of 6 pots.

Table 1.1 The effect of irrigation regime on stomatal conductance (g_s), leaf water potential (LWP) and leaf relative water content (RWC) of *Cotinus* and *Hydrangea*.

	g_s (mmol m^{-2} s^{-1})		LWP (MPa)		RWC	
	Sunny	Cloudy	Sunny	Cloudy	Sunny	Cloudy
Cotinus						
150 %	176	199	-1.17	-0.63	0.92	0.93
50 %	83	105	-1.45	-0.80	0.91	0.90
20 %	35	39	-1.71	-0.98	0.89	0.86
LSD(5%)	*43.6*		*0.284*		*0.034*	
Hydrangea						
150 %	226	233	-0.73	-0.47	0.97	0.97
50 %	77	128	-0.99	-0.50	0.96	0.96
20 %	40	81	-1.61	-0.87	0.90	0.92
LSD(5%)	*43.3*		*0.207*		*0.015*	

Plant Growth

Even the mildest RDI regime (i.e. 80% ETp), significantly reduced the final plant height of the *Cotinus* and *Forsythia* plants (Figure 1.3), and effects were evident within 14 days of starting the RDI regimes (Figure 1.4). The degree of growth reduction increased as the severity of RDI increased. Similar growth reduction was evident in the length, diameter and fresh weight of annual shoots at the end of the season, but the number of shoots was not affected (data not shown). More detailed measurements on a subsamples of shoots indicated that growth reductions were due to both reduced number and reduced length of internodes (data not shown).

There was very little extension growth of *Hydrangea* shoots even in the well-watered controls so that there was little opportunity for RDI to exert an effect. For that reason, significant effects were confined to stem diameter, leaf area and weight (data not shown). However, the length of shoots produced on these plants in the following year showed a substantial carry-over effect of RDI (data not shown).

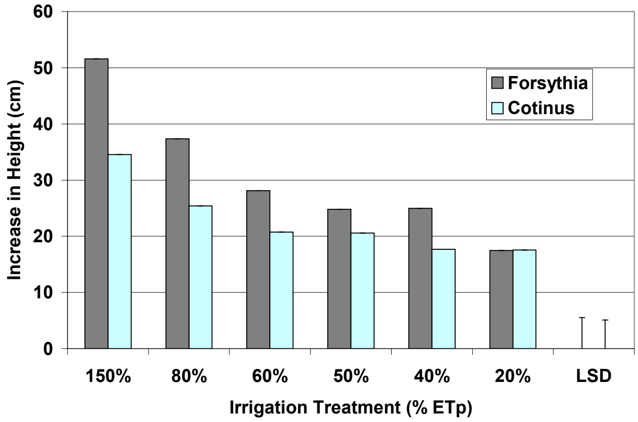


Figure 1.3. Effect of the severity of RDI on plant height growth of *Forsythia* x *intermedia* cv. Lynwood and *Cotinus coggygria* cv. Royal Purple, measured from the start of the RDI treatments to the end of the growing season.

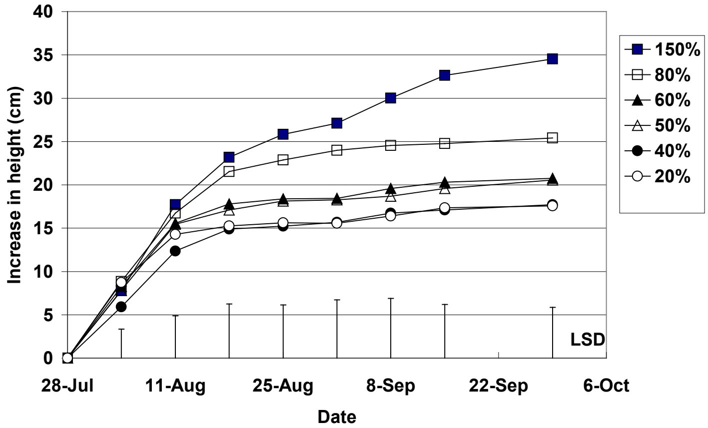


Figure 1.4 Effects of RDI on the plant height growth curve of *Cotinus coggygria* cv. Royal Purple. (Bars = LSD, P=0.05).

Root distribution

An attempt was made to determine how root growth was affected by the severity of RDI and whether the concentration of water application near the dripper caused uneven root development. The roots could not be extracted from the medium without massive loss of the finer branches but the distribution of roots visible at the surface of the root ball indicated greater root development on the dripper side. The total amount of root visible decreased with increasing severity of RDI, especially in Hydrangea (Table 1.2).

Table 1.2 Effect of the severity of RDI on root growth and development as measured from the percentage of the surface of the root ball covered by roots at the end of the growing season

Irrigation treatment % ETp	Percentage root cover		
	Forsythia	*Cotinus*	*Hydrangea*
150	70	95	80
80	74	69	66
60	68	65	49
50	69	58	47
40	62	66	36
20	57	50	18
$LSD_{(P=0.05)}$	*18.3*	*15.5*	*16.2*

Main Conclusions

- *Cotinus* and *Forsythia* were able to adapt to a water supply substantially below their potential to use water (i.e. to RDI).
- Adaptation was achieved mainly by reduction in stomatal conductance sufficient to achieve an equilibrium between water use and water supply.
- Adaptation did not completely prevent leaves suffering water deficit but it prevented visible lesions (e.g. shrivelled or scorched leaves) except in the most severe RDI regime tested (20% ETp).
- RDI reduced vegetative growth, even when the irrigation deficit was small (i.e. under the 80% ETp regime). The degree of growth inhibition increased as the severity of RDI increased.
- Growth control by RDI could be useful to nurserymen as a means of reducing the pruning required to maintain compact plants or as a means of holding back plants.
- Using drip irrigation, RDI resulted in a locally wet zone close to the dripper and very dry medium on the opposite side of the pot. It thus includes an element of PRD but, with the dripper kept in the same position throughout, root development on the dry side was inhibited.

Experiment 1.2: Effects of stage of plant development on responses to RDI

Physiological processes differ in their sensitivity to the water status of the tissues, e.g., cell expansion is more sensitive to desiccation stress than cell division. It was therefore important to establish whether sensitivity to RDI in HNS plants varied with the stage of growth over the course of the growing season. Such knowledge is essential for the development of robust recommendations on the use of RDI by nurserymen.

Methods and Materials

Plant material

Cotinus coggygria cv. Royal Purple
Forsythia x intermedia cv. Lynwood

One-year-old plants were potted into the standard growing medium in February 2000 and grown on in a polythene tunnel. They had been pruned twice to encourage branching in the first year but received no further pruning during the experiment.

Irrigation treatments

A single severity of RDI (50% ETp) was applied at different times of year, for a period of 8 weeks, or continuously, as detailed below:

50% ETp June-July - RDI during early primary shoot expansion.
50% ETp July-Aug - RDI during late primary shoot expansion.
50% ETp Aug-Sept - RDI during secondary shoot development and expansion.
50% ETp Sept-Oct - RDI during growth cessation
50% ETp All - RDI for the entire season.

There were two control treatments:

150% ETp All - Plants kept well-watered throughout by applying 150% ETp
Sand – Plants on capillary sandbeds in which the water table was maintained by a header tank so that daily fluctuations of the water content in the growing medium were minimised.

Outside the specified periods, plants in the RDI treatments received 150% ETp.

To explore the distinction between RDI and PRD, main plots of 10 plants were divided into 2 subplots; in one subplot the dripper was moved from one side of the pot to the other every four weeks while in the other it was not moved.

Other experimental details were similar to those described earlier for Experiment 1.1.

Results and discussion

Immediate effects of RDI

The stage of growth at which RDI was imposed had a substantial influence on the growth response of both species. In *Cotinus*, the immediate impact of RDI was greatest during June and July, when shoots and leaf area were expanding rapidly, and least late in the season when extension growth was coming to an end (Figure 1.3). However, when generous irrigation was restored after early season RDI, plants grew substantially *faster* than the control plants so that, at the end of the season, they were as tall as the controls. The acceleration of extension growth on rewatering suggests that cell division had been less inhibited by the RDI treatment than cell expansion, leading to an accumulation of immature cells which expanded rapidly when water availability allowed it. In *Forsythia*, growth recovered after early season RDI but did not exceed that in controls so that, at the end of the season, the plants were still significantly smaller than the control plants (Figure 1.6).

In both species, the effect of RDI during the first month of treatment was much less than in the second month. This presumably reflects the time required to deplete the water reserves of the medium sufficiently for plant water deficits to develop, which was about 2 weeks in Experiment 1.1.

Long-term effect of RDI

In *Cotinus*, the largest long term effect from 8 weeks of RDI was from RDI in July-August. It had a substantial immediate effect combined with no recovery of growth on rewatering

(Figure 1.5). Absence of any regrowth after RDI in July-August may be attributable to the inhibitory effect of shortening daylength rather than a specific effect of RDI at this stage of growth. The net effect was to reduce the final size of the plants almost as much as continuous RDI. In *Forsythia*, growth can continue long after the end of August if conditions are favourable and some late growth was recorded in plants exposed to RDI in July-August. However, the amount of growth was less than in well-watered controls so that the effect on final height was, as in *Cotinus*, almost as great as continuous RDI (Figure 1.6).

In both species, plants on the capillary sandbed grew significantly taller than in the well-watered drip treatment (i.e. 150% ETp). This difference suggests that a single dripper failed to keep the whole pot moist, allowing sufficient drying on the opposite side of the pot to induce a PRD effect. Some support for this suggestion comes from the small (and almost significant) additional reduction in height of plants in the 150% ETp treatment from alternating the position of the dripper at 4-week intervals (Table 1.3).

Table 1.3 The effect on plant height on *Cotinus* and *Forsythia* due to drippers being fixed in the one location, or moved every 4 weeks. Data recorded on 25 September 2000.

	Cotinus		Forsythia	
	Fixed	Moved	Fixed	Moved
150% ETp All	81	72	105	93
50% ETp June-July	91	93	86	74
50% ETp July-Aug.	54	52	65	61
50% ETp Aug.-Sept.	77	74	72	73
50% ETp Sept.-Oct.	82	84	95	93
50% ETp All	42	47	59	55
LSD	*11.6*		*14.9*	

Moving the dripper had no effect on the growth response to RDI at 50% ETp in either species and irrespective of the time when RDI was applied. This suggests that, at this severity of water deficit and in these species, the direct effect on leaf water status (i.e. the hydraulic signal) was greater than the effect of chemical signals produced by roots exposed to drying soil. This question is examined further in Experiment 1.4.

The effect of RDI on shoot extension was partitioned into effects on number of internodes and length of internodes by detailed measurements on a sample of shoots at the end of the season. The results (Figure 1.7) support the analysis of the growth curves. In *Cotinus*, continuous RDI reduced both the total number of internodes and their length throughout the shoot. Early RDI reduced the length of lower internodes that would have completed their extension during the treatment period (particularly internodes 6-10) but thereafter many internodes reached greater length than in the 150% ETp controls and the total number of nodes was similar to the control shoots. RDI in July-August reduced both the length of internodes that expanded during the treatment (internodes 11-20) as well as reducing the total number of internodes by the premature cessation of growth. Later RDI had similar effects but, since internodes become shorter towards the end of the season, the effect on final length was relatively small.

Similar effects on numbers and lengths of internodes were evident in *Forsythia* except that there was no increase in length of upper internodes following early RDI treatment (data not shown).

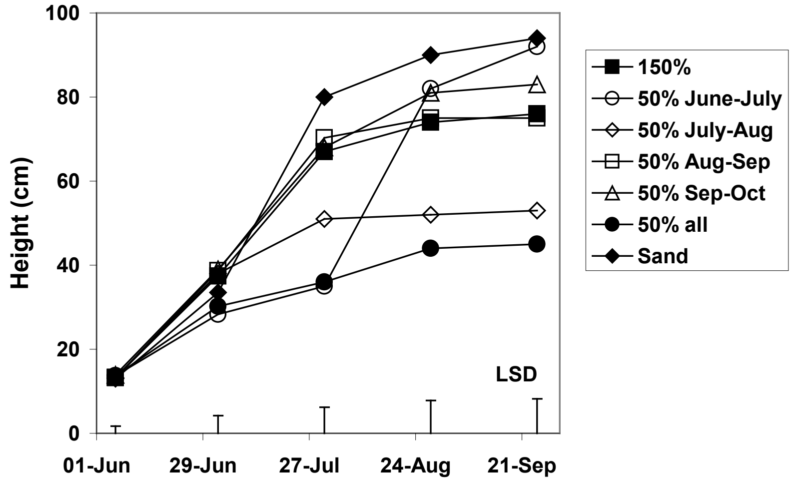


Figure 1.5 The effect of timing of RDI on plant height growth of *Cotinus coggygria* cv. Royal Purple.

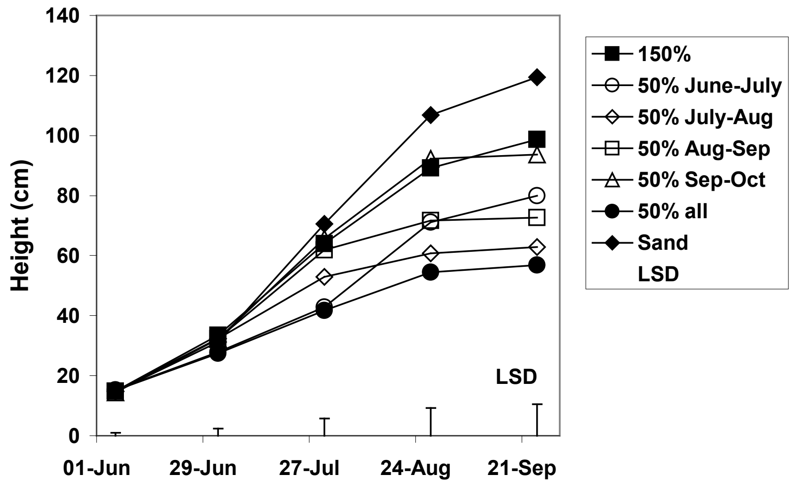


Figure 1.6 The effect of timing of RDI on plant height growth of *Forsythia* x *intermedia* cv. Lynwood

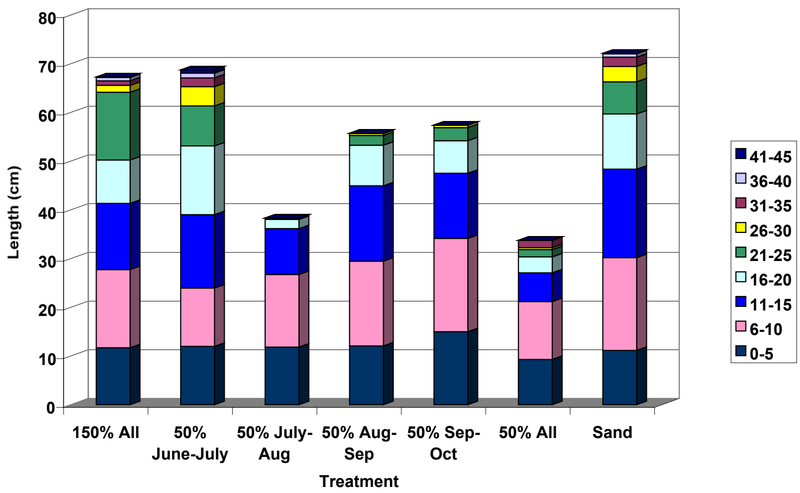


Figure 1.7 The effect of timing of RDI on the number and length of internodes (numbered from the shoot base) in *Cotinus coggygria* cv. Royal Purple.

Main Conclusions

- RDI applied early in the growing season, during a period of vigorous vegetative growth, dramatically reduced shoot extension rates during the treatment but growth recovered quickly afterwards.
- In *Cotinus*, but not *Forsythia*, there was a compensatory acceleration of growth after early season RDI so that final plant size was not affected
- Mid-season RDI reduced final shoot lengths almost as much as continuous RDI because growth was substantially reduced during treatment and there was little or no further growth after rewatering.
- To achieve a desired final plant size, RDI should start a few weeks before that size is reached and then maintained to the end of the season.

Experiment 1.3: Time required for adaptation to RDI and persistence of adaptation after rewatering

By reducing irrigation to a proportion of ETp rather than withholding water completely, the RDI protocol used in earlier experiments ensured that the soil water deficit developed slowly, as it would in most natural environments. This experiment aimed to determine whether this *gradual reduction* in water availability is necessary for effective adaptation and thus avoidance of drought induced lesions. This information is important for the development of optimal RDI protocols.

It also examined a related question: does the adaptation persist after rewatering long enough to be of value as a protection against subsequent stress? Such protection could be of commercial value. For example, could crops grown on the nursery be pre-conditioned to adapt better to the stresses that often develop at the retail stage, or even after planting in the garden or landscape.

Material and methods

Plant material

Liners of *Forsythia* x *intermedia* cv. Lynwood, grown in 1litre pots, from cuttings propagated in May 2000, and pruned once to induce branches

Three phases of the experiment

1. 1st drought ((28 Aug. - 20 Sept.): the 3 regimes below were compared
2. Recovery (20 Sept. - 4 Oct.): all plants well watered
3. 2nd drought (4 Oct. - 20 Oct): a second drought was imposed (RD only)

Irrigation treatments

1. Well Watered Control (WW): 200% ETp throughout
2. Slow onset Drought (SD): 50% ETp
3. Rapid onset Drought (RD): Starting 5 days after SD, no irrigation until soil water content equated with SD treatment, then 50% ETp.

Combining the three phases (1st drought - recovery - 2nd drought) with the drought treatments, the full list of treatments becomes:

Control A	(WW - WW – WW)
Control B	(WW - WW – RD)
Slow drought	(SD - WW – RD)
Rapid drought	(RD - WW – RD)

Measurements and experimental design

This experiment focussed on detailed plant water relations measurements in each of the three phases. Additionally, leaf samples were frozen for later analysis of ABA content by radio-immunoassay (see General Methods).

The experimental design was a randomised complete block design, with 5 blocks and 10 plants per plot. The large number of plants per plot was required to allow for destructive sampling, including cutting off all shoots at soil level and oven drying the medium to determine its water content accurately. Two plants per plot were used for each harvest.

Results and discussion

It took 14 days for plants in the ‘slow onset’ drought regime (SD), receiving 50%ETp, to restrict their water loss to match the water applied and thereby for soil water content to stabilise. Without any irrigation, plants in the ‘rapid onset’ regime (RD), reached the same soil water content in 6 days, after which they were switched to the 50%ETp regime. Thereafter, soil water content remained stable and very similar in the two drought treatments (Figure 1.8). This implies that stomatal adjustment reduced water loss to match water supply, irrespective of the speed at which the soil water deficit developed. However, severe wilting occurred in the ‘rapid onset’ treatment but not in the ‘slow onset’ treatment.

Measurements of stomatal conductance (g_s), leaf water potential (LWP), and soil water content (SWC) were then made over the course of 10 days, during which both treatments were held at 50%ETp. The results confirmed that there were no differences in g_s or SWC but revealed that LWP was significantly lower in the ‘rapid onset’ treatment (Figure 1.9).

Since the leaf area of the plants would have been closely similar, these results imply a lower resistance to water uptake from the medium in the 'slow onset' drought, compared to the 'rapid onset' plants. Lower resistance to water uptake could be due to ABA induced increase in root permeability in roots exposed to dry soil, or perhaps to a shift in resource allocation resulting in slightly greater root growth in the 'slow onset' treatment.

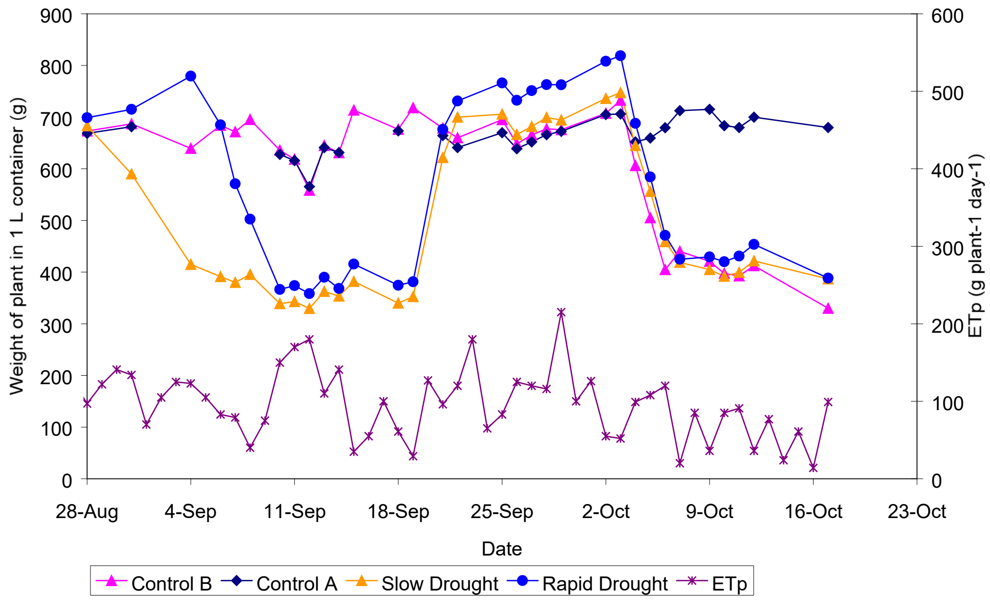


Figure 1.8. Changes in weight of *Forsythia* x *intermedia* cv. Lynwood container plants, as a measure of the changes in water content of the growing medium during the two drought periods. (Weighed 3 h after irrigation. Subtract 200 g to obtain the approximate water content of 1L of medium).

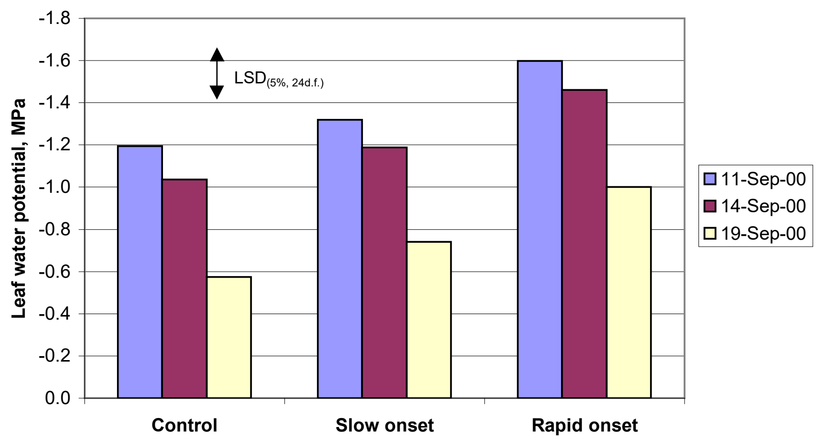


Figure 1.9. Midday leaf water potential on three separate days during the first controlled drought.

After the first drought period all plants were returned to a well-watered regime for 2 weeks to allow the medium to rehydrate and the plants to regain full turgor. After measurements of LWP and g_s had confirmed that recovery was complete, a second 'rapid drought' was imposed. Again, a group of plants were kept well-watered for comparison (Control A).

When remeasured 13 days into the second drought, previously droughted plants had higher g_s and LWP (i.e. less negative) than plants that had not been stressed before (Figures 1.10).

This suggests that some of the adaptation to the initial drought persisted to the end of the recovery period and increased the plant's ability to tolerate drought.

During the first drought, the concentration of ABA in the leaves increased by an average of 60%, relative to well watered controls, irrespective of how quickly the drought was imposed (Figure 1.11). On 2 October, at the end of the recovery phase, the ABA concentration was still high in the slowly droughted plants but, in the rapidly droughted plants, had returned to that of the well watered control plants. However, the speed of onset of the first drought had no significant effect on ABA levels (Figure 1.11) or water relations (Figure 1.10) during the second drought.

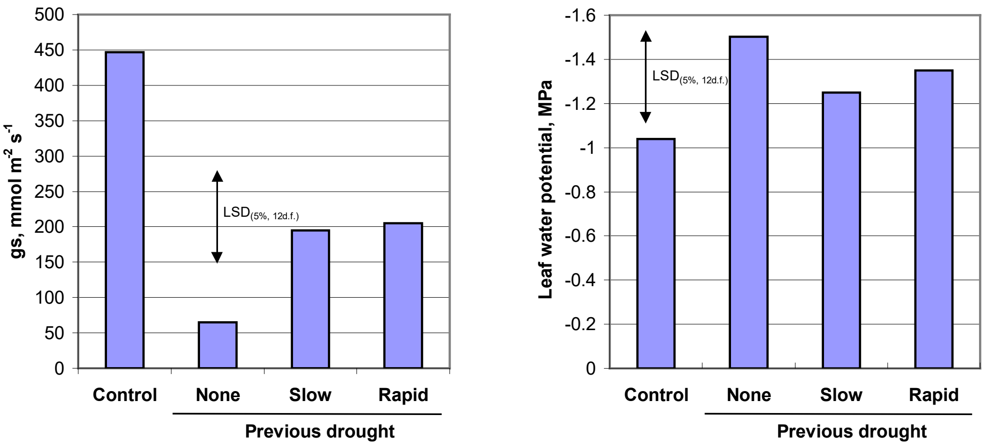


Figure 1.10 Stomatal conductance (g_s) and leaf water potential of *Forsythia* leaves during the second, rapid, drought.

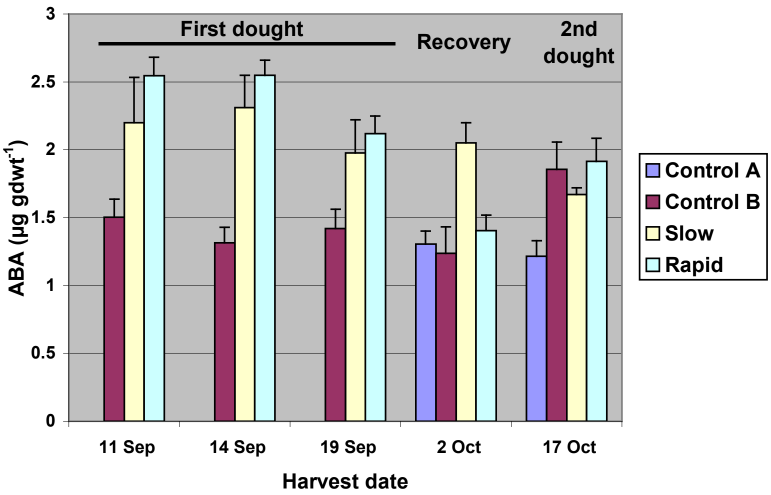


Figure 1.11 Changes in leaf ABA concentrations Forsythia over two cycles of drought (50% RDI). The first drought was imposed either slowly ('Slow') or rapidly ('Rapid') but the second was imposed rapidly to all except Control A plants, which remained well watered.

Main conclusions

- When drought develops slowly plants adapt better, reducing the drop in LWP and thus the danger of damage.

- Therefore RDI protocols must be designed to develop a water deficit slowly and progressively.
- The benefit of slow drought appeared to be due mainly to an increase in the hydraulic conductance of the root system, but this will require further work to confirm.
- There was little evidence that stomatal adaptation was influenced by the rate of onset of drought. In both treatments transpiration declined as volumetric water content approached 20%.
- Leaf ABA concentrations were increased by ~ 60% during RDI and, if drought developed slowly, were still elevated 2 weeks after generous irrigation was restored.
- The adaptive changes protected plants from later drought, even after two weeks of generous watering.

Experiment 1.4: Comparison of RDI with PRD

When irrigation is restricted and the growing medium starts to dry out, water no longer moves easily and parts of the pot can become very dry while others are quite moist. Using drip irrigation to implement RDI, a relatively moist zone tends to form around the dripper while more remote parts of the pot become very dry (Figure 1.12). This is characteristic of the PRD technique. To determine whether this PRD element was critical to the successful implementation of RDI, and to compare it with a precisely defined PRD system, we decided to adopt a 'split-pot' system. 'Split-pot' experiments were a feature of the research that led to the development of PRD as a practical technique. By physically separating the 'wet' and 'dry' halves of the root system the volume of roots in each part is clearly defined and there is no limit on how generously the 'wet' side is irrigated.

Figure 1.12 Wet zone around the dripper in the 2 L pot of Forsythia on 25%ETp

Material and methods

Plant material

Cotinus coggygria cv. Royal Purple in 'split-pots'
Forsythia x intermedia cv. Lynwood in 'split-pots'

Split-pots consisted of two 9 x 9 cm square pots (1 L) held together with pegs (Figure 1.3). In April 2001, the roots of one-year-old plants, removed from 7cm pots, were carefully teased apart so that half could be planted into each half of the split-pot. Plants were well watered for 8 weeks to allow for root development prior to the start of the irrigation treatments on 11 August.

Figure 1.13 Cotinus established in the 'split-pot' system. These plants are controls that are receiving 100 % ETp to both sides of the pot.

Irrigation treatments

Control = 200% ETp, on both sides (100% ETp to each side)
RDI = 50% ETp on both sides (25% ETp to each)
PRD 1 = 200% ETp on one side, side changed after 3 weeks (west then east)
PRD 2 = 200% ETp on one side, (west side throughout)
Irrigation was applied by high precision drippers and was divided into three applications per day to minimise local drying around roots.

Soil and plant water relations were measured frequently over a 6-week period. Physiological measurements were largely confined to the *Forsythia* plants.

Results and discussion

Soil water status

ThetaProbe readings of the surface 6 cm showed that the medium remained moist (50-60 % v/v) in the controls and on the wet side of the PRD treatments. Under RDI, it stabilised at ~ 18 %, while on the dry side of PRD it dropped more quickly and stabilised at ~ 8 %. Following the change-over of irrigated side in PRD 1, the water status of the two sides took about 10 days to fully reflect the change. Data from septum tensiometers buried at the base of the pots confirmed that the dry side of PRD pots became drier than the RDI pots. Soil water tension reached 300 - 400 HPa after 7 days and thereafter readings became erratic in the PRD pots as the tensiometers reached the practical limit of their measurement range.

Plant water relations

During the early stages of the experiment, g_s was reduced by both RDI and PRD, compared to control plants (Figure 1.14). With the decline in light levels and temperatures as the season progressed, g_s declined in all treatments and only in RDI treated plants did it remain significantly below control. Changing over wet and dry sides in treatment PRD 1 had no effect on g_s.

On three occasions when leaf water potential (LWP) was measured, it was lower (i.e. more negative) in RDI and PRD treatments than in control plants (Figure 1.15). However, only on the last occasion (20 September) were there any significant differences, the LWP in RDI plants then being significantly below that in control and PRD treated plants. Since the RDI plants were receiving only 50% ETp, the fact that their LWP was not consistently below that of control plants indicates that stomatal adjustment was very effective in maintaining leaf water potentials above the level at which leaves would be damaged. Unlike other experiments, the water was divided evenly between both halves of the root system to avoid a 'pseudo-PRD' effect. It was also divided into three applications per day and this may have helped to maintain LWP since, for a short time after each application, there would have been relatively moist zones around each dripper.

These results are consistent with the hypothesis that a high moisture content around half a root system is sufficient to maintain LWP of PRD plants close to that in plants with the entire root system well-supplied with water. The reduction in g_s in the PRD plants is consistent with idea that chemical signals from the dry half of the root system can trigger reductions in g_s independent of LWP. The evidence is particularly clear for 22 August, when a large and significant effect on g_s coincided with a small and non-significant difference in LWP.

Why did RDI cause greater reduction in g_s than PRD? Assuming that root signals were no stronger in the RDI treatment than in the PRD treatments, then this must be attributable to the direct effect of water deficit, even though this was not consistently reflected in a difference in LWP. However, it is possible that root signals from the PRD treatments were attenuated by over-drying of the medium on the dry side, so that transport of the signals to the shoots was prevented. The slightly lower g_s in PRD 1 than PRD 2, following the changeover of wet and dry sides in PRD 1, is consistent with this suggestion though the difference not significant.

Plant growth

RDI reduced final plant height by 25-30 % in *Forsythia* and *Cotinus* (Figure 1.16). The effect of PRD was smaller and only in *Cotinus* was it significant. As in the case of effects on g_s, these results indicate that roots signals alone, in the absence of any shoot water deficit, do not reduce growth as much as true drought, in which the effect of root signals is combined with the direct effect of shoot water deficit. That conclusion is consistent with the observation, in Experiment 1.2, that moving the dripper from one side of the pot to the other at 4-week intervals reduced growth of Controls (150% ETp) but had no effect on the severity of growth reduction from RDI at 50% ETp.

Transient wilting of *Forsythia* plants in the RDI treatment was seen occasionally in the early afternoon on bright days, but no permanent leaf damage occurred.

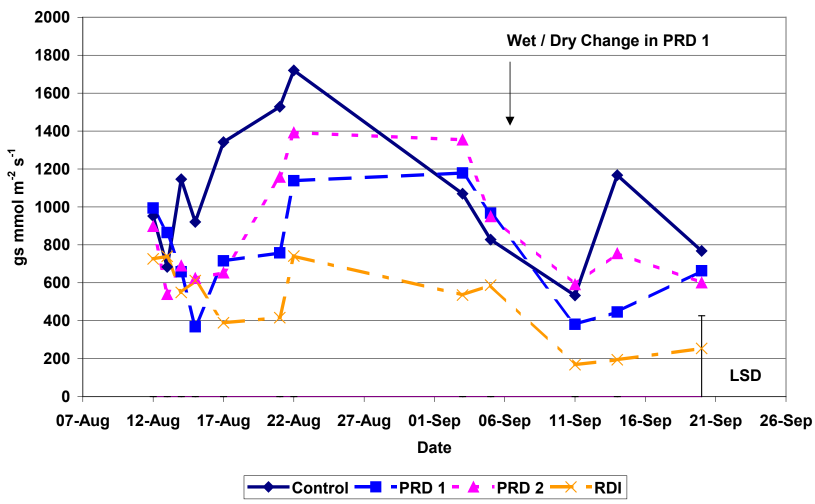


Figure 1.14 Stomatal conductance in *Forsythia* as affected by 'split-pot' irrigation treatments

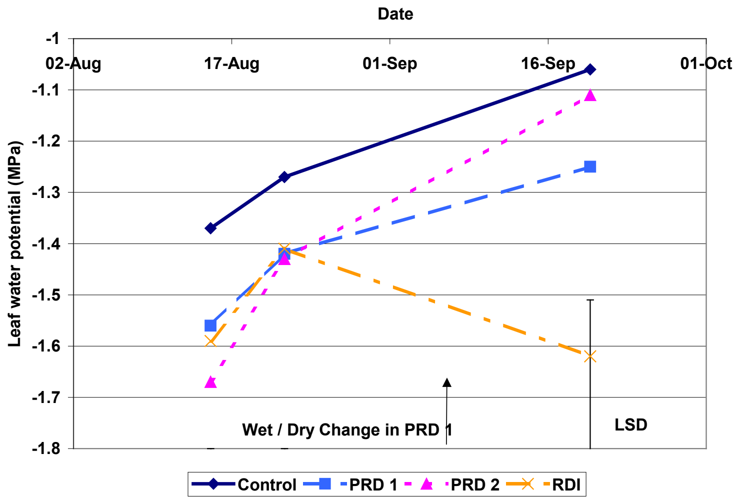


Figure 1.15 Leaf water potential in *Forsythia* as affected by 'split-pot' irrigation treatments

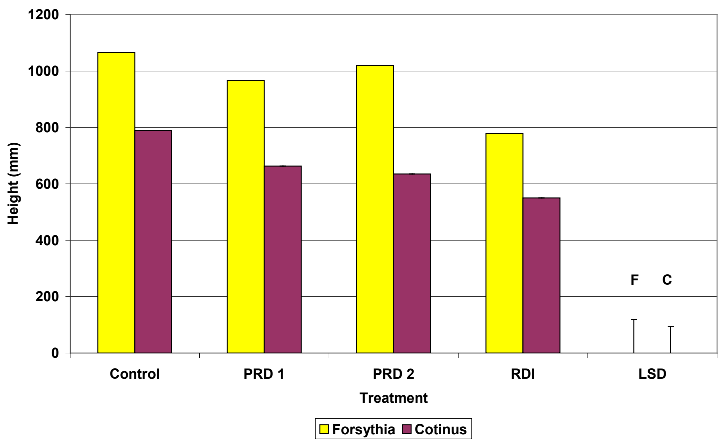


Figure 1.16 Final plant height in *Forsythia* and *Cotinus* as affected by 'split-pot' irrigation treatments

Main conclusions

- There was no evidence that asymmetric application of water (as in conventional drip irrigation) was critical to successful implementation of RDI on *Forsythia* and *Cotinus* (i.e. to achieving a useful degree of growth reduction without leaf damage)
- There was good evidence for the operation of root signals reducing shoot growth and g_s in *Cotinus* and *Forsythia* (considered further in Unit 2)
- At 50% ETp, effects of RDI on growth and g_s are probably dominated by the direct effect of water shortage, rather than chemical root signals, but further work will be required to confirm this unambiguously

Experiment 1.5: Response to RDI in a wider range of species

This experiment, conducted in the final year of the project, looked for differences in response to RDI amongst ecologically contrasting HONS species such as evergreens, climbers, and plants considered to be particularly tolerant of drought and intolerant of wet soil conditions.

Methods and materials

Plant material

- *Choisya ternata* cv. Sundance in 2 L pots
  (yellow leafed, prone to leaf scorch, evergreen)
- *Cornus alba* cv. Elegantissima in 5 L pots
  (variegated leaves, shoots prone to long internodes and 'leggy' growth)
- *Lavandula angustifolia* cv. Munstead in 2 L pots
  (tolerant of drought and intolerant of wet soil)
- *Lonicera periclymenum* cv. Belgica in 2 L pots
  (climber, long internodes and excessive growth make it difficult to manage)
- *Cotinus coggygria* cv. Royal Purple in 3 L pots
- *Forsythia* x *intermedia* cv. Lynwood in 2 L pots

C*otin*us and *Forsythia* were included for cross-reference to earlier experiments. Plants were in a well ventilated twin-span polythene house on Mypex covered gravel.

Irrigation treatments

Control (C)	200% ETp (applied at 2 L/h)
Drought (D)	50% ETp (applied at 4 L/h)
Severe Drought (SD)	25% ETp (applied at 2 L/h)

Irrigation was applied by high precision drippers (Netafim PCJ-CNL). Water applied to C was divided into 6 applications per day to minimise run-through and counteract local drying around roots.

Estimating ETp

ETp estimates were based on the Skye EvapoMeter (see Unit 4). Calibration factors were determined by comparison with weight loss of at least 5 plants of each species over 5 days. Calibration factors varied between species but most of the variation was attributable to differences in canopy area (Figure 1.7).

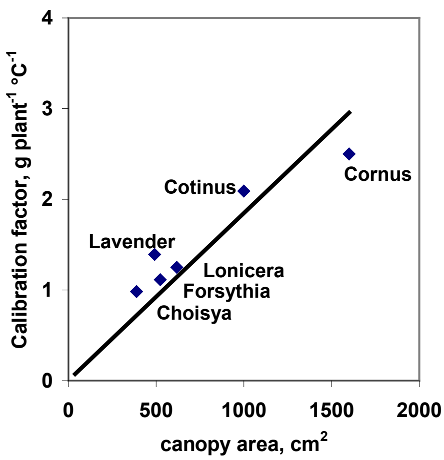


Figure 1. Variation in calibration factor for the EvapoMeter in relation to canopy area (i.e. area of ground covered per plant).

As the plants grew they covered more ground and used more water. New calibration factors determined after about 4 weeks showed increases ranging from 56% for *Choisya* to 109% for *Forsythia*. By this time, the RDI treated plants were already markedly smaller than the controls. To maintain the same severity of stress, the increase in calibration factor used for the drought treatments was reduced in proportion to their growth reduction. In previous experiments, weight loss of well-watered reference plants was used to estimate ETp of droughted plants. With that approach, the severity of RDI regimes tended to decrease with time, as the reference plants grew larger than the droughted plants.

Measurements and experimental design

Measurements were similar to those described for earlier experiments apart from a detailed destructive harvest at the end of the experiment. This included the determination of root dry weight without extracting the roots from the medium. Shoots were removed at ground level and the entire pot, containing roots and medium, was oven dried at 80 °C for at least 48h. Root dry weight was then estimated by subtracting the weight of a similar pot containing growing medium but no plant.

The experimental design was a randomised complete block with 5 blocks. There were 4 plants per plot, the central two of which were used for most measurements. Each species was treated as a separate experiment.

Results and discussion

Soil water content

Irrespective of species, the medium dried out rapidly in both RDI treatments but after about 10 days the rate of decline slowed down and after about 20 days it stabilised (Figure 1.18). This indicates that *all species tested* were able to gradually adjust their water use to match the restricted supply. During this adaptation stage, some wilting was evident, but only in *Forsythia* did any leaf scorching occur, and that was confined to a few of the older leaves. Wilting was also very evident in Lavender, despite its reputation as a plant that thrives in dry conditions. In common with many yellow-leafed cultivars, *Choisya* is prone to leaf scorch yet it suffered little wilting and no leaf scorch from the RDI treatments.

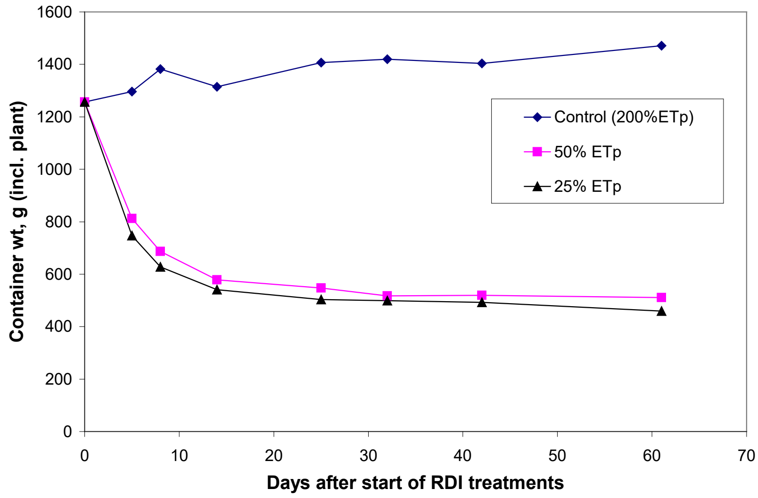


Figure 1.18 Changes in water content of media in response to RDI treatments, as reflected in changes in weight of containers of *Choisya ternata* cv Sundance. Other species showed similar trends.

Plant water relations

Once the plants had adapted to the RDI regimes, leaf water potential (LWP) and stomatal conductance (g_s) were determined to measure the severity of stress (Figures 3 and 4). Leaf water potential was significantly reduced by RDI, averaging -1.3, -1.7, and –2.1 MPa in plants receiving 200%, 50% and 25% ETp respectively ($P<0.001$). There were small but significant ($P<0.001$) differences between species but no significant differences in the response to RDI between species. The lowest LWP (i.e. the most negative) was observed in *Forsythia*, in the SD treatment, which also showed the most severe wilting, but LWP was almost as low in *Cotinus*, which showed no wilting. This can be explained by the higher osmotic potential (OP) of the leaf cell sap in *Cotinus* compared to the other species (data not shown). Differences between irrigation treatments in the OP of fully rehydrated leaves are evidence of osmotic adjustment to drought by an increase in the concentration of solutes in the cell sap. This occurred in all species and was not particularly marked in *Cotinus*.

Differences in stomatal conductance confirm that adjustment to RDI was mainly achieved by reduction in the size of stomatal pores (Figure 1.20). There were significant differences between species, both in absolute terms and in the response to RDI ($P<0.001$). The latter is attributable mainly to the relatively low g_s in well watered *Choisya* compared to the other species.

To look for a reason why Forsythia suffered markedly greater stress than Choisya (lower LWP, more wilting and leaf damage), we monitored g_s intensively over a 24 h period to study the diurnal variation. In *Forsythia,* g_s increased as irradiance increased early in the day, and this was evident even in the droughted treatments (Figure 1.21). In contrast, *Choisya* showed no increase in g_s after the first measurement (at 07:00 h), and instead declined progressively over the daylight hours, irrespective of treatment. There was no evidence, in either species, that stomata responded to the short-term local increase in water availability following the daily irrigation in the RDI treatments at 11:00 h. These results suggest that Choisya suffered less stress under RDI than Forsythia because its stomata were more tightly controlled by water status. Forsythia is a more vigorously growing plant than Choisya and, on the evidence of this experiment, appears to be adapted to make use of whatever light is available for photosynthesis, even at the risk of suffering damaging levels of water deficit.

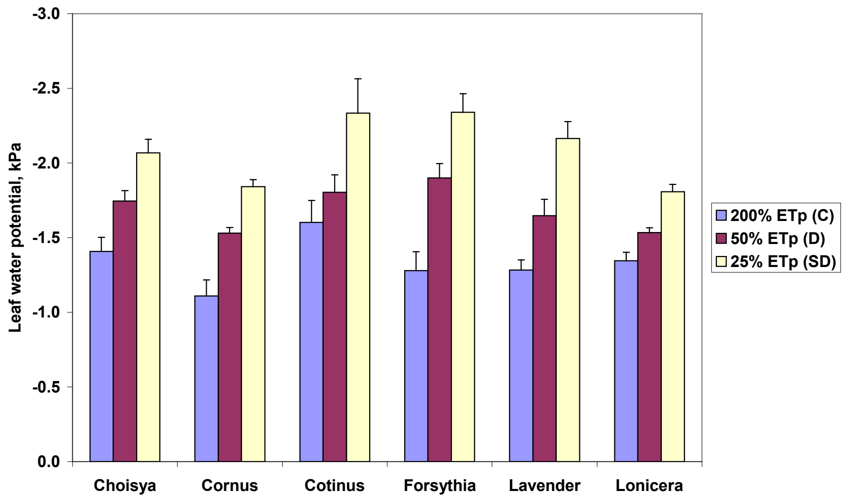


Figure 1.19 The effect of RDI on leaf water potential in different species. Plotted values are means of data collected between 0800 and 1630 GMT on 18 and 19 July, 2002

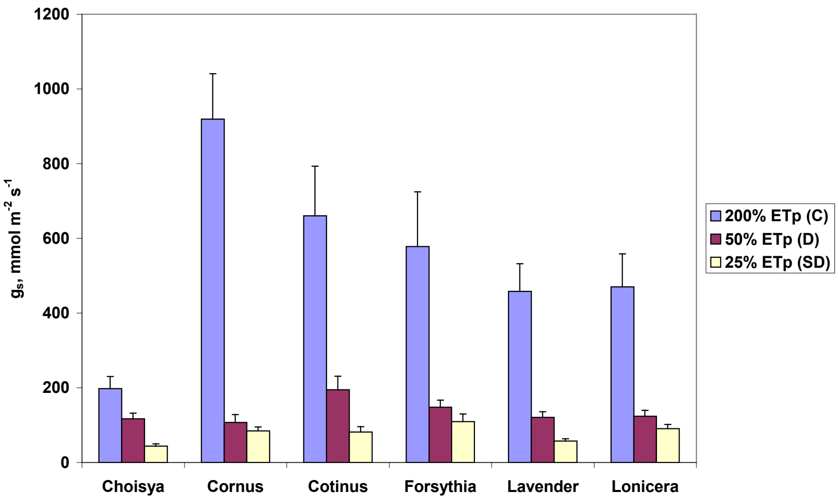


Figure 1.20 The effect of RDI on stomatal conductance (g_s) in different species. Plotted values are means of data collected between 0800 and 1630 GMT on 18 and 19 July, 2002

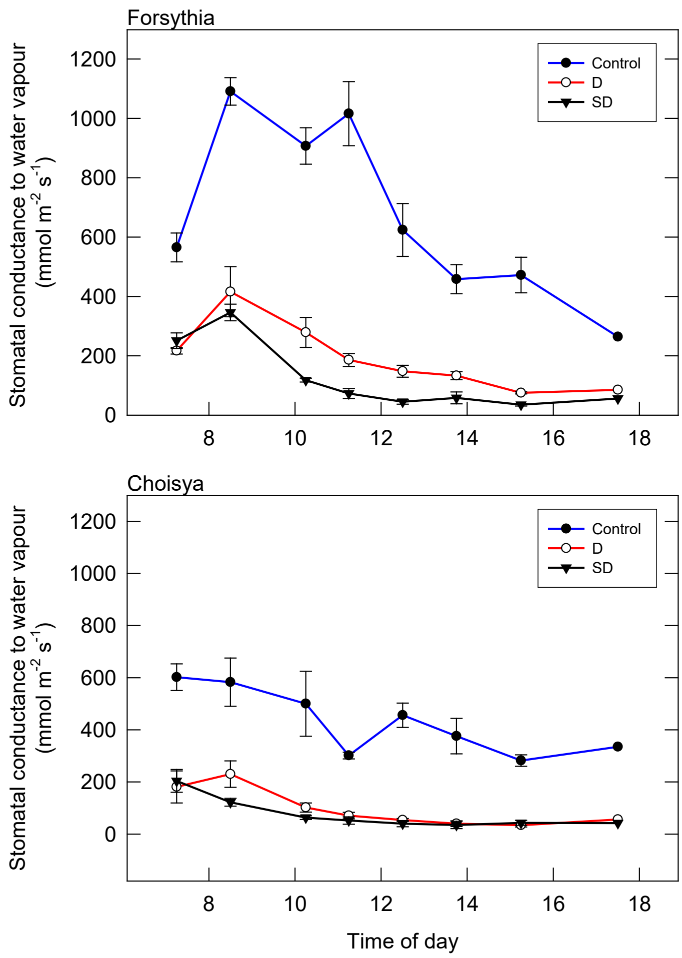


Figure 1.21 Variation in stomatal conductance over the course of the day in *Forsythia* cv. Lynwood and *Choisya ternata* cv. Sundance growing under two RDI regimes (D and SD) compared to well watered control (C). C was irrigated at 200% ETp, D at 50% ETp and SD at 25% ETp. Plotted values are means ± SE for 21 August 2002 (largely cloud free day).

Plant growth

Growth of all species was dramatically reduced by RDI (Figure 1.22). Shoot extension was almost completely stopped by both RDI regimes so that differences between 50% ETp and 25% ETp were small.

A detailed destructive harvest at the end of the growing season, showed significant effects ($P<0.001$) of RDI on all variables measured except root dry weight, the number and height of origin of new shoots, and specific leaf area. In contrast to the lack of effect on root dry weight, RDI reduced the dry weight of new shoots by up to 92 %, so that the partition of dry matter between roots and shoots changed substantially in favour of roots (Figure 1.23). Shoot extension growth, as measured by the total length of shoots produced after the start of the RDI treatments, was reduced by up to 81%, due largely to reductions in internode lengths (Figure 1.23). The effects of RDI on internode lengths in strong leading shoots were even greater than indicated in the graph. For example, in Lonicera, RDI reduced the mean internode length amongst leading shoots from 16 cm to 4 cm.

In terms of visual impact, the effect of RDI was probably greatest in *Lonicera* (Figure 1.24). There was no wilting but internodes were much shorter so that the shoots did not reach the top of the canes (115 cm) until the end of the season. RDI had no obvious effect on flowering but leaves were smaller and darker green.

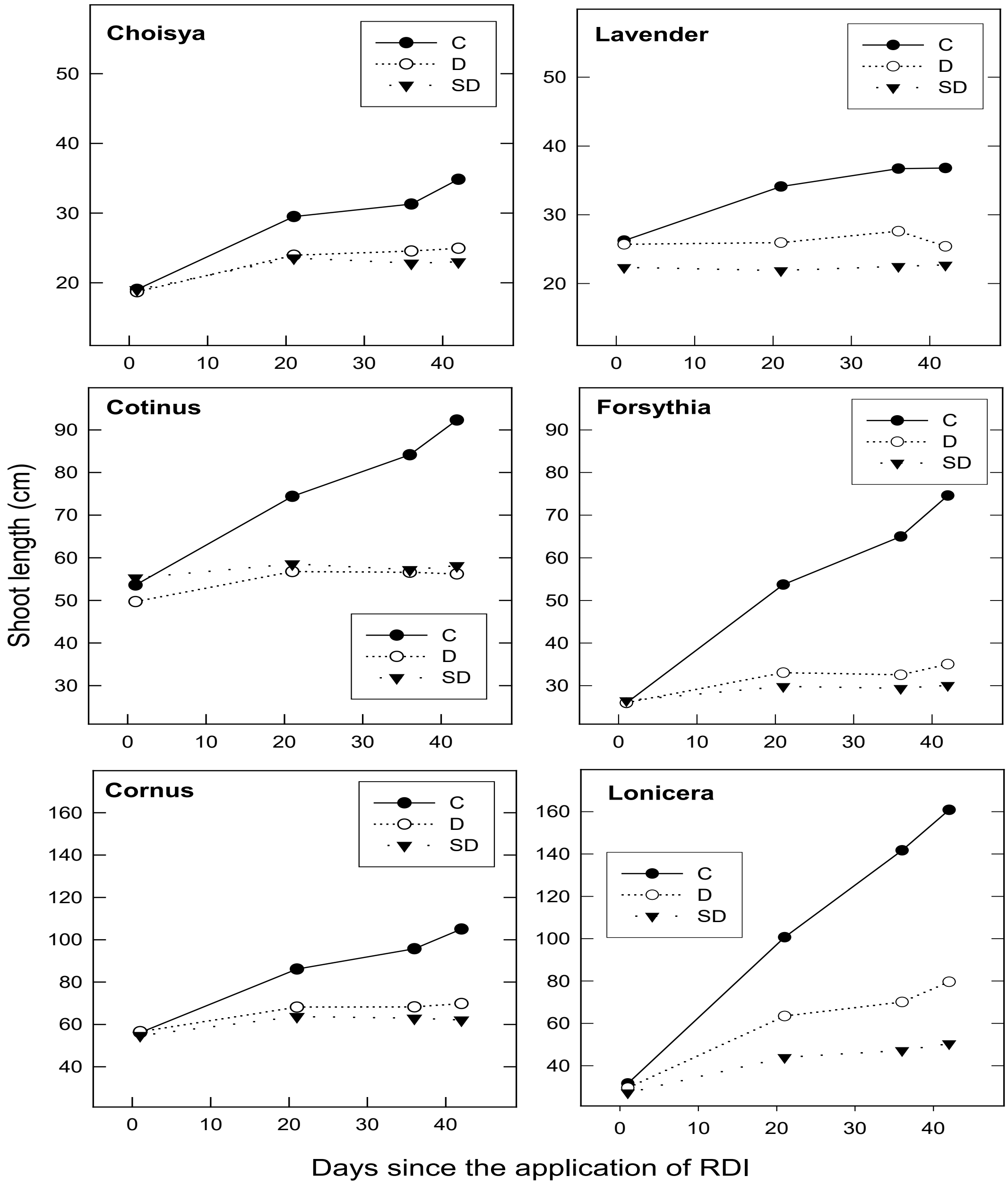


Figure 1.22. Effects of RDI on growth of C*hoisya ternata* cv. Sundance*, Lavandula* cv. Munstead, C*otinus coggygria* cv. Royal Purple*,* F*orsythia* cv. Lynwood*, Cornus alba* cv. Elegantissima, *and Lonicera periclymenum* cv. Belgica. The graphs show height growth under two RDI regimes (D and SD) compared to well watered control (C). C was irrigated at 200% ETp, D at 50% ETp and SD at 25% ETp.

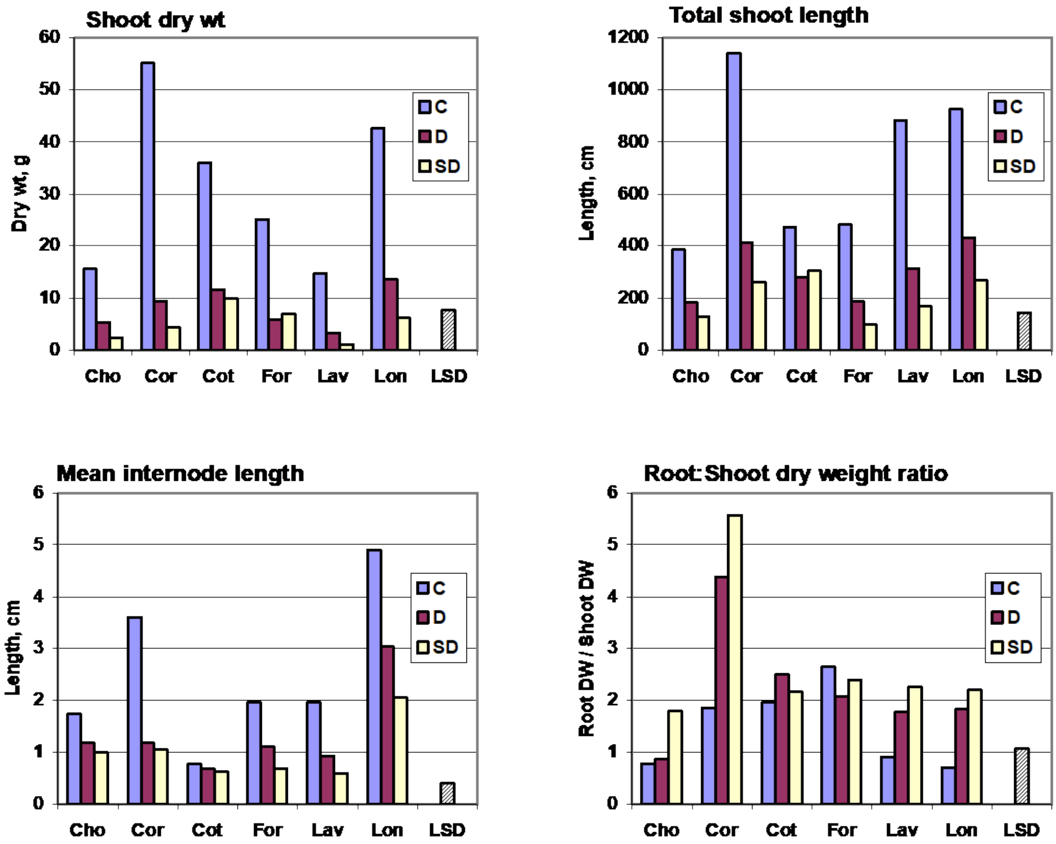


Figure 1.23 Effects of RDI on growth and dry weight partitioning of Choisya, Cornus, Cotinus, Forsythia, Lavender, and Lonicera, based on destructive harvests at the end of the growing season (November).

Water use efficiency

As an additional measure of ability to adapt to drought, estimates of instantaneous water use efficiency (WUE) were obtained, for Control and Severe Drought treatments, using portable photosynthetic gas exchange equipment. The data showed increases in WUE ranging from 5 to 20 % in all species except *Cotinus* (data not shown). *Lavandula* could not be included because the leaf chamber was not suitable for its small leaves. *Cornus* had significantly lower WUE than other species, perhaps because of its variegation. These results suggest that, for many HONS species, when g_s is reduced by RDI and/or PRD, photosynthesis is not reduced as much as water use. This implies that controlled drought may lead to an accumulation of carbohydrate reserves in the plant which, together with the increased root:shoot ratio, could promote rapid establishment in the garden or landscape. However, data of this sort provide only a 'snapshot' of the photosynthetic efficiency at one particular time and further work is required to explore thoroughly this aspect of the response to drought in HONS.

200% ETp 50% ETp 25% ETp 200% ETp 50% ETp 25% ETp

Figure 1.24 The effect of RDI on *Lonicera* four weeks after the start of the treatment (left) and at the end of the growing season (right, in February). Photographs of other species are in Appendix 5.

Main conclusions

- A wide range of HONS species can adapt to RDI, at least down to 25% ETp, without suffering stress lesions.
- With RDI maintained throughout the growing season, shoot growth was reduced proportionately more than the reduction in water use, despite an increase in instantaneous WUE.
- RDI resulted in substantial increases in root:shoot dry weight ratio in some species because reductions in shoot growth were not matched by reductions in root growth.
- Despite its reputation as a drought tolerant plant, there was no evidence that Lavender was insensitive to RDI, at least when growing in a container.
- *Forsythia* was the only species to suffer visible ill effects from RDI. Low LWP was accompanied by prolonged turgor loss (wilting) which lead to some leaf scorch in the more severe RDI treatment (25% ETp).
- The sensitivity to drought of *Forsythia* was attributable to stomatal behaviour: even in leaves that were severely stressed, g_s remained relatively high and increased with light level in the early morning.
- Osmotic adjustment to RDI was evident in leaves of all species and could not explain the greater drought sensitivity of *Forsythia*.
- RDI did not cause the 'leaf scorch' in *Choisya* cv. Sundance. This suggests that the 'leaf scorch' to which yellow-leaved plants are prone is probably not induced by water stress.
- The potential practical benefits from RDI appeared to be largest in the climber, *Lonicera*. RDI at 50% ETp prevented leading shoots from growing beyond the tops of the supporting canes and reduced internode lengths from 16 cm to 4 cm.

Experiment 1.6: RDI under overhead irrigation

We were conscious that the promising results obtained with RDI would only be *directly* relevant to the industry if they could be reproduced under less precisely regulated conditions and using overhead irrigation. Therefore, in 2001, we attempted to implement RDI under overhead irrigation outdoors and under protection.

Methods

The outdoor beds consisted of a polythene sheet covered with Mypex. This was intended to allow some redistribution of water from wet to dry areas but the surface was uneven and some local puddling occurred. Under protection the polythene was covered with capillary matting to aid redistribution and the matting was covered with perforated black polythene to reduce evaporation.

The amount of irrigation to be applied was determined using a simplified gravimetric method. At the start of the season, the weight at pot capacity was determined for a few 'reference' plants. These were weighed daily and the amount of irrigation required to return them to pot capacity was calculated, using a previously determined figure for the rate of water application from the sprinklers. The reference plants were irrigated along with the rest of the crop and they were not weighed again after irrigation. The control beds received the calculated amount; RDI beds received a percentage of the calculated amount (initially 50%, then 33% and finally 25%).

Results

Outdoors, pot weights remained approximately constant on the control bed over the course of the season and were consistently lower on the RDI beds. Actual weights on the RDI beds fluctuated from 600 g to 1300 g due to rainfall, so that weights never stabilised as they did in the under the more controlled conditions of drip irrigated experiments under protection (e.g. Experiment 1.5, Figure 1.18). Nonetheless, final plant height was reduced by 16% in *Forsythia* and 22% in *Cotinus* (data not shown). There was no damage to the foliage and the RDI plants appeared to be slightly better shaped than the Controls. Also there was markedly less weed growth in the RDI treatments as a result of the surface of the medium being dry for much of the time. Whilst this would not remove the need for herbicides in commercial production, it might help ensure that good control is achieved and would also contribute to control of mosses and liverworts.

Under protection, it proved difficult to regulate the amount applied to the RDI beds. Pot weights either tended to remain high or to become progressively lower until supplementary irrigation was applied to rescue severely wilting plants. As a result, 6% of *Cotinus* and 11% of *Forsythia* plants suffered permanent damage to foliage.

Conclusion

From this it was clear that additional work was required to find a practical alternative to drip irrigation for implementation of tight control of growth such as we achieved experimentally (e.g. 1.1).

Experiment 1.7: Behaviour of capillary matting in relation to RDI

This experiment followed on from Experiment 1.6 and aimed to identify the reasons that it proved difficult to maintain a stable RDI regime under protection. The focus of attention was the capillary matting, which was intended to counteract non-uniformity of overhead irrigation, and improve water use efficiency, by redistributing water that reached the bed surface.

Materials and methods

The approach adopted was to make detailed measurements of water movement into and out of the containers. At the outset, the bed was carefully levelled. As in 2001, it was lined with 125 um polythene which was then covered with capillary matting and perforated black polythene. Plants (*Forsythia*, 3L pots) were allocated to the following treatments:

Treatments

C pots on capillary matting, undisturbed
CD pots on capillary matting, regularly disturbed for weighing
G gravel mulched pots, on capillary matting, undisturbed
GD gravel mulched pots, on capillary matting, regularly disturbed for weighing
FS pots placed on a large saucer (19cm diameter) to collect and funnel water to the base of the pot
OH overhead only: pots separated from the capillary matting so that they only receive water directly from the overhead irrigation.

There were 5 blocks with at least 1 plant per treatment in each block.

The bed was irrigated every 2 to 3 days with a percentage of ETp, estimated by the weight loss of 5 reference plants (watered to constant weight, removed from the bed during irrigation, and standing in a plastic dish to prevent capillary uptake). The target irrigation was 150% ETp until 11 September when it was reduced to 50% ETp to impose RDI.

Apart from the undisturbed pots in treatments C and G, all pots were weighed before irrigation and 10 minutes after each irrigation. The time course of pot weights showed whether stable RDI was established. From the *differences* in weight change between particular treatments it was possible to estimate the components of pot water balance illustrated in Figure 1.25 and listed below:

1. Overhead (i.e. entry via the top of the pot, either direct or after interception by the foliage)
2. Surface (i.e. free water collecting on the surface of the mat that is taken up during or shortly after irrigation)
3. Capillary (i.e. taken up from the mat between overhead irrigations)
4. Run-through (i.e. overhead irrigation that is not absorbed by the medium but instead runs through rapidly and is lost through the base of the pot). It was measured as the weight of water that collected in a reservoir fitted to the base of pots in the OH treatment (see Figure 1.25)

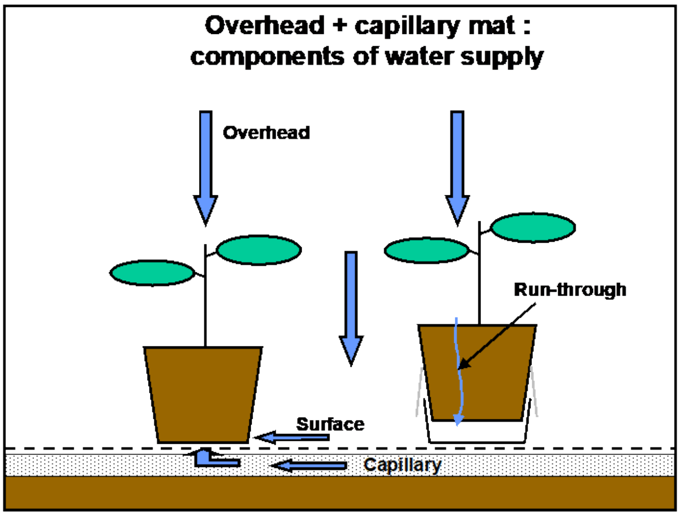


Figure 1.25 Diagram showing the components of pot water balance that were measured

Results and discussion

Stability of RDI

Irrigation at 150% ETp maintained a roughly stable water content such that pot weight in the CD treatment fluctuated between 1500 and 2000 g (Figure 1.26). When RDI was imposed weights initially decreased, but this trend was reversed after the second irrigation event (9 Sept.). At this stage, irrigation times were based on an assumed 'catchment area' for each pot of 25 x 25 cm, this being the spacing between pot centres. The weight gains recorded on 9 Sept. indicated that some water must be reaching the pots from further afield, particularly the gaps between experimental blocks that were used to reach the plants for weighing. Taking account of these gaps increased the estimated catchment area almost 3-fold. Using this figure to calculate irrigation, pot weights declined rapidly so that by 23 Sept. many plants were wilting severely. For two days, irrigation was again based on the smaller catchment area and pot weights rose rapidly. Switching back to the larger catchment area, and applying irrigation daily instead of every 2-3 days, resulted is a slow decline to a stable equilibrium at around 1000 g (equivalent to a SWC of about 30 %).

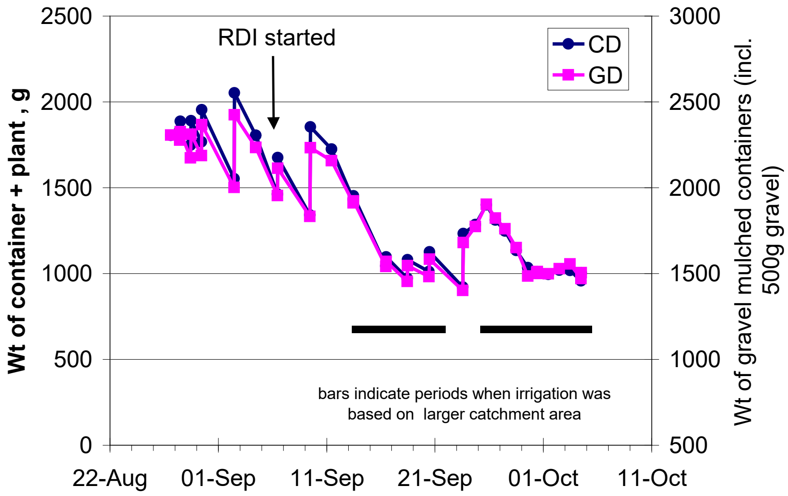


Figure 1.26 Weight changes of pots in the CD and GD treatments (plotted against different scales to adjust for the weight of the gravel mulch on GD pots). Depending on the effective water catchment area used in irrigation calculations, pot weights either increased or decreased (see text for details). Plotted values are means of 5 containers.

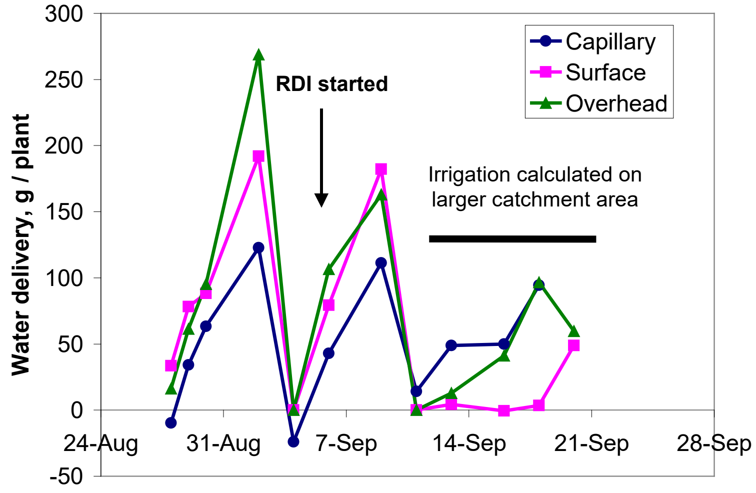


Figure 1.27 Components of water supply to containers in the CD treatment. Notice that uptake from the bed surface during irrigation was generally more important than capillary uptake, and that capillary uptake was only large when the overhead irrigation was heavy.

Water redistribution

Despite the apparent success in obtaining stability, the weight of individual pots was quite variable so that some plants were severely stressed while others were not, suggesting that the capillary matting was ineffective in redistributing water from wetter areas to drier areas. Analysis of the components of water supply to the CD pots (Figure 1.27) shows that capillary uptake was almost always the smallest component and that it varied in parallel with the amount of overhead irrigation applied. This suggested that the mat could only supply substantial amounts of water when it had been well wetted by heavy irrigation. Support for this suggestion was obtained in laboratory measurements of short-term uptake from capillary matting discs adjusted to a range of water content. Water uptake by a droughted plant (weight ~1000 g) declined steeply as the water content of the mat fell below saturation so that it was less than 1 g/h at a water content of 50% (v/v) (Figure 1.28). Assuming that the same relationship applies to water movement across the bed, it is clear that the capillary matting would become largely ineffective once its water content started to decline as RDI was imposed.

Other factors

The data in Figure 1.26 show that the gravel mulch had no detectable effect on either evaporation (i.e. weight loss) or water capture (i.e. weight gains). Surprisingly, very little run-through was collected, even when pots had dried down to a weight of about 1000 g and the medium was shrinking from the sides of the pot. When such a pot is hand-watered, run through is very obvious. Not surprisingly therefore, run-through is often raised as a potential barrier to the application of RDI in commercial HNS production. This result shows that it should not be a problem as long as pots are rewetted using the overhead irrigation system so that water is applied relatively slowly. In this experiment, the mean application rate was actually rather high at 28 mm/h but run-through was negligible. No wetter was used in the medium.

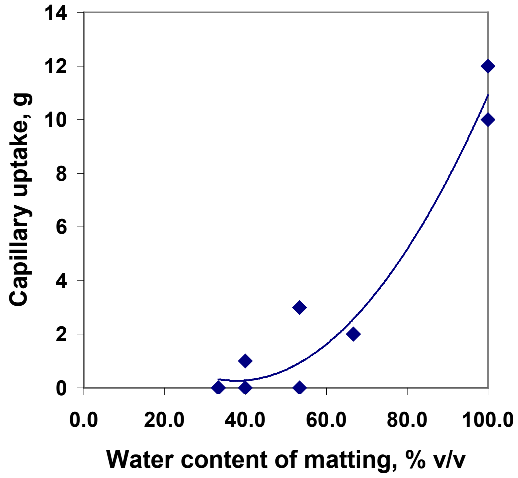


Figure 2.18 The effect of the water content of capillary matting on the amount of water taken up in by a droughted plant, over 90 minutes.

Main conclusions

- Capillary uptake only makes a large contribution to the water supply under an RDI regime if the duration of irrigation is long enough to saturate the mat.
- Depending on how wet the mat becomes, the effective catchment area for each plant can vary enormously (about 3-fold under the conditions of this experiment).
- This variation makes it difficult to achieve a stable RDI regime with daily irrigation in this sort of system. Although a stable regime was eventually established in this experiment, it is doubtful whether this would have been the case under the higher and more variable evaporative demands of mid-summer.
- Delaying irrigation until the requirement is enough to thoroughly saturate the mat would probably work better. However, that is effectively a form of 'flood and drain' and would require perfectly level beds.
- The capillary matting does not prevent substantial variation in water supply between individual pots. Indeed, as the matting dries down in some parts of the bed before others, it actually magnifies differences in water supply for reasons stated above.
- Run-through is not a substantial problem, at least at the rate of irrigation used here (28 mm/h).

Unit 2: Root derived signals involved in adaptation to drought and the potential to manipulate them to conserve water (Objective 3)

This Unit describes work primarily directed towards the following scientific objective, though also relevant to objectives 1 and 2 (see Unit 1):

Objective 3. Investigate the effects of naturally-occurring root-generated abscisic acid (ABA) and the influence of possible key co-factors (xylem pH) on growth and functioning of container-grown plants and devise methods to utilise root signalling to reduce transpiration and regulate shoot extension.

Background

Plants have evolved strategies to protect themselves in times of drought. The first line of defence is closure of stomata (pores in the leaf surface through which water is lost and carbon dioxide (CO_2) for photosynthesis is taken up). Leaf growth rates are reduced and, under severe drought, some leaves abscise, thereby limiting the transpiring leaf area. Stem extension rates are reduced so that plants become more compact and low growing and thereby experience lower evaporative demand. These changes promote the conservation of valuable water, carbon and nitrogen during times of stress. They 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 these signalling processes will inform the development of a wider variety of practical techniques to conserve water and regulate growth.

Chemical signals are sent from roots in drying soil to the shoots via the transpiration stream – a flow of water and solutes within specialised cells called xylem vessels which effectively form microscopic tubes extending from the roots into the leaves. The contents of the xylem vessels flow into the spaces within the cell wall matrix of the leaf (the apoplast) and eventually reach the stomatal pores in the leaf epidermis where certain chemical signals exert their effect. Chemical signals that exhibit increased flux from roots to shoots in the xylem upon root exposure to drying soil include the plant hormone abscisic acid (ABA) and the precursor of the plant hormone ethylene. Abscisic acid is a potent inhibitor of leaf and stem growth rates, and induces the closure of stomatal pores in leaves. Recently it has also been shown that changes in the pH of the xylem sap flowing between the roots and the shoots can be induced by drying soil, and that these changes can influence stomatal aperture and growth rates in leaves. For a review of chemical signalling in plants, in particular in relation to abscisic acid and xylem/apoplastic pH, see Wilkinson and Davies (2002).

For studies of root-sourced chemical signals, it is useful to dry only a part (usually 50%) of the root system, to stimulate signal production, whilst keeping the remaining roots moist to minimise water deficits in the shoots. This is the basic concept behind the technique of 'partial root-zone drying' (PRD), which therefore features prominently in this Unit. Although it was originally used as a tool for studying chemical signalling, in the early nineties PRD was developed as a commercial deficit irrigation technique (see below). Here it is compared with two other approaches to imposing a controlled water deficit. The first is intermittent watering (INT), in which water is withheld until the available soil water is almost exhausted before irrigating to replenish the soil water holding capacity. The second is 'regulated deficit irrigation' (RDI) in which plants are irrigated regularly but receive less water than they require (i.e. less than the potential evapotranspiration, the amount of water a well-watered crop would use). With INT and RDI, water would normally be applied uniformly whereas, for PRD, water application is localised to one side of the plant. The driver for examining PRD in addition to the other deficit irrigation techniques is that it can maintain shoot water potentials, whilst under RDI reductions in water status may, under some circumstances (but see Unit 1) lead to a loss of plant quality (e.g. small leaf size or tissue lesions). Our primary objectives were a) to determine whether these techniques can be used to regulate plant growth and water use, and b) to learn more about the involvement of chemical signals in the response of plants to soil drying.

It has already been demonstrated that PRD maintains shoot water potentials whilst stomatal closure and reductions in shoot growth can still be induced by chemical signals sent from the portion of the roots exposed to drying soil (Dry et al., 2001). To maintain plants in a state of responsiveness to chemical signals over prolonged periods it is necessary to swap the side of the root system that is being irrigated approximately every 10-14 days. Pioneered at Lancaster University, PRD is now being applied widely in the production of grapevines in Australia, reducing water use and improving grape quality by redirecting resources from foliar growth (see Davies et al 2002). Experiments to test its application to the control of water use efficiency and quality in many other crops are underway all over the world.

Effects of soil drying in general and under controlled irrigation, on ABA, pH and ethylene; and 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 chemicals used by HONS to control stomatal aperture and growth have been elucidated, we hold the potential to manipulate the strength of these by methods other than controlled deficit irrigation. There is evidence in the literature that certain compounds, whether naturally present in soils or added via fertigation, can either directly or indirectly influence the abscisic acid concentration and/or the pH of the xylem sap (see Degenhardt et al. 2000, Wilkinson and Davies 2002). In particular, there is evidence that acidification of the soil, for example with ammonium salts, induces the retention of abscisic acid within roots (ABA tends to accumulate within the most alkaline compartment), and thereby increases its concentration in the xylem (Peuke et al. 1994). There is also evidence that potassium bicarbonate can alkalise and ammonium salts can acidify xylem sap (Mengel et al. 1994). Since there are pitfalls associated with controlling plant water use and growth habit using deficit irrigation techniques, we investigated whether these fertigation techniques can switch on the same signalling mechanisms that are induced by soil drying, in moister soils than those in which they normally occur. We also explored whether leaf apoplastic pH can be controlled with foliar sprays so as to reduce stomatal apertures and plant growth rates. There is circumstantial evidence in the literature that foliar sprays can change the pH of the leaf apoplast (Tagliavini et al. 1994 – kiwifruit trees). If changes in sap pH 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 or soil water status. This approach therefore holds out the possibility of saving water and labour on commercial nurseries without the dangers inherent in deficit irrigation.

This Unit presents a) a comparison between PRD and other deficit irrigation techniques (RDI and INT), and b) research into the role of chemical signals in the response of woody shrubs to restricted irrigation. We show how plant signalling systems can be exploited to control growth and save water with minimum risk of plant damage. The work involved a series of experiments, most of which addressed more than one aspect of the problem. For the sake of clarity, details of all the experiments are presented together, before considering the results in relation to separate aspects of the problem.

Materials and methods

The experiments in this Unit were carried out at Lancaster University. Unless otherwise stated, they were randomised complete block designs laid out in a polythene tunnel. Most data are presented as time courses, where mean values and SE of the mean are presented for each time point. The standard growing medium was used.

Partial root-zone drying (PRD)

In these studies, the technique of partial root-zone drying (PRD) was achieved without an impermeable barrier between the wet and dry parts of the root system (as in Dry et al. 2001). Instead, water was supplied to one side of the pot via plastic tubing sunk to a depth of ~ 5 cm and the pot was tipped towards the watered side (Figure 2.1). Measurements with a ThetaProbe confirmed that the medium dried out substantially on the non-watered side (e.g. Fig. 2.2). Watered and unwatered sides were reversed at intervals of 10 - 20 days to prevent the roots in the drying side from becoming so desiccated that they would cease to send signalling compounds to the shoots.

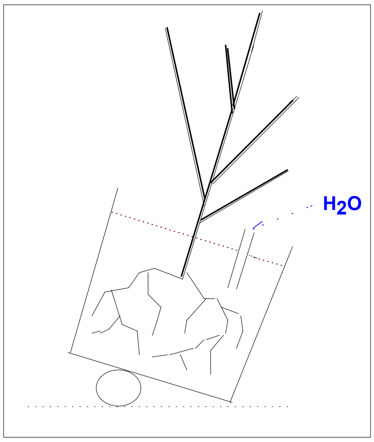


Figure 2.1 Diagrammatic representation of controlled irrigation via PRD.

Experiment 2.1

Plant material

Forsythia x *intermedia* cv. Lynwood, 1-year old plants in 5 L pots

Irrigation treatments

WW = well-watered (500 ml daily uniform application)
PRD = partial root-zone drying (250 ml daily, applied to one side of pot)
INT = intermittent watering (1000 ml every 3-4 days, uniform application).

Measurements

There were 3 positional blocks with 8 plants per treatment in each block. Three plants per treatment were monitored daily for stomatal conductance (g_s), volumetric soil water content (SWC) and growth (extension rates of the first ~7 leaves and ~5 internodes from the apex). Measurements were taken at the same time every day (~ 1400 h). Stomatal conductance was measured in the first fully expanded leaf (usually the fourth from the apex) using a porometer (AP-4, Delta-T Devices Ltd.) which also measured incident light level (as photosynthetic photon flux density, or PPFD) and leaf surface temperature.

At intervals of 3-5 days (total of 6 occasions) leaves were sampled from one additional plant for determination of bulk leaf ABA, ethylene generation (by gas chromatography), RWC and LWP. At the same time, xylem sap was collected from detached shoots in the pressure chamber at overpressures of 2-4 bars (initial) and 4-8 bars (high pressure). The pH was determined in each extract (Micro Combination pH electrode, Lazar Research Laboratories, Inc.), which were then combined, frozen and stored at -20 °C until assayed for ABA.

Experiment 2.2

Plant material

Cotinus coggygria cv. Royal Purple, 1-year old plants in 3 L pots.
Hydrangea macrophylla cv. Blue Wave, 1-year old plants in 3 L pots.

Irrigation treatments

A drip irrigation system was used to apply three different irrigation regimes:
WW = well-watered (from a centrally placed 4L/h dripper)
RDI = regulated deficit irrigation (from a centrally placed 2L/h dripper)
PRD = partial root-zone drying (using a 2L/h dripper, in place of the tube shown in Fig. 2.1)

Measurements

As for Experiment 2.1 but with additional destructive harvests (10 at intervals of ~ 6 d). Leaves were harvested for bulk leaf ABA determination and RWC. Shoots (~15-20cm long) were used to measure shoot water potential and to extract xylem sap for pH and ABA determination.

For each species, there were 3 positional blocks with 10 plants per treatment in each block. The two species were separate experiments.

Experiment 2.3

Plant material

Forsythia x *intermedia* cv. Lynwood, 2-year old plants in 10 L pots

Irrigation treatments

A drip irrigation system was used to apply three different irrigation regimes:
WW = well-watered (500 ml per day)
SD = soil drying (non-watered)

Measurements

Measurements were taken on days 1,2,3,4,5 and 8 as follows: Three plants per treatment were monitored daily for θ_v (at 1030 h and 1400 h), g_s, PPFD and leaf surface temperature (at 1100 h and 1430 h). After 1400 h, samples were taken of leaves for RWC and ABA, of shoots for water potential, and of xylem sap for pH and ABA.

For each species, there were 3 positional blocks with 6 plants per treatment in each block.

Experiment 2.4

Plant material

Forsythia x *intermedia* cv. Lynwood. 1-year old plants in 3 litre pots in a polytunnel.

Treatments

Treatments comprised two levels of irrigation (well watered and RDI) combined with addition of two chemicals that were expected to influence xylem sap or leaf ABA concentrations and/or xylem sap pH. The chemicals were:

A. ammonium chloride (NH_4Cl)

B. potassium bicarbonate ($KHCO_3$)

For simplicity, these are generally referred to simply as A and B.

Plants were irrigated by hand daily as follows:

WWC	= Well-watered controls	(300ml water daily)
RDIC	= RDI controls	(150ml water daily)
RDIA	= RDI + A	(150ml 8mM NH_4Cl)
RDIB	= RDI + B	(150ml 8mM $KHCO_3$)
WWAB	= Well-watered A+B	(300ml 8mM NH_4Cl and 8mM $KHCO_3$)
RDIAB	= RDI A+B	(150ml 8mM NH_4Cl and 8mM $KHCO_3$)

For the last 2 weeks of the experiment, the volumes of irrigation were increased to 400 ml (well watered) and 200 ml (RDI).

Measurements

Measurements, taken at intervals of ~5 days (total of 8 occasions) were as follows: θ_v at 1300 h, g_s plus PPFD and leaf surface temperature at 1330 h. After 1430 h, samples were taken of leaves for RWC and ABA, of shoots for water potential, and of xylem sap for pH and ABA.

There were 3 positional blocks with 8 plants per treatment in each block.

Supplementary experiment

All possible combinations of chemicals and irrigation regimes were applied as a separate set of plants, with 3 replicate plants per treatment combination. At the end of the experimental period (7 weeks) leaf, internode and total shoot lengths were measured.

Experiment 2.5

Plant material

Forsythia x *intermedia* cv. Lynwood, 1-year old plants in 3 L pots

Treatments

Plants were irrigated daily by hand with of one of the following solutions:

Control	= water
A	= 5mM NH_4Cl
B	= 5mM $KHCO_3$
A+B	= 5mM NH_4Cl + 5mM $KHCO_3$

All plants were well-watered levels (~500ml/day) for the first week and thereafter the volume of the solution supplied was gradually reduced over the course of the experiment (3 weeks).

Measurements

Every 2-3 days, measurements were made as in Experiment 2.4

Experiment 2.6

Plant material

Forsythia x *intermedia* cv. Lynwood, 1-year old plants in 3 L pots

Treatments

Plants were well watered daily by hand (~300ml water)

Plants were sprayed daily with either water or a buffer solution (KH_2PO_4/K_2HPO_4) and then the stem was injected with either water or an ABA solution. All combinations of pH (5.0, 5.8, 6.7 and water control) and ABA injection (10^{-5}M, 10^{-6}M and water control) were tested.

Measurements

Measurements were made every day, on 3 replicate plants of each treatment combination. At 1030 h and 1400 h, g_s, PPFD and leaf temperature were measured with the porometer. Leaf and internode lengths were measured at ~ 1600 h. At the end of the experiment (8 days), samples were taken of leaves for RWC and ABA, of shoots for water potential, and of xylem sap for pH and ABA.

Experiment 2.7: detached leaf transpiration bioassays

Plant material

Forsythia x *intermedia* cv. Lynwood: detached leaves from greenhouse grown plants. Leaves (3rd to 7th below growing apices) were detached from plants which had been kept for 1 h in the dark, and petioles were re-cut under water before immediate transfer to treatment solutions, in order to prevent blockage of the xylem vessels with air (embolism).

Treatments

ABA:	aqueous solutions at concentrations of 10^{-4}, 10^{-5}, 10^{-6} and 10^{-7}M
pH:	phosphate buffer (0.5mM KH_2PO_4, 0.5mM K_2HPO_4) adjusted to pH values from 5.2, 6.2 and 7.2 using 0.1M KOH or HCl
Control	pure water

Method

5.0 ml aliquots of the test solutions were placed in 6.0 ml plastic vials covered in aluminium foil to prevent evaporation. Leaves were introduced through slits in the foil so that petioles were submerged. They were placed under lights (PPFD 400 µmol m^{-2} s^{-1}) at 24°C before 1100 h. They were weighed at ~ 30 min intervals for up to 5 h, after which the leaf areas were measured in a planimeter. Transpiration rates were converted to mmol m^{-2} s^{-1} (the same units as for g_s, but not the same measurement because no account is taken of the concentration difference driving transpiration).

Results and discussion

Establishment of PRD and analysis of its effects on plant physiology (water relations, growth and water use).

The aim of the research in this section was to compare the success of PRD and RDI (and INT) in reducing overall water use and promoting more compact growth without compromising other aspects of crop quality. PRD has the advantage that it might protect plants from potentially deleterious reductions in shoot water potential induced under RDI (and INT). Two controlled irrigation techniques were evaluated in *Forsythia* (PRD and INT) and two in *Hydrangea* and *Cotinus* (PRD and RDI).

Soil moisture content

In Experiments 1 and 2, soil moisture content (SMC) was relatively high and stable in both the WW treatment and in the wet side of the PRD pots, but decreased progressively in the dry side of the PRD pots and uniformly throughout the RDI pots (Fig. 2.2). As expected, SMC oscillated markedly in the intermittently watered pots (INT, Fig. 2.2A). A PRD regime was achieved without a physical barrier between the wet and dry sides of the pot. However, all three species compensated for the lack of moisture in the drying side by taking up more from the wet side so that SMC was depleted relative to the WW treatment. This was most evident in *Cotinus* (Fig 2.2.D).

Stomatal conductance

Stomatal conductance declined, compared to WW control plants, at the same rate in the PRD and the RDI treatments but, on most occasions, was higher in the INT treatment (Fig. 2.3). This suggests stomatal adaptation to a fluctuating SMC was less effective than to a steady low SMC

Growth

The growth rate of shoots (Fig 2.4) and leaves (Fig 2.5) was generally greatest in the WW plants. For example, the mean internode extension rates in *Forsythia* were: WW = 2.6, PRD = 1.7, INT = 1.4 mm day^{-1}, $LSD_{(5\%, df=32)}$=0.51. When *Hydrangea* leaf growth was plotted as the cumulative increase in leaf length for two size classes it was evident that PRD had no effect of the final length of leaves (Fig 2.6 A)but slowed the growth of younger leaves (Fig. 2.6 B). In contrast, RDI reduced the final length of leaves (Fig. 2.6 A).

Shoot water status

Although stomatal conductance and growth rates of *Forsythia* were reduced by PRD, the water status of shoots, as measured by water potential and leaf RWC, was the same as in WW plants (Figs 2.7 A and 2.8 A). This provides strong evidence that the effects on stomatal aperture and shoot growth were the result of chemical signals from the roots in drying zone of the PRD pots, as has been determined for grapevine (Stoll et al., 2000). In marked contrast, shoot water potential and RWC was significantly lower in the INT plants than in either WW or PRD plants.

Avoidance of stress under PRD was less clear in the other two species. In *Hydrangea,* water potential and RWC of PRD plants was intermediate between that of WW and RDI plants (Figs. 2.7 B and 2.8 B). In *Cotinus*, shoot water potentials were anomalously high, suggesting that exudation of oil from resin canals (responsible for the distinctive smell of this species) may have masked the true balance pressure. However, RWC was similar in PRD and RDI plants, and significantly lower than in WW plants only in 2 out of 8 occasions.

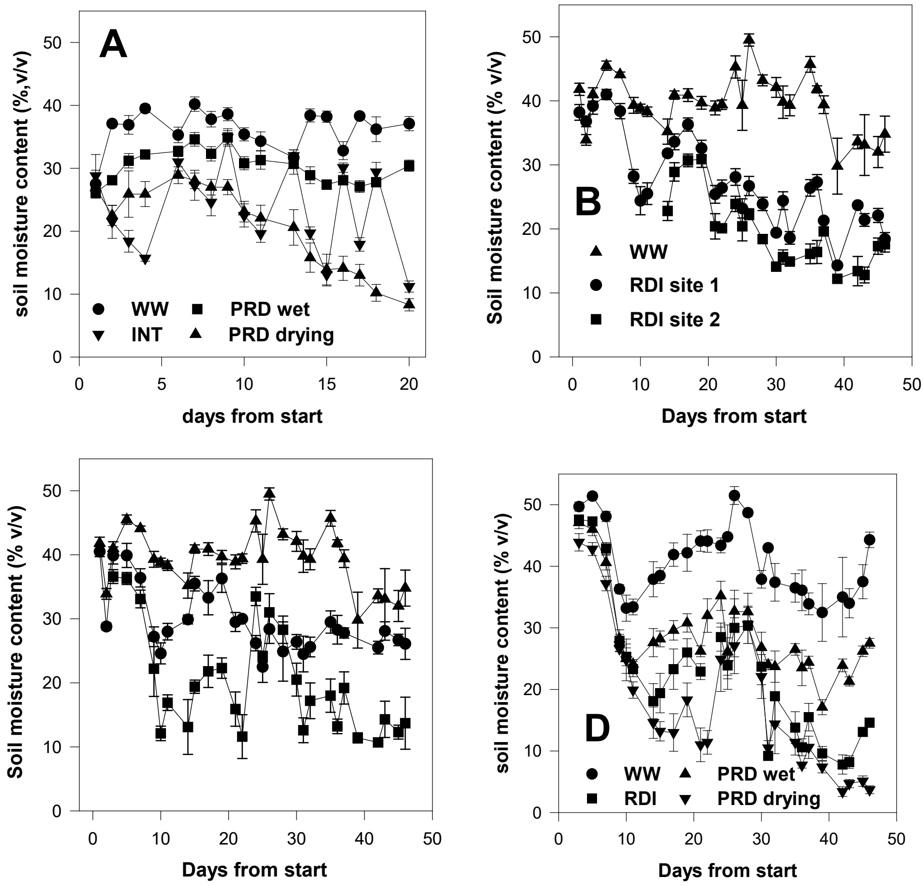


Figure 2.2 Effect of controlled irrigation on volumetric soil moisture content in *Forsythia* (A), *Hydrangea* (B and C; for C, ▲ = WW; ● = PRD wet side; ■ = PRD drying side) and *Cotinus* (D). Plotted values are means ± SE (n=3).

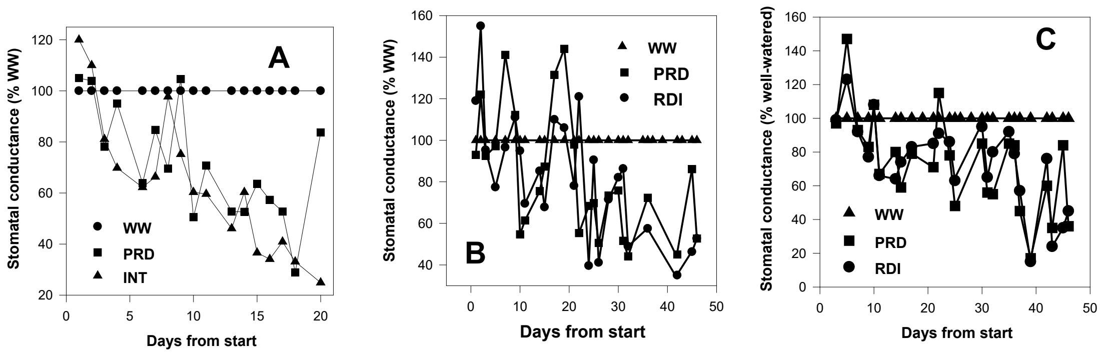


Figure 2.3. Effect of controlled irrigation on stomatal conductance (expressed as a % WW) in *Forsythia* (A), *Hydrangea* (B) and *Cotinus* (C). Plotted values are means (n=3).

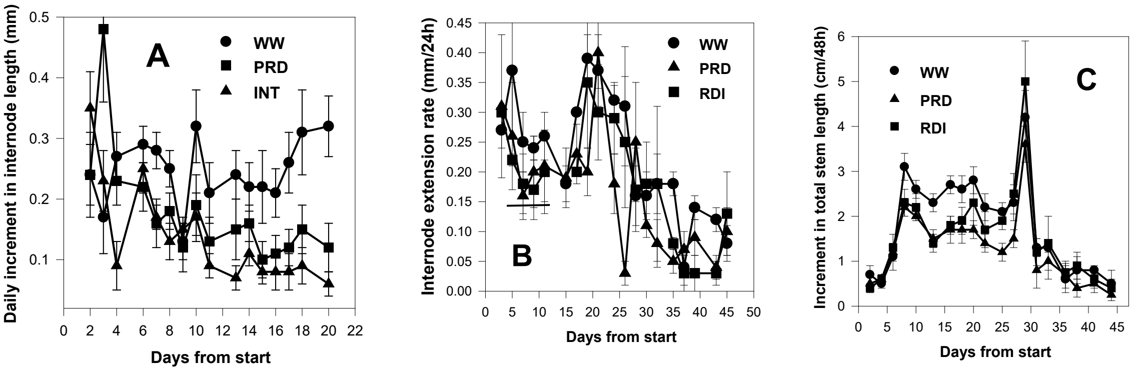


Figure 2.4 Effect of controlled irrigation on mean daily/48hrly internode/shoot extension rate in *Forsythia* (A), *Hydrangea* (B) and *Cotinus* (C). Plotted values are means ± SE (n=3).

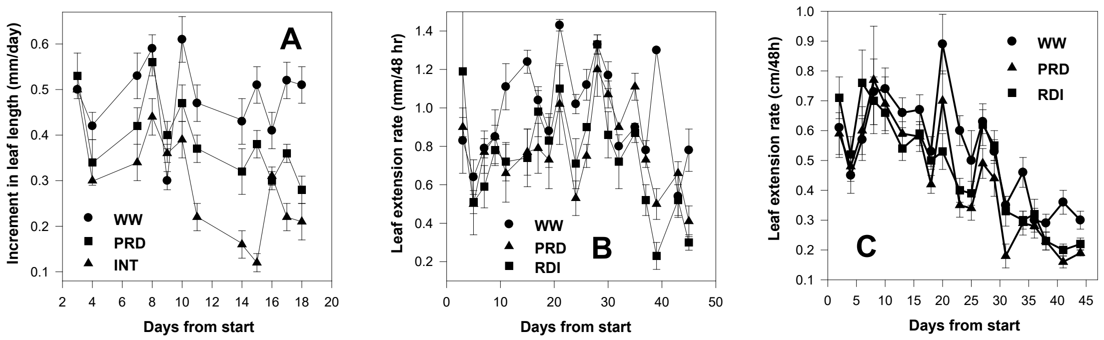


Figure 2.5 Effect of controlled irrigation on mean daily/48hrly increment in leaf length in *Forsythia* (A, leaves in the range 5-8cm long), *Hydrangea* (B, leaves in the range 8-12cm long) and *Cotinus* (C, leaves in the range 4-6cm long). Plotted values are means ± SE (n=3).

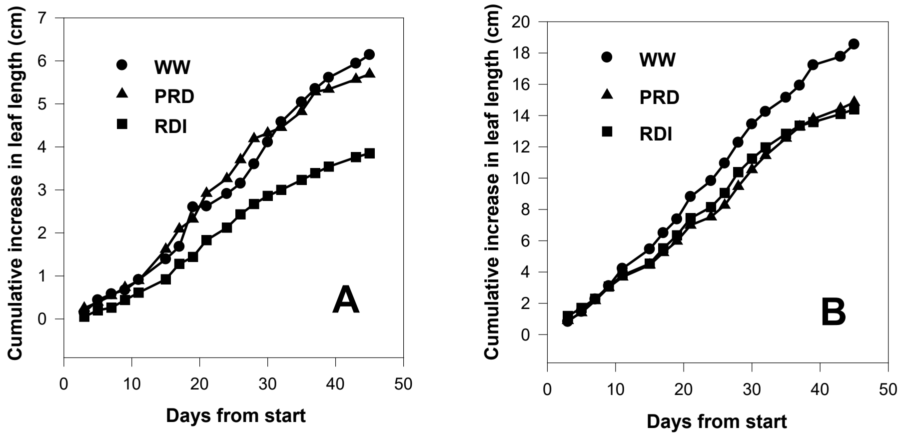


Figure 2.6 Effect of controlled irrigation on mean cumulative increase in leaf length in *Hydrangea* (A, leaves >12 cm long; B, leaves 8 -12 cm long). Plotted values are means (n=3).

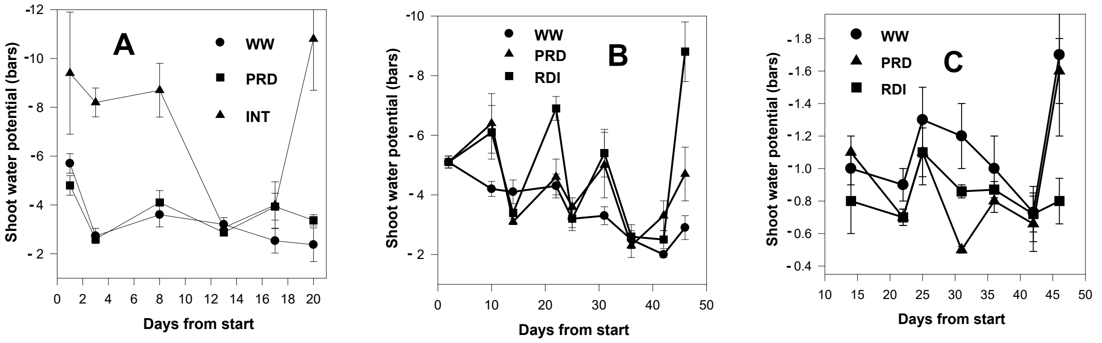


Fig 2.7 Effect of controlled irrigation on shoot water potential in *Forsythia* (A), *Hydrangea* (B) and *Cotinus* (C). Plotted values are means ±

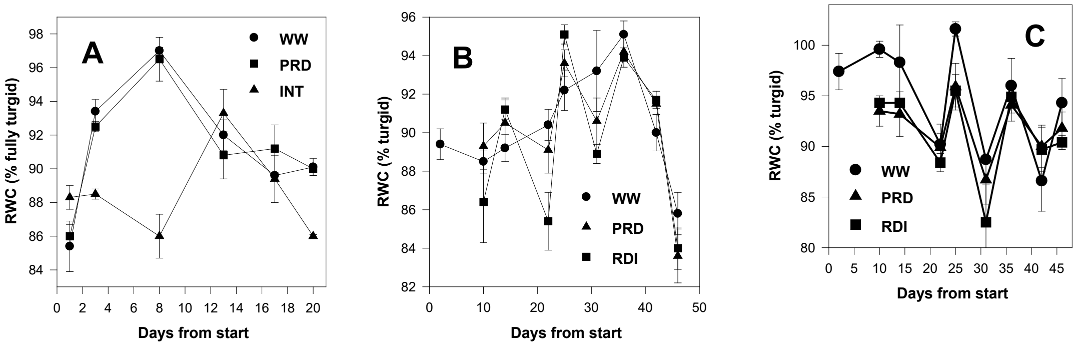


Figure 2.8 Effect of controlled irrigation on leaf relative water content (RWC) in *Forsythia* (A), *Hydrangea* (B) and *Cotinus* (C). Plotted values are means ± SE (n=3).

Main conclusions

- PRD was achieved successfully without an impermeable barrier to separate the wet and dry halves of the pot.
- PRD can reduce growth and water use while plants receive enough water to maintain shoot water status at the same level as in well watered controls. This was demonstrated most clearly in *Forsythia*; but there was evidence that it applies also in *Hydrangea.*
- Reduction of stomatal conductance and growth in the absence of any decrease in shoot water potential is good evidence for the operation of root-generated chemical signals in response to soil drying.
- All types of controlled deficit (PRD, INT and RDI) reduced growth and stomatal conductance and therefore have potential as practical means of regulating growth and saving water. However, under some circumstances, use of PRD may have advantages over the other techniques as maintenance of shoot water status improves some aspects of plant quality (e.g. leaf size).

Examination of the chemical signals generated as soil dries and in response to the aerial environment: do chemical signals determine effects of soil drying and evaporative demand on shoot physiology?

The aim of the research described in this section was to elucidate the chemical signalling systems operating in HNS species to control growth and stomatal conductance. ABA has been implicated as a putative root signal (Zhang and Davies, 1990), as have alterations in xylem sap pH (Wilkinson et al 1998, Stoll et al. 2001). Unexpected results led us to broaden the scope of the study to include local signalling systems within the leaf, which appear to be sensitive to specific components of the aerial environment, in addition to root generated signals.

Changes in ABA concentrations in xylem sap and leaf tissue, in the pH of the xylem and apoplastic sap, and in the generation of ethylene in the leaves were monitored as the soil dried in Experiments 1, 2, and 3. Correlation and regression techniques were used to search for links between chemical signals and physiological effects in response to rhizospheric or aerial cues. The hypothesis that ABA and pH act as chemical signals was tested by feeding/spraying detached shoots and intact plants of *Forsythia* with known concentrations of pure ABA and with buffer solutions at a range of pH.

Abscisic acid (ABA)

Data from Experiments 2.1 and 2.2 showed that the concentration of ABA in leaf samples (abbreviated to 'bulk leaf [ABA]') tended to be higher in plants under deficit irrigation than in well watered controls (Figure 2.9). Under PRD, [ABA] in *Forsythia* leaves was significantly greater than control on days 3, 13 and 20, and under INT it was significantly higher on all dates compared to WW plants (Figure 2.9A). In *Hydrangea*, bulk leaf [ABA] was significantly greater than control in both water deficit treatments (RDI and PRD) on most days (Figure 2.9B).

Xylem sap [ABA] tended to be higher than that in WW plants as soil gradually dried around SD plants (Figure 2.10A – *Forsythia* Experiment 2.3), or under RDI and PRD (Fig. 2.10 B – *Hydrangea* Experiment 2.2), and on many occasions the difference was significant.

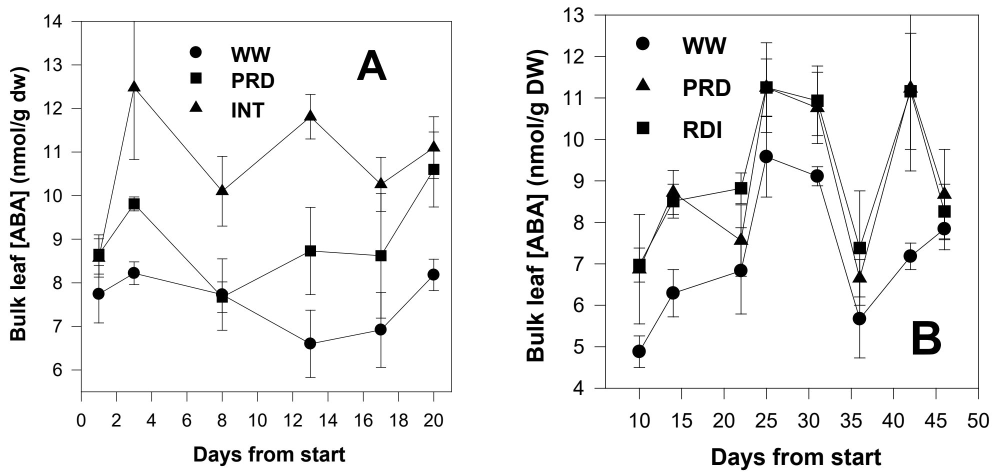


Figure 2.9 Effect of controlled irrigation on bulk leaf [ABA] in *Forsythia* (A) and *Hydrangea* (B). Plotted values are means ± SE (n=3).

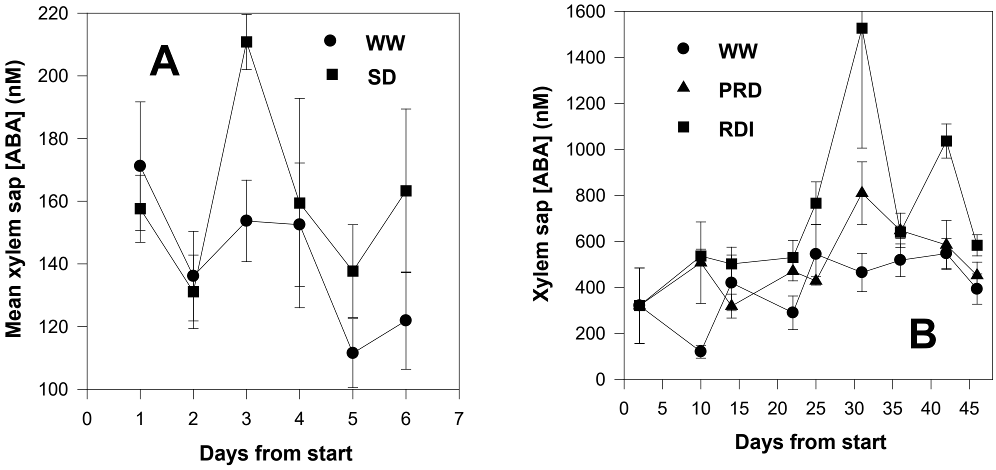


Figure 2.10 Effect of progressive soil drying (SD) and controlled irrigation (PRD and RDI) on xylem sap [ABA] in *Forsythia* (A) and *Hydrangea* (B). Plotted values are means ± SE (n=3).

Ethylene

Ethylene production by *Forsythia* leaves was unaffected by the deficit irrigation treatments implemented in Experiment 2.1, even though on some occasions the soil only contained 25% of the WW moisture (data not shown). For this reason ethylene was no longer considered to be a realistic candidate for the chemical signal(s) sent from roots exposed to drying soil in this species, and was left untested in *Hydrangea* and *Cotinus*.

Sap pH

In *Forsythia* the pH of xylem sap exuded from shoots at an over-pressure of 2-4 bars (initial pH) ranged from 6.3-6.7 in WW plants, down to pH 6.0 in PRD plants (day 20) and pH 5.8 in INT plants (day 13) (Figure 2.11A; Experiment 2.1). This indicates that soil drying acidified the xylem sap sent to the shoots of *Forsythia* plants exposed to drying soil. Acidification of xylem sap in response to soil drying is the opposite of what has been observed in many species although a similar response has been reported in *Ricinus* (Schurr and Schulze 1995). In herbaceous species, soil drying is normally associated with an increase in xylem sap pH (i.e. alkalisation) and, in several species, this change has been shown to be a real signal that can induce stomatal closure (Wilkinson et al., 1998) and reduce leaf growth rates (Bacon et al., 1998). High pH in the apoplast (i.e. sap in xylem and cell walls) causes ABA to accumulate in the sap to concentrations capable of closing stomata. A low pH in the apoplast prevents such accumulation and is associated with open stomata. It was therefore unexpected that xylem acidification and stomatal closure were simultaneously apparent as soil dried around *Forsythia* plants.

In *Hydrangea* and *Cotinus* there was no consistent effect of soil drying on xylem sap pH (Figure 2.11B and C; Experiment 2.2). In well-watered *Hydrangea,* xylem sap pH was very variable, ranging between 5.8 and 7.0. In well-watered *Cotinus,* xylem sap pH varied over a much narrower pH range (5.7-6.2).

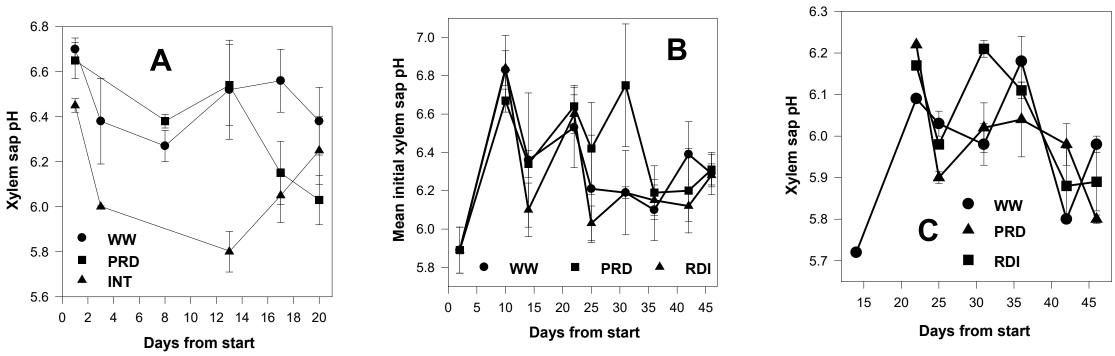


Figure 2.11 Effect of controlled irrigation on the pH of the initial aliquots of xylem sap expressed from shoots of *Forsythia* (A), *Hydrangea* (B) and *Cotinus* (C). Plotted values are means ± SE (n=3).

Correlations between signals and physiological responses to soil drying and evaporative demand

Correlation and regression methods provided additional insight into the nature and regulation of signals that influence stomatal conductance and shoot growth rate in *Forsythia*. When data from all three treatments in Experiment 2.1 are pooled, Figure 2.12 shows that the decrease in xylem sap pH in response to soil drying (see Figure 2.11A) was loosely correlated with reduced stomatal conductance and reduced leaf extension rate. Similarly, the increase in bulk leaf [ABA] in response to soil drying was loosely correlated with the reduced stomatal conductance and reduced leaf extension rate (Figure 2.13).

Data from Experiments 2.1 and 2.2 also showed that stomatal conductance and leaf growth tended to decrease as PPFD increased (a measure of light intensity). This negative correlation was evident for stomatal conductance in *Forsythia* and *Hydrangea* but not *Cotinus* (Figure 12.14 A, B and D) and for leaf extension rates in *Hydrangea* and *Cotinus* (Figure 12.14 C and E). High PPFD is generally associated with higher leaf and air temperatures and with lower atmospheric humidity, all of which contribute to evaporative demand and thereby tend to reduce leaf water potentials. However, g_s and leaf growth rate did not correlate well with shoot water potentials (data not shown), indeed high PPFD and low g_s were often associated with particularly high LWP. This suggests that effects on g_s and leaf growth of PPFD and/or associated elements of evaporative demand are partly mediated by chemical signals, as well as the water status of the shoot (i.e. the 'hydraulic signal') .

The pH of xylem sap increased with PPFD in *Forsythia* and *Hydrangea* (Figure 2.15), but no such relationship was detected in *Cotinus* (data not shown). As expected, therefore, as xylem sap pH increased, stomatal conductance tended to decrease (Figure 2.16 A). However, when plants experiencing drying soil were included in the analysis, the clear relationship between pH and conductance is lost (Figure 2.16 B). This was presumably because soil drying reduced xylem pH (see Figure 2.11 A) and this effect overrode the influence of PPFD and other components of evaporative demand on pH. Evaporative demand is likely to be perceived in the leaves and, in the intact plant, changes in pH would probably be restricted to sap within the leaf apoplast (i.e. xylem of leaf veins and the cell wall matrix). We expect that the xylem sap extracted by over-pressurising leaves in a

Scholander pressure chamber will be a mixture of sap that was in the stem and sap that was in the leaves at the moment of excision. Therefore, there is inevitably some "dampening" of signals generated in leaves by signals generated in the roots.

Bulk leaf [ABA] also increased with PPFD (Figure 2.17), as well as during soil drying (Figure 2.9 A). As described above increasing bulk leaf ABA is associated with closing stomata and slower leaf growth rates (Fig. 2.13).

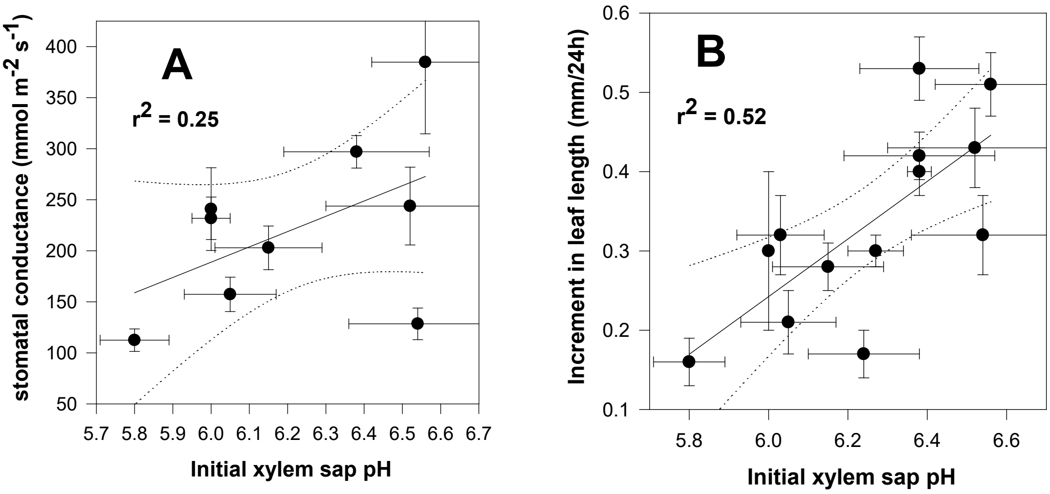


Figure 2.12 Correlations between mean stomatal conductance (A) and mean increment in leaf length/day (B), and the pH of the initial aliquot of xylem sap expressed from shoots of *Forsythia*. Plotted values are means ± SE of pooled data from WW, PRD and INT plants in Experiment 2.1 (n=9).

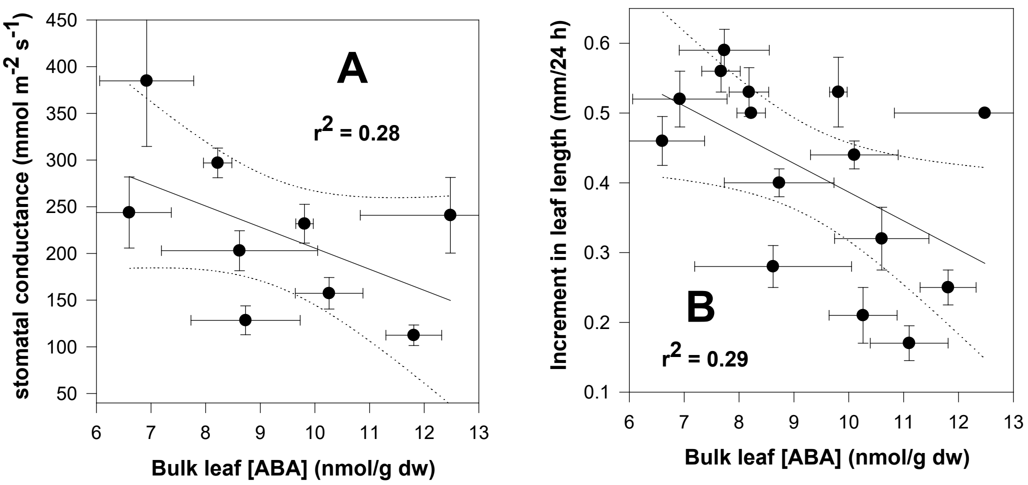


Figure 2.13 Correlations between stomatal conductance (A) and daily increase in leaf length (B), and the bulk leaf [ABA] from *Forsythia* plants in Experiment 2.1, with all 3 treatments pooled (WW, PRD, INT). Plotted values are means ± SE

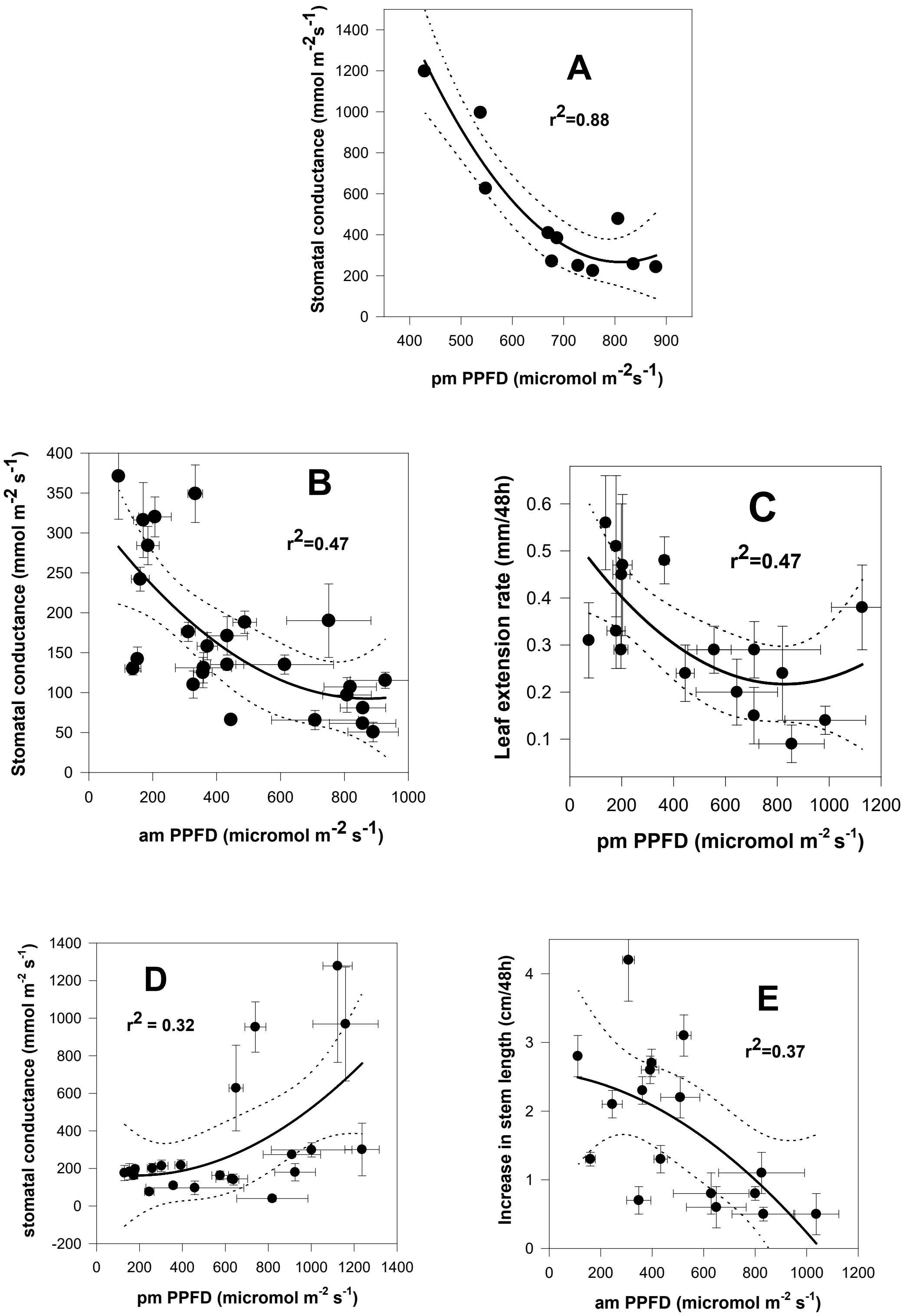


Figure 2.14 Correlations between PPFD and stomatal conductance in *Forsythia* (A, Experiment 2.1, pm, n=1) and between mean PPFD and stomatal conductance and leaf extension rate in *Hydrangea* (B and C, Experiment 2.2, am and pm respectively, leaf extension rates for leaves over 12cm long, n=3) and *Cotinus* (D and E, Experiment 2.2, pm and am respectively, n=3). Plotted values are means ± SE

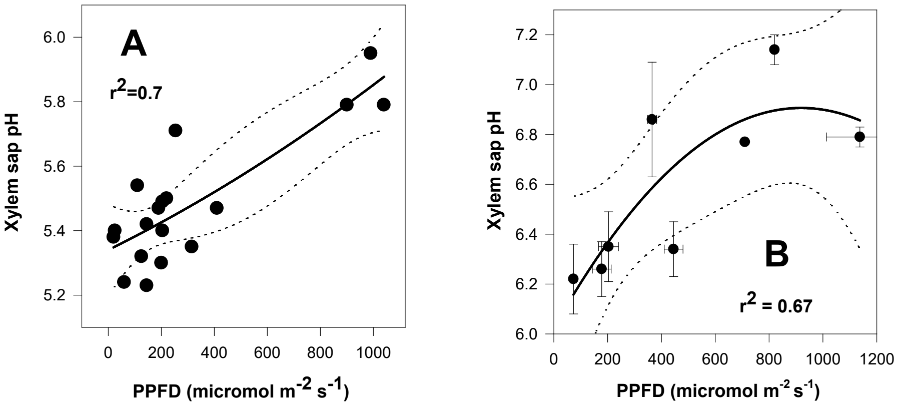


Figure 2.15 Correlations between ambient PPFD and xylem sap pH expressed from shoots of well-watered *Forsythia* (A, n=1 – Experiment 2.1, pH of initial aliquot) and *Hydrangea* (B, n=3 – Experiment 2.2, pH of final aliquot) plants.

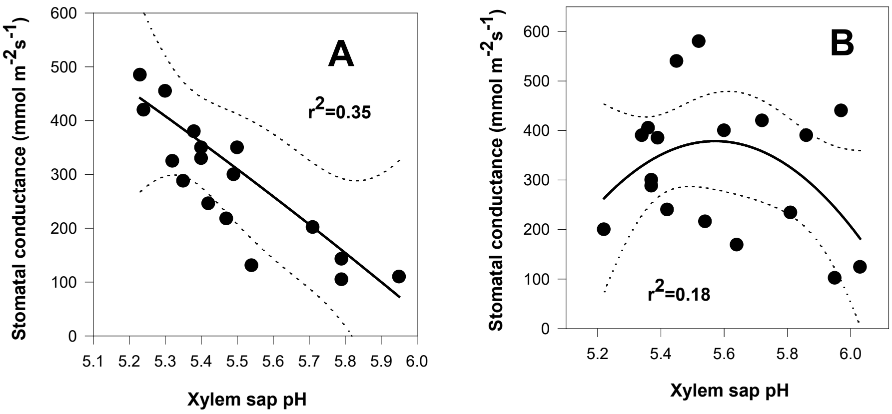


Figure 2.16 Correlation between xylem sap pH and stomatal conductance in *Forsythia* (Experiment 2.3) plants that were kept well-watered (A), or experienced soil drying (B).

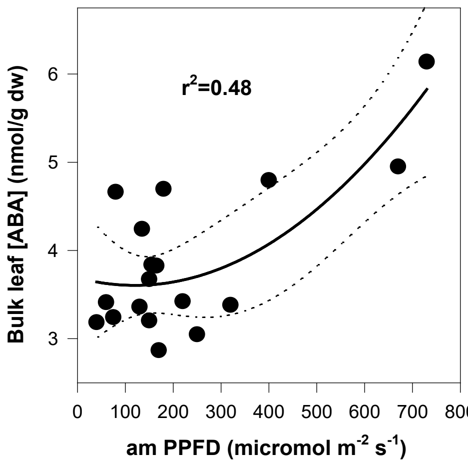


Figure 2.17 Correlation between ambient PPFD (am) and bulk leaf [ABA] (pm) in well-watered *Forsythia* plants (Experiment 2.3).

To summarise, both soil drying and increasing PPFD (or evaporative demand) reduced stomatal apertures (except in *Cotinus*) and reduced leaf growth rates. Both soil drying and increasing PPFD increased bulk leaf [ABA] (in the case of PPFD in *Forsythia* only), and this was not always associated with reduced shoot water potential. Therefore, it seems likely that ABA acts as a signal triggering some of the physiological changes caused by soil drying and PPFD.

Soil drying acidified xylem sap (i.e. reduced pH) in *Forsythia*, while PPFD was clearly associated with a strong alkalisation of the xylem sap (i.e. increased in pH) in both *Forsythia* and *Hydrangea*, yet both stimuli were associated with closing stomata. In the following section, we show that sap alkalisation has the potential to act as a signal mediating the effect of changes in the aerial environment on stomatal aperture. On the other hand, soil drying-induced acidification appears likely to be a non-signal side-effect, though more research is required to confirm this.

Responses to feeding leaves with the putative signals - ABA and pH

When ABA was fed directly into the transpiration stream of detached *Forsythia* leaves transpiration from the leaves decreased in a concentration dependent manner (Figure 2.18). The decrease in transpiration, indicative of reduced stomatal aperture, was greatest over the concentration range 10^{-7} to 10^{-5} M. This indicates a sensitivity of *Forsythia* stomata to ABA that is comparable to that which has been observed in unrelated species.

Similarly, ABA supplied by daily injection into the stems of intact *Forsythia* plants (Experiment 2.6) reduced stomatal conductance in a concentration dependent manner (Figure 2.19A) and also reduced leaf extension rates (Figure 2.19B). It is reasonable to assume that some of injected ABA will enter the xylem and mix with sap transported from the roots, but the resulting ABA concentration in the xylem sap entering the leaves is unpredictable. Given this uncertainty, the slightly lower sensitivity to injected ABA, compared with ABA fed to detached leaves, is not surprising.

Unlike stomata in *Commelina*, barley and tomato (see Wilkinson and Davies 2002), in *Forsythia*, the response to the pH of buffer solutions fed to detached leaves via the transpiration stream was inconsistent (Figure 2.20).

However, results with detached tissues are often different from those determined in whole plants. In an attempt to determine the effect of sap pH within the leaf apoplast of intact plants, pH buffers were sprayed onto the leaves of intact *Forsythia* plants (Experiment 6). To counteract the plants' own pH regulation mechanisms, including the arrival of sap from the roots in the transpiration stream, plants were sprayed every day. Under these circumstances, a buffer solution at the relatively high pH of 6.7, equivalent to sap from plants at high PPFD, reduced stomatal conductance (Figure 2.21). In contrast, there was no effect from a buffer at the relatively low pH of 5.3, equivalent to sap from plants in drying soil (Figure 2.21).

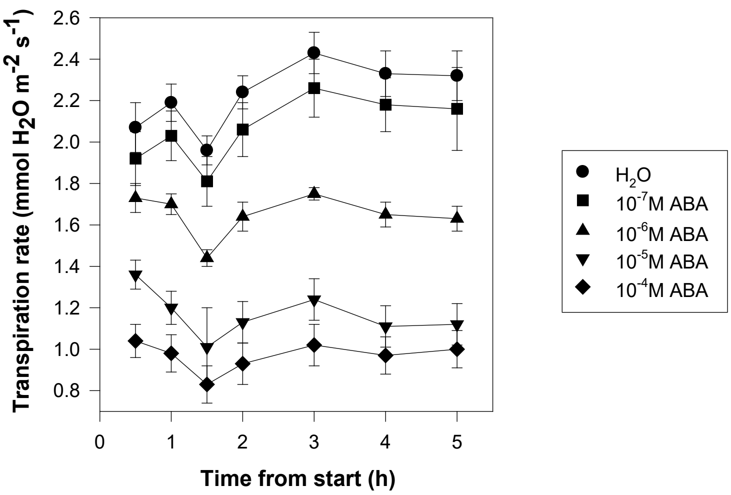


Figure 2.18 Effects of feeding ABA solutions to detached *Forsythia* leaves on the rate of transpirational water loss. Plotted values are means ± SE (n=5).

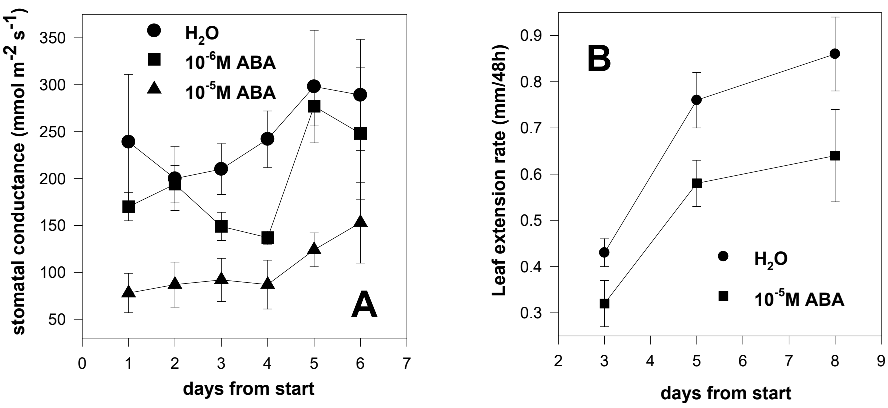


Figure 2.19 Effects of exogenous [ABA] supplied by injection into the stems of intact well-watered *Forsythia* plants, on stomatal conductance ~5 h after injection (A) and on leaf extension rate (B; leaves less than 5 cm long). Plotted values are means ± SE.

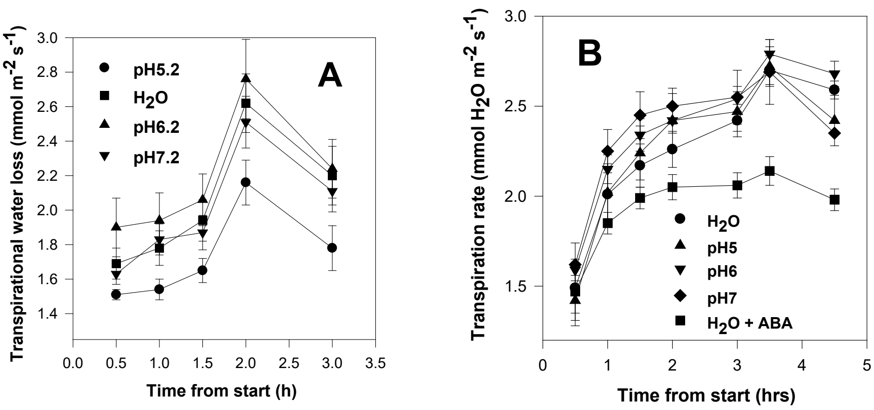


Figure 2.20 Effects of the pH of buffer solutions fed to detached *Forsythia* leaves (B; which includes $5x10^{-7}$M ABA for comparison), on the rate of transpirational water loss. Plotted values are means ± SE (n=6).

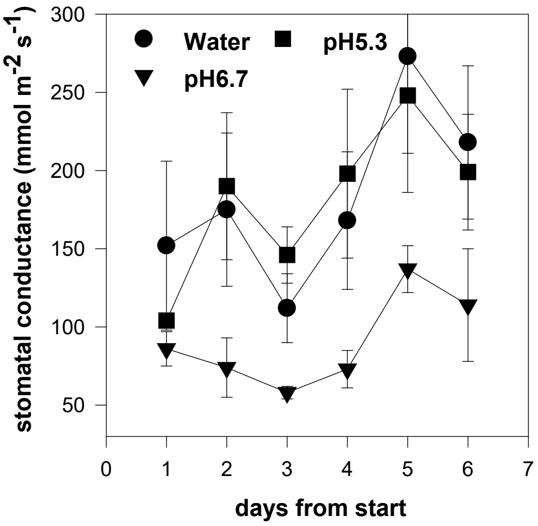


Figure 2.21 Effects of the pH of buffer solutions sprayed onto the foliage of intact well-watered *Forsythia* plants (daily, at 0900 h), on the stomatal conductance measured 5-7 hours after spraying. Plotted values are means ± SE (n=3).

Main conclusions

- In *Forsythia*, reductions in g_s and leaf growth generated by soil water deficit were associated with higher concentrations of ABA in the xylem sap and a more acid pH (Cameron et al., in press), even when shoot water status was maintained (under PRD).
- In other species the results were less clear: in *Hydrangea* there was no significant effect of soil drying on sap pH but there was a small increase in ABA concentration; in *Cotinus*, it proved impossible to obtain reliable ABA data due to interfering substances in the plant and there was no effect on pH.
- Results of feeding experiments were consistent with ABA acting as a chemical signal inducing reductions in g_s and growth.
- The change in pH in *Forsythia* in response to drying soil was in the opposite direction to that seen in most other plants (i.e. more acid rather than more alkaline), and it was concluded that the pH change did not act as a root to shoot signal of soil drying in this species.
- Measurements in *Forsythia* and *Hydrangea* showed that g_s tended to decrease when evaporative demand was high (high light, low humidity, etc.) and, in well-watered plants, this was correlated with a rise in sap pH (i.e. more alkaline) as well as a rise in ABA concentration in the leaves. This suggests that, in these species, sap pH is involved in the control of stomata within individual leaves rather than as a long distance signal of soil drying.
- The observation that the aerial environment can influence stomata and growing cells via changes in sap pH is entirely new, potentially very important to the scientific community, and has been published in Wilkinson and Davies (2002) and Davies et al (2002).
- Stomatal responses to spraying *Forsythia* leaves on intact plants with pH buffer solutions were consistent with a role for pH as a local signal with an important influence on g_s. This is a completely novel observation and could have far reaching implications, both scientific and practical.

Manipulation of chemical signals for practical benefits.

It would be advantageous to be able manipulate plant water use efficiency and growth without having to implement techniques such as RDI and PRD, which depend on precise control of the amount of irrigation and/or its point of application. Application of RDI generally involves some reduction of plant water status, as well as substantial depletion of available soil moisture, which reduce the safety margins protecting crops from damage by desiccation stress (e.g. leaf scorch). With PRD, it may be possible to maintain favourable plant water status, but the safety margin of soil water reserves is still small, and the technique could be expensive to implement.

In this section we report the results of attempts to exploit the signals produced by the plants in response to drought (drying soil and/or high evaporative demand) without exposing plants to water deficit. Specifically, we aimed to alter the abscisic acid concentration and the pH of xylem sap in intact *Forsythia* and *Hydrangea* plants growing in moist soil, and thereby, to reduce growth and water loss independently of the environment.

Two approaches were tested. Firstly, we applied specific mineral nutrient supplements to the medium, that have been reported to affect xylem sap pH in sunflower (Mengel et al.1994) and leaf and/or xylem [ABA] in castor bean (Peuke et al. 1994). On the basis of these publications, potassium bicarbonate was intended to increase xylem sap pH and ammonium chloride to reduce xylem sap pH, or to increase its ABA concentration. Both these nutrient supplements were added to the irrigation water. Secondly, we attempted to mimic the effect of high evaporative demand from the aerial environment on stomatal aperture and leaf growth rates, by spraying the foliage of intact well-watered *Forsythia* plants with pH buffer solutions, with the expectation that the most alkaline pH would close stomata and reduce growth.

Nutrient applications to the soil.

Ammonium chloride (chemical 'A') alone, or mixed with potassium bicarbonate (chemical 'B'), reduced stomatal conductance of well-watered plants compared to controls given water only (Figure 2.22).

Ammonium chloride reduced leaf and internode lengths, potassium bicarbonate reduced internode and total shoot length, while a mixture of the two increased both leaf and shoot length dramatically (Figure 2.23). It seems likely that, had the experiment continued for longer, the reduction in internode length with ammonium chloride application would have been reflected in total shoot length.

These effects are largely consistent with the expectations from the literature, except that potassium bicarbonate failed to cause stomatal closure. Also unexpected was the increase in growth caused by a mixture of the two nutrients.

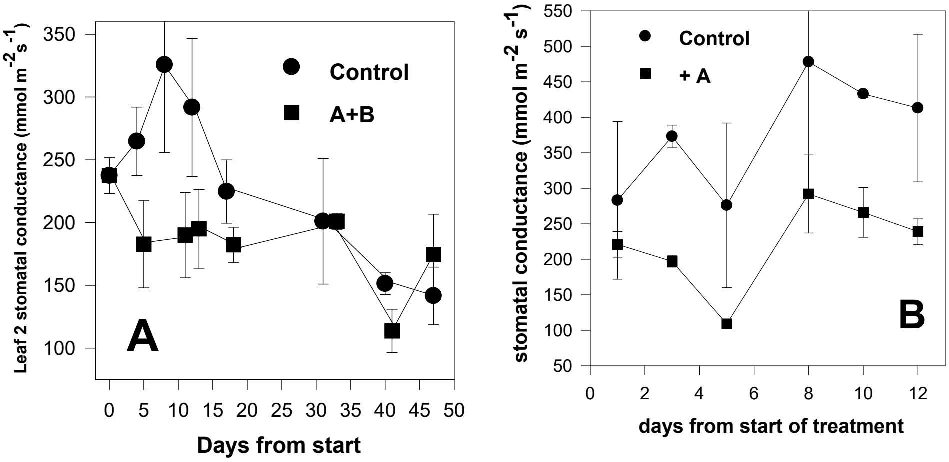


Figure 2.22 Effect of nutrient supplements (A=ammonium chloride; B= potassium bicarbonate) on stomatal conductance in well-watered *Forsythia* plants. Plotted values are means ± SE (n=3) from experiments 4 (graph A) and 5 (graph B).

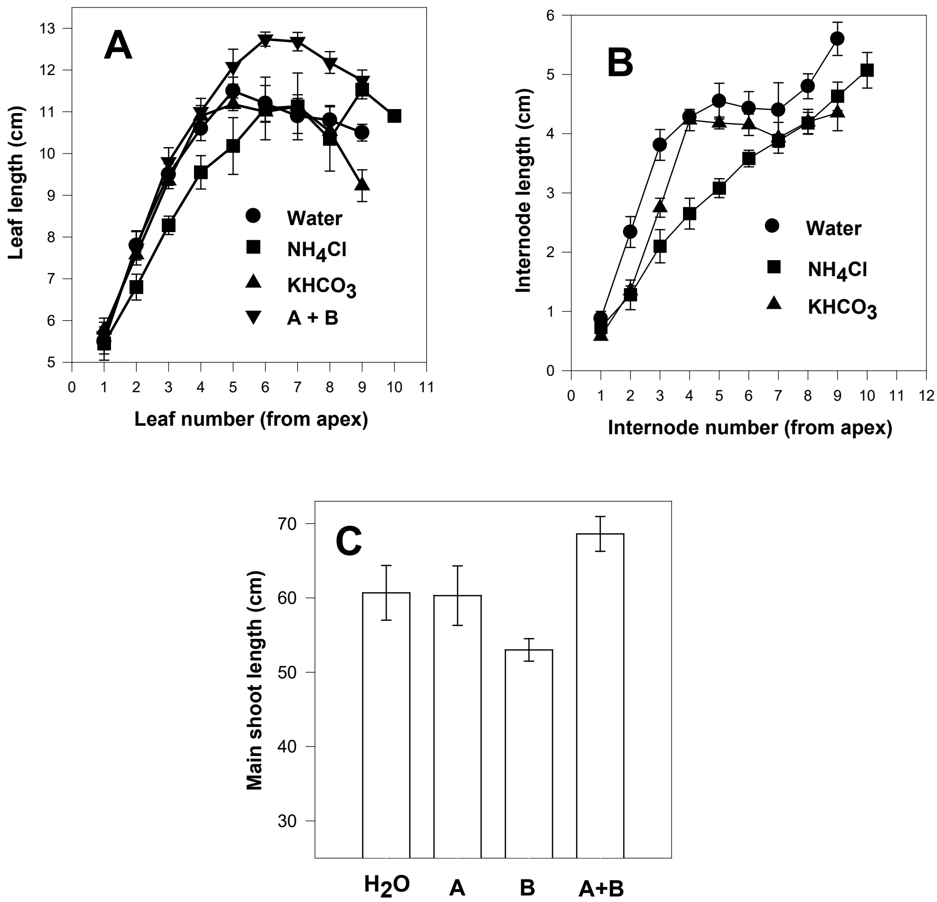


Figure 2.23 Effect of nutrient supplements (A=ammonium chloride; B= potassium bicarbonate) on leaf, internode and total shoot length in well watered *Forsythia* plants. Treatments were applied for 7 weeks before data were collected (Experiment 2.4). Plotted values are means ± SE (n=3).

Table 2.1 Effects of nutrient supplements interacting with soil drying in *Forsythia* plants irrigated (Experiment 2.4). A = ammonium chloride, B = potassium bicarbonate. Tabulated values are means ± SE (n varied from 4 to 13).

Nutrient supplement	**Soil moisture content**		
	Wet (SMC > 45 %)	**Intermediate** (SMC 25 - 45 %)	**Dry** (SMC < 25 %)
Stomatal conductance (g_s, mmol m^{-2} s^{-1})			
Control	504.1 ± 96.3	310.7 ± 43.6	263.5 ± 38.2
A+B	338.4 ± 49.2	280.5 ± 24.3	301.4 ± 41.8
A	-	348.1 ± 46.4	266.8 ± 29.4
B	-	225 ± 30.4	267 ± 37
Xylem sap pH			
Control	5.74 ± 0.14	5.31 ± 0.06	5.52 ± 0.06
A+B	5.66 ± 0.04	5.51 ± 0.07	5.33 ± 0.02
A	-	5.24 ± 0.02	5.67 ± 0.13
B	-	5.57 ± 0.07)	5.49 ± 0.10
Xylem sap ABA concentration, nM			
Control	334.6 ± 35.9	329.3 ± 74.3	431.4 ± 64.9
A+B	215.0 ± 18.8	326.9 ± 22.2	325.4 ± 31
A	-	265.9 ± 27.1	447.7 ± 50.9
B	-	280.5 ± 44.2	442.5 ± 55.3
Bulk leaf ABA concentration, μg (g DW)$^{-1}$			
Control	2.38 ± 0.13	1.97 ± 0.18	2.48 ± 0.11
A+B	2.10 ± 0.24	2.77 ± 0.24	2.64 ± 0.22
A	-	2.92 ± 0.23	2.03 ± 0.13
B	-	2.55 ± 0.25	2.78 ± 0.35
Shoot water potential, bar			
Control	-5.67 ± 0.45	-5.64 ± 0.33	-7.72 ± 0.68
A+B	-6.90 ± 0.46	-7.64 ± 0.34	-8.8 ± 0.31
A	-	-5.74 ± 0.46	-7.7 ± 0.79
B	-	-7.05 ± 0.58	-8.09 ± 0.45

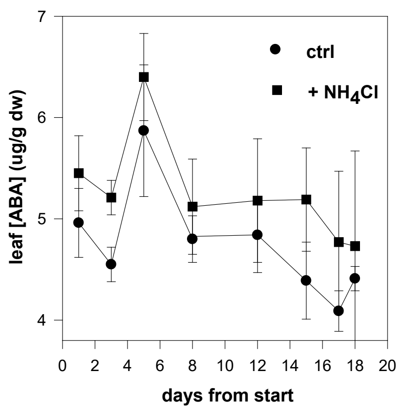


Figure 2.24 Effect of 5mM ammonium chloride supplied to the soil with the irrigation medium at well-watered rates, on the mean [ABA] measured in leaves of *Forsythia* plants, compared to controls supplied with water only (n=3, Experiment 2.5).

We measured changes in xylem sap pH and plant [ABA] induced by the nutrient treatments to determine whether these signals were mediating their physiological effects in the way that was predicted. As expected, ammonium chloride increased the [ABA] in *Forsythia* leaves of well-watered plants but not in the xylem sap (Experiment 2.5, Figure 2.24). The same was true in plants growing at intermediate soil moisture content in Experiment 2.4, which also confirmed that it did not affect shoot water potential, and that it did not reduce xylem sap pH as had been predicted from the literature (Table 2.1).

Potassium bicarbonate increased xylem sap pH as predicted (Experiment 2.4, Table 2.1) and had no effect on ABA concentrations in bulk leaf samples or xylem sap. Unexpectedly, it reduced shoot water potential. The pH change was not replicated in Experiment 2.5, possibly due to the lower concentration of nutrient salts applied.

A combination of both A and B unexpectedly and dramatically reduced xylem sap ABA concentrations in well-watered and drying plants (Table 2.1) This treatment also reduced shoot water potential.

These analytical data suggest that ammonium chloride alone reduced g_s and growth by stimulating ABA accumulation in leaves of well-watered plants, while potassium bicarbonate reduced internode and total shoot lengths by increasing xylem sap pH and, unexpectedly, by reducing shoot water potential. When mixed together these two nutrients appear to have interacted in an interesting way, with the result that ABA concentration in well watered plants was reduced. The reduction in concentration of this powerful growth inhibitor may explain the growth promotion observed with the mixed nutrient treatment.

The low shoot water potential seen in potassium bicarbonate treated plants, whether applied alone or in the mixture (Table 2.1), may have contributed to the reduction of g_s in well-watered plants treated with this nutrient. The low water potentials may in turn be a consequence of reduced ABA concentration in these plants. ABA is known to promote the uptake of soil water by roots and the retention of water in plant cells, via affects on cell membrane permeability, thereby favouring relatively high shoot water potentials.

Effects of foliar sprays.
Forsythia plants were sprayed daily with buffers adjusted to a range of pH values. We showed earlier (Figure 2.21) that the most alkaline buffer (pH 6.7, equivalent to sap from plants at high PPFD) resulted in the lowest g_s values and data in Figure 2.25 show the same treatment also significantly reduced leaf extension rate. This treatment had no effect on shoot water relations, xylem [ABA] or bulk leaf [ABA] (data not shown). It is assumed that alkaline pH (associated with high evaporative demand – see above) affects stomata and growing cells by causing the endogenous ABA entering the leaf with the xylem to remain in the apoplast and accumulate there to a high enough concentration to affect physiology (see Wilkinson and Davies, 2002). This ABA redistribution can be effective without increasing bulk leaf ABA concentrations. Under more acidic conditions (associated with lower evaporative demand) the ABA entering the leaf is normally removed from the apoplast by the cells of the leaf so that it cannot accumulate in the apoplast and exert an effect on shoot physiology.

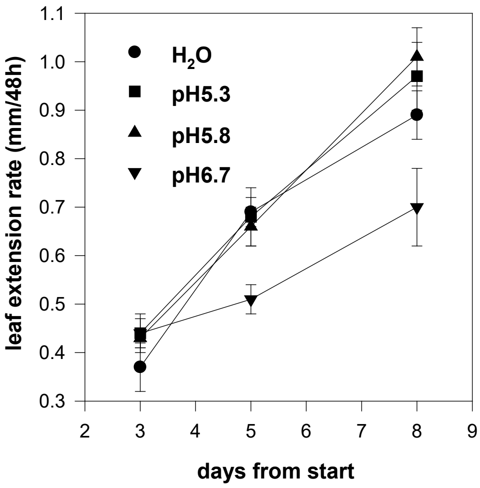


Figure 2.25 Effects of the pH of buffer solutions sprayed onto the foliage of intact well-watered *Forsythia* plants (daily, at 0900 h), on leaf extension rate. Plotted values are means ± SE (n=3).

Main conclusions

- Spraying intact well watered *Forsythia* with a buffer solution at pH 6.7 (i.e. relatively alkaline), substantially reduced g_s and leaf extension rate. This simple and inexpensive technique has the potential to reduce water use and control growth of HONS without any danger, inherent in deficit irrigation techniques, of damaging the plants from accidentally over-stressing them.
- The pH and ABA concentration of the sap moving from the roots to the shoots can be influenced by the nutrient balance of the soil solution. Ammonium chloride was expected to reduce pH and increase [ABA], and potassium bicarbonate to increase pH. When either of these compounds was added to the irrigation water of well-watered plants it reduced growth of *Forsythia.* However, only with ammonium chloride was this accompanied by reduced g_s (and would therefore be expected to reduce plant water use).
- Ammonium chloride addition to irrigation water may therefore have practical potential as a means of reducing excessively vigorous growth and conserving water without the difficulty of precisely regulating water deficit.
- A mixture of both nutrients increased growth of well-watered plants while reducing shoot water potential and g_s. This was a result of reduced xylem sap ABA concentrations.
- This work has opened up exciting and novel possibilities based on relatively short-term laboratory scale experiments. Further work is required to develop both nutrient addition and foliar pH spraying into robust practical techniques.

Unit 3: Evaluation of instruments for estimating the irrigation needs of container-grown HONS (Objective 4)

This Unit covers work towards the following scientific objective:

4. Develop a performance specification, and evaluate existing and novel equipment to determine the most appropriate technique for estimating irrigation requirements of container-grown plants.

Background

Plants grown in containers have limited water storage; when water losses exceed input from rainfall, some form of artificial irrigation is required to ensure their survival. In the UK, by far the most commonly used method of irrigation is overhead sprinkler. Whilst it is not the most efficient way to apply water, it is cheap to install and adaptable. There are large differences in spray uniformity and selection of the most suitable product can be something of a lottery. Few users calibrate their irrigation systems, so most are unaware of the variability across the beds. The total volume of water applied per unit area is determined by the duration of application. Times are normally controlled separately for each bed by some form of irrigation control panel, either analogue or digital. Uniformity of irrigation is discussed further in Units 4 and 5.

Drip irrigation achieves much higher efficiency of water application than overhead spray, but is normally only used in the UK for large, well-spaced pots.

The structure of the bed on which the containers rest can have a profound effect on water supply to the crop. Opinions differ as to the best type of standing base, and the choice depends largely on local conditions, such as the slope and natural drainage characteristics of the site. Containers are normally separated from the underlying substrate by a layer of gravel or sand to prevent contamination, to aid disinfection between changes of stock and to prevent water-logging. In addition, it is now common practice to cover the bed with a water permeable synthetic textile membrane such as Mypex to improve hygiene and reduce maintenance. If there is an impermeable polythene membrane underneath the beds, opportunities for collecting and recycling water are increased. When sand beds are used, a 'water table' can be maintained in the sand as a means of applying capillary irrigation, as in the well documented ‘Efford sand-beds’. Although this has been shown to be a very efficient and controllable irrigation system, it is not widely used, primarily because of its high installation costs.

For maximum industry relevance in the experiments at HRI Efford, it was decided to use an overhead spray irrigation system, coupled to a digital timer control. Existing sand beds were initially covered with a double layer of Mypex but, in the final year, the Mypex was removed for a comparison with a standing base of gravel.

There are three main factors that determine the rate of water loss from plants:

- the atmospheric demand
- the area of leaf exposed (the size of the plant)

- the control that plants can exert on the rate that water is being lost from their leaves through the stomata

Atmospheric demand

The atmospheric demand is the "power" of the atmosphere to remove water from a water surface (evaporation), or a leaf (*transpiration*). It depends on 4 main factors:

- Solar radiation (brighter sunshine → more evaporation)
- Temperature (higher temperature → more evaporation)
  The leaf stomata open more as temperature rises, allowing more evaporation. Temperature also changes the ability of the air to hold water, the humidity.
- Air humidity (lower air humidity = greater drying power → more evaporation)
- Wind speed (more wind → more evaporation)

There is a further factor, related to windspeed, which also affects the efficiency of water vapour transport away from e.g. a field or a nursery bed. This is its aerodynamic 'roughness' which creates turbulence in the air. Airflow over taller vegetation, with plants of varying heights, will be more turbulent and better able to carry away water vapour than over a field of smooth short grass.

These factors interact with each other. Clearly, temperature is linked to solar radiation, and both temperature and wind influence humidity. In a nursery environment, all of these factors can be controlled to some extent, allowing some limited reduction in "atmospheric demand" to be imposed. Wind speed can be reduced with windbreaks of trees, or netting, or greenhouses. Solar radiation and temperature can also be reduced by windbreaks and by screening overhead. Many greenhouses are now equipped with such screening, often with automatic controls. Greenhouse humidity and temperature can also be altered, for example through irrigation, or by adjusting the ventilation.

Leaf area

The amount of water lost by a plant depends on its size, because this determines how much solar radiation it can absorb. Bigger plants generally have more leaves and can absorb more radiation, hence they need more water. In a nursery bed situation, the density of plants, is also important: if the same sized plants are "pot thick" the bed will *transpire* more water than if the same plants are spaced. (The critical factor is in fact the area of leaves per unit of ground area, also known as the *leaf area index*).

The size of the plant also affects its ability to obtain water - bigger plants generally have bigger root systems. In the open ground this means that they have access to a greater volume of soil and water. However, in container grown stock, where the rooting volume is limited and fixed, the bigger plants have access to a proportionally smaller stock of water than small plants in the same size containers.

Plant controls

The third main factor determining the rate of water loss from plants is their ability to control the opening of their stomata. They can reduce the rate of water loss by closing their stomata. They can also do this by rolling their leaves, or by shedding them, and may use a combination of strategies in sequence as their ability to take up water decreases. Some plants are well adapted to minimising water loss, with hairy or waxy leaves. The amount of stomatal control that takes place depends on the environmental conditions, for example solar radiation intensity, humidity or soil water availability in the soil. It also depends on the species and its provenance (genetic adaptations, depending on the environment in which it evolved).

Potential versus actual evaporation

In general, when plants are well supplied with water, their water use is mainly determined by the *atmospheric demand*. If there is also enough leaf area to intercept all of the solar radiation, then the crop (or bed of plants) will transpire at the *potential evaporation rate*, i.e. at the rate determined by the *atmospheric demand*.

If the *potential evaporation* can be measured or estimated, this provides a very important figure from which to determine the required amounts of irrigation to apply. However, to accurately determine the irrigation requirements (the amount of water required to replenish that which has been used), the *actual evaporation rate* needs to be known.

The *actual evaporation rate* may be less than the *potential evaporation rate* for two main reasons:

- when the plants are small, they do not intercept all of the solar radiation (do not fully cover the ground).
- when there is insufficient water available in the soil/growing medium. This means that the rate that the plants are able to take up water through their roots is less than the rate at which the atmosphere is demanding it. This leads to *water stress*.

Irrigation methods based on the measurement of *potential evaporation* must take these factors into account.

Existing technologies for regulating irrigation

There are various means to determine when and/or how much to irrigate, which involve measurements of:

- the atmosphere
- the plant
- the growing medium

A review of existing sensors and control equipment and a search for relevant patents provided a basis for selecting the types of equipment to focus on in this project. The full results of that search are in Appendix 3 and are reflected in the following review.

Measurements in the atmosphere

All of the following methods provide a constantly available supply of water for evaporation and subsequently provide a measure of *potential evaporation* as described earlier. This may not equate to the *actual evaporation* of the plant canopy, so additional factors such as leaf area index and soil water availability may have to be accounted for as controlling factors. Generally, a single measure of evaporation should be adequate for a whole nursery, with the above adjustments made according to the conditions of each bed.

The most commonly used instrument for manual measurement of potential evaporation is the evaporation pan. This comprises a shallow, galvanised steel pan about 1 metre in diameter which should ideally be set at ground level. Water level is read daily to the nearest 0.02mm by means of a micrometer screw which allows both daily open water evaporation and rainfall excess over evaporation to be measured. The water loss from a tank of water is clearly not exactly the same as that from a plant, but pans can provide a very useful indication of transpiration losses. The advantage of pans is that they are relatively cheap, and can be placed in "typical" nursery situations in terms of exposure.

Automatic weather stations (AWS) are now widely available and measure the individual components for the calculation of Penman potential evaporation:

- solar radiation
- air temperature
- air humidity
- wind speed

They are many different manufacturers, but all are relatively expensive, starting at about £2k. Sensor readings are stored on a data logger, generally as hourly averages and are subsequently processed via laptop or personal computer to derive daily totals of potential evaporation, normally according to the Penman formula. This assumes that evaporation is occurring from a uniform, short green grass surface with a constant supply of water.

Over the last 3 years, this project has evaluated a much simpler and cheaper instrument for deriving a daily evaporative index. The instrument was conceived at HRI East Malling (Harrison-Murray, 1991), initially developed for control of fog and mist for propagation of leafy cuttings and later for its potential in irrigation control (Harrison-Murray, 1995). It was subsequently modified and manufactured as a commercial product by Skye Instruments Ltd. as the 'Evaposensor' and 'Helios EvapoMeter' at a combined price of around £500 (Figure 4.4). The Evaposensor has two temperature sensors set in two small, black plates that are fully exposed to the atmosphere and solar radiation in an attempt to simulate leaf surfaces. One 'leaf' is kept wet by covering in a black wick, whilst the other remains dry. The temperature difference between the two 'leaves' is measured and degree hours of temperature difference are calculated by the EvapoMeter and accumulated in memory.

A daily Penman-based reference crop evaporation (Et_{ref}) was calculated using the automatic weather station sensors as an indicator of the evaporative demand of the atmosphere on the crop. Figure 3.2 compares Et_{ref} with the daily cumulative temperature difference between the wet and dry plates of the Evaposensor

Measurements on/in the plant

The simplest measure is that of plant geometry based on the fact that leaves tend to droop at the onset of water stress as a result of loss of turgor within the cell walls. Various methods have been used to measure this change in leaf angle, but none are really appropriate for the production of commercial stock, as there is a requirement to irrigate before the onset of wilting to preserve the vigour of the plant.

Remote sensing of plant canopies to monitor changes in leaf surface temperature, reflectance and fluorescence have been shown in some cases to be sensitive to changes in leaf water content, but have not yet been successfully calibrated to operate over extended periods and with different varieties.

Other methods, which are scientifically attractive but are not currently appropriate for commercial application include sap flow measurement and leaf porometry. The former enables the rate of water transport from roots to leaves to be calculated, whilst the latter measures the rate of vapour loss at the leaf itself.

Measurements in the growing medium

The growing medium provides a store of water for the plants to draw on for their requirements. The amount of water that can be stored depends on the type of growing medium used and the size of container. A container of growing medium can be *saturated* by immersing it in a bucket of water, so that all of the spaces (pores) in the medium become water-filled. If it is then removed and stood on a flat surface, some of the water will drain out, and some will be retained. When the drainage stops, the container is said to be at *container capacity*. If more water is added (e.g. by sprinkler irrigation), it will simply drain away until *container capacity* is reached again, and the water added will have been wasted. Both *saturation* and c*ontainer capacity* depend on the properties of the growing medium and are usually expressed in terms of a *water content*, or *moisture content*. This is the weight of water per unit volume of growing medium, usually expressed as gm/cm^3. *Container capacity* – as its name suggests, also depends on the size of the container.

There are two main approaches to the estimation of water content in horticultural situations:

1. Direct Method:
- Weighing

2**.** Quasi-Direct Methods via:
- Manual estimation of weight
- Soil conductance/resistance
- Sensor resistance
- Thermal conductivity
- Water-swellable materials
- Soil tension
- Soil dielectric

Direct method

The direct method of weighing a known volume of wet and then oven-dried soil in order to calculate the proportion of water present by volume is the acknowledged reference method for calculating soil moisture content, as it is the most accurate and reproducible method available. For a given bed, it is not necessary to follow the oven-drying procedure each time, once the dry matter weight has been established. For outdoor stock, the method also automatically allows for the contribution of rain, ensuring that the best use is made of this free resource. Corrections do have to be made for the increases in weight as the plant grows, but this is not difficult. Weighing is much used in experimental work, but may not be very practicable for routine use in a production nursery. The simplest method of weighing pots in nursery beds is to use portable digital scales; 2000g x 1g scales can be purchased for 50-100 UK pounds and will provide an adequate measure of soil moisture.

Weighing is also an attractive method for automatic control of irrigation because it circumvents the need for calibration. Commercially available scales are not suited to the harsh environment, or being left under constant load, so the use of alternative pressure sensor or load cell systems have been attempted with varying degrees of success, but none appear to be commercially available. A simple prototype was assembled, but was not sufficiently reproducible to be used in the experiment. In tightly-packed beds, the interaction of the plant canopy can introduce errors in the weighing method and leaves little room for the installation of a weighing system. In addition, the weighing platform breaks the hydraulic link between growing medium and underlying bed. This may not be a problem when the bed is clean gravel, but is likely to be unrepresentative for sand beds where a capillary link is present.

Quasi-direct methods

Manual estimation of pot weight is a tried and tested approach which is widely favoured by nurserymen because of its speed of use. It has the advantage that a range of pots can be quickly assessed and a course of action taken in relation to other controlling factors, such as predicted weather conditions. The disadvantages are that success only comes with experience and that automation of the technique is not possible. However, it provides an accepted benchmark against which automatic systems can be compared.

The moisture content of a growing medium can also be calculated by measuring a moisture-dependent variable, of which there are several. A considerable choice exists in the type of sensor which can be used, with some being better suited to purpose than others.

i. Soil conductance/resistance

Sensors can be made small to fit into a pot, but have the disadvantage of requiring calibration for each soil type and may be strongly affected by any chemical changes in the soil composition caused by the application of fertilisers etc. although some e.g. Sutron Corporation's 5600-0080 claim to have internal compensation for changes in salinity. This is a solid state, electrical resistance-type sensor which covers the entire soil moisture range required in irrigation agriculture. Delta-T also supply the SigmaProbe

ii. Sensor resistance

The principle of operation of sensor resistance is that the resistance across two electrodes varies according to the resistance of a material that is integral to the sensor, rather than the resistance of the soil. The most commonly used variable resistance material is the gypsum block. Their operational problems are well documented: relatively short operational life in acid soils, relatively slow response time, hysteresis effect due to strong affinity for water (wets up faster than dries down). They are generally not well suited for horticultural irrigation control, but are still one of the cheapest ways of measuring soil moisture (typical costs: gypsum block 15 pounds, resistivity meter 100 pounds) especially if a large number of sensors is required.

iii. Thermal conductivity

Sensors are similar to gypsum block sensors except they measure thermal conductivity rather than electrical conductivity and hence the electrical conductivity of the water is not an inherent problem. The temperature in a porous block is measured before and after a small heat pulse is applied to it. The amount of heat flow from the pulse-heated point is largely proportional to the amount of water contained within the porous material; a wet material will heat up slower than a dry one. This rise in temperature is measured with an accurate thermistor in the sensor tip and calibrated to the soil water content of the medium. The heating technique uses more power than others methods and may not be suitable when mains power is not available, especially when the time increment is small.

iv. Water-swellable materials

These offer a simple method of controlling the flow of water when incorporated into some form of valve. They work on the principle that a synthetic polyacrylamide or similar gel is kept in close contact with soil water via a porous membrane so as to stay in equilibrium with the soil matric potential. As the gel absorbs water, it swells and applies pressure on the valve mechanism until the water supply is eventually cut off. As the soil dries, the cycle is reversed and irrigation water is released. The cut off points can be adjusted to different soil matric potentials by adjustment of the valve mechanism. One commercially available instrument is the Irristat (http://www.pipeline.com/~lenornst/irrist2.pdf). It is designed primarily for drip irrigation, either in pots or in field situations, but the principle should be adaptable for the control of overhead spray systems. The basic valve has the advantage of not requiring electric power, but could be readily adapted to trigger an electric switch for the control of overhead irrigation.

v. Soil tension
Soil tension is measured with tensiometers. These operate by allowing the soil solution to come into equilibrium with a reference pressure indicator through a permeable ceramic cup placed in contact with the soil. They are not affected by the osmotic potential of the soil solution (the amount of salts dissolved in the soil water), as the salts can move into and out of the ceramic cup unhindered. They measure soil matric potential with good accuracy in the wet range but usually only operate between saturation and about -70kPa and are thus not well suited for measurement in the dry end of the spectrum. Air bubbles may enter at this point (termed the air entry potential) and if the soil is very coarse, this occurs even sooner (wetter). They therefore require careful maintenance during dry periods when frequent topping up with de-aired water may be required. The other perceived disadvantage of tensiometers is a relatively slow reaction time, especially if the ceramic pot is in poor contact with the surrounding soil due to air spaces.

The main advantage of tensiometers is that they measure soil matric potential which is a direct measure of the availability of the water to the plant root and is independent of soil type. The suction within the water reservoir can be measured with a pressure transducer which enables the electronic output to be logged at frequent time intervals if required

vi. Soil dielectric
There is probably more choice in the current availability of soil moisture sensors based on the measurement of soil dielectric properties than any other method. This is largely because the methodology and sensors are robust and remain reproducible over extended periods and are ideally suited to continuous or time event recording on data loggers. All the sensors within this group use an oscillator to generate an AC field which is applied to the soil in order to detect changes in soil dielectric properties linked to variations in soil water content. Because the dielectric of water (~81) is very much higher than soil (typically 3 to 5) and air (1), the dielectric constant of soil is determined primarily by its water content.

Capacitance sensors consist essentially of a pair of electrodes (either an array of parallel spikes or circular metal rings) which form a capacitor with the soil acting as the dielectric in between. This capacitor works with the oscillator to form a tuned circuit, and changes in soil water content are detected by changes in the operating frequency.

Frequency Domain sensors work similarly, but use a swept frequency. The resonant frequency (at which the amplitude is greatest) is a measure of soil moisture, and the amplitude is a measure of soil electrical conductivity. Like capacitance sensors, their measurement is made at a single frequency, but the exact frequency depends on soil moisture content.

The accuracy of Time Domain Reflectometer (TDR) measurements depends on precise measurement of time and precise calibration with the relative volumetric content of water around the probe. The presence of water in the medium affects the speed of the electromagnetic wave (slows it down slightly) which can be detected.

Generally, capacitance sensors permit more freedom of choice in the design of electrode geometry and operating frequency than is the case with TDR systems. Most of these sensors operate at lower frequencies (100MHz or less) and can therefore detect "bound" water in fine-particle soils. This bound water is water that is strongly attracted to the surface of soil particles and can constitute more than 10% soil moisture content. Much of it is available to plants, but is not detected effectively by TDR systems operating at frequencies > 250MHz
The technology required to produce a robust instrument is relatively expensive, but little or no maintenance results in a lower lifetime cost than some other systems. The Delta-T Devices ML2 sensor for example costs around £320 and normally requires a data logger (typically £1500) to allow the output signal to be used to control the irrigation system.

Performance specification

The techniques identified within this report for using less water on horticultural nursery stock whilst maintaining, or improving, crop quality all require a more precise knowledge and control of the amount of water being put onto a crop than is current practise. Most irrigation of HNS is currently carried out with overhead spray systems. These are inefficient in terms of water delivery, with much water being lost onto surrounding pathways. Control is typically manual and based on timing, rather than direct measurement of water volume. The water use data collected from the four growers shows that water application is typically in blocks of 5 minutes, from 5 to 15 minutes, with occasional 20 minute applications in very dry conditions. In order to achieve the greater precision required, some form of automated controller is needed which can respond to the water needs of the crop.

There will be a reluctance from growers to invest in the hardware to control irrigation unless it can be shown to deliver substantial benefits. The benefits must not only be in saving water, which is a relatively cheap resource, particularly for growers with their own boreholes, but also in labour savings and improved crop quality. Growers need to be assured that any equipment they invest in will deliver those benefits. To this end, a specification is required which will ensure that equipment is designed against growers' needs and which will allow objective testing against those needs. A formal specification will also help equipment manufacturers understand the needs of the industry and design products which meet those needs.

The prime objective of a specification is to ensure that equipment produced to meet it, is fit for purpose - i.e. that it can operate in the environment where it's needed and gives the required functionality and result. At the same time, a specification must not be so restrictive that it stifles technological development or so onerous as to make it unachievable at a realistic cost. Thus contents ought to be kept to a minimum whilst ensuring that all operational requirements are met. Contents must also be realistic and defensible in terms of operational requirements and site conditions.

An irrigation control system could include a number of elements:

1. a sensor to measure some parameter from which water need can be determined
2. a means of taking the reading from the sensor and determining how much water should be applied
3. a means of turning the water on and off
4. a means of recording data from the sensor and water applied to enable historical analysis of water use

The specification development in this project focussed around items 1 and 2, where item 2 is an automatic system linked to item 3. Item 2 could also be a manual method, e.g. paper based model, a software tool which would run on a standard PC or a dedicated computer unit. The other items are already widely available in forms suited for HNS irrigation. Even given these limitations, there are a number of options available depending on the complexity of the system. Figure 3.1 shows a simple system, in which a sensor responding to plant water need (e.g. soil moisture sensor) is linked directly to a controller. The controller then operates the valves supplying water against the desired regime.

In the more complex system shown in Figure 3.2, multiple sensors are linked to transmitters which take the sensor signals and carry out some processing before sending data to the controller. Transmission of data to the controller is by cable and a low power radio link. Each monitor (sensors and transmitter) may be deployed at different locations within the nursery and the central controller is able to operate the valves for the water supplies to those locations independently. Data storage is also included to allow historical information on sensor inputs and watering patterns to be analysed against crop performance indicators (e.g. quality, size, mortality) to further refine the watering regimes against local climatic conditions and crop requirements. A further refinement may be the inclusion of a sensor which measures the water applied, e.g. flowmeter in the water supply line, and signals the controller to close the supply when the desired amount of water has been delivered. The choice of complexity for any individual grower will depend on many factors but will be principally an economic one weighing the benefits of any system against the costs (see Unit 5).

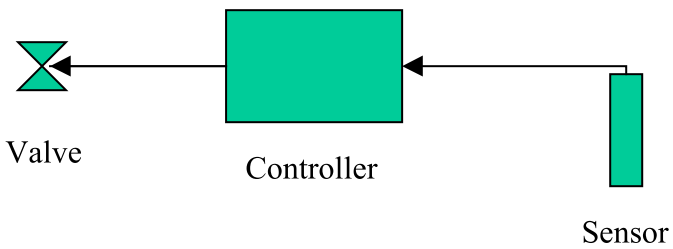


Figure 3.1 Simple control system

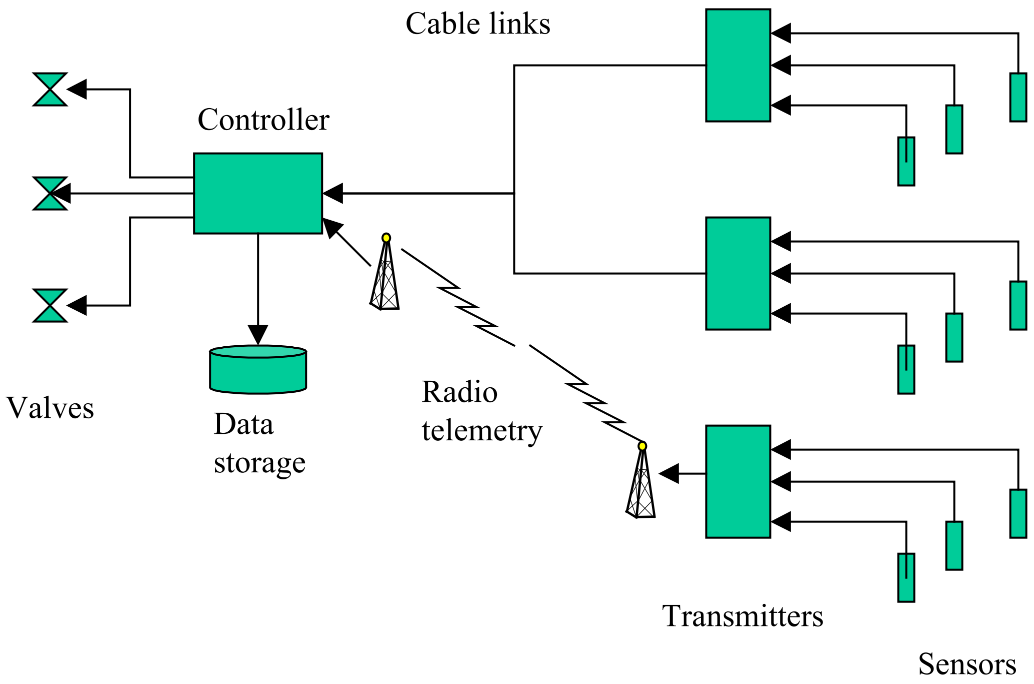


Figure 3.2 Complex control system

The specification can be broken down into a number of key areas:

- Operational Requirements - These define what the equipment is supposed to do and how well it should perform.

- Mechanical Requirements - This section addresses the build of the equipment and robustness for the purpose to which it is being put, taking into account site conditions and working practices.

- Electrical Requirements – This section defines any electrical requirements of the equipment, including outputs for data loggers, switching valves etc.

- Environmental Requirements - Clauses within this section address the environment within which the equipment will be expected to operate.

Any requirements laid down under European or UK legislation, e.g. compliance with EMC and low voltage directives or health and safety warnings, have not been included as these are mandatory. It is illegal to sell equipment in the UK which is not CE marked to the relevant standards and therefore these requirements are taken as read.

The specification is included in this report as Appendix 2.

Comparison of selected sensors

The sensors which were evaluated fell into two categories:

1. Those that make measurements which can be used to estimate the "evaporative demand" of the atmosphere, which to a large extent determines evaporative losses from plants. These measurements are not container, or bed specific.

a. An automatic weather station (Delta-T Devices)
b. The "Evaposensor" (Skye Instruments, developed at East Malling)

2. Those which measure the water content of the growing medium (directly or indirectly) i.e. container based measurements, related to the container and plant where the instrument is located. Those tested were:

a. The ThetaProbe, measuring soil dielectric (Delta-T Instruments)
b. The mini-tensiometer, measuring soil water potential (Skye Instruments)

Comparisons were made in the course of experiments described in Unit 4.

Estimating water use from evaporative demand : Automatic weather station (AWS) and Evaposensor (ES)

The automatic weather station had the following sensors installed:

- Radiometer, measuring solar radiation.
- Thermometer measuring shaded air temperature
- Relative humidity sensor
- Anemometer, measuring windspeed.
- Wind direction sensor
- Raingauge.

The AWS was installed in the centre of the experimental plots to represent, as well as possible, the conditions over the beds themselves. The evaporative "power" of the atmosphere, or the "evaporative demand" exerted on plants is determined by the solar radiation, windspeed, humidity and temperature. These data, measured by the AWS as hourly averages, were used to calculate a daily "reference" evaporation (ET_{ref}) using the Penman Monteith formula using the form outlined in Allen et al., (1994). This is the evaporative loss that might be expected from a short crop which is well supplied with water (i.e. not water-stressed).

The Evaposensor consists of two horizontal leaf-like blades, parallel to each other and painted black. Each contains a sensitive temperature sensor. The blades are 4 cm x 1 cm and mounted 1.3 cm apart. One blade is covered by a black cotton wick, which dips into the water reservoir and is kept wet by capillary action. A data logger was used to measure the temperature of each blade at 10 minute intervals and record hourly averages which were subsequently summed to provide daily totals. There were generally 2 evaposensors connected to the logger and a third was linked to an EvapoMeter, which integrates readings taken at one minute intervals and displays the total values when required.

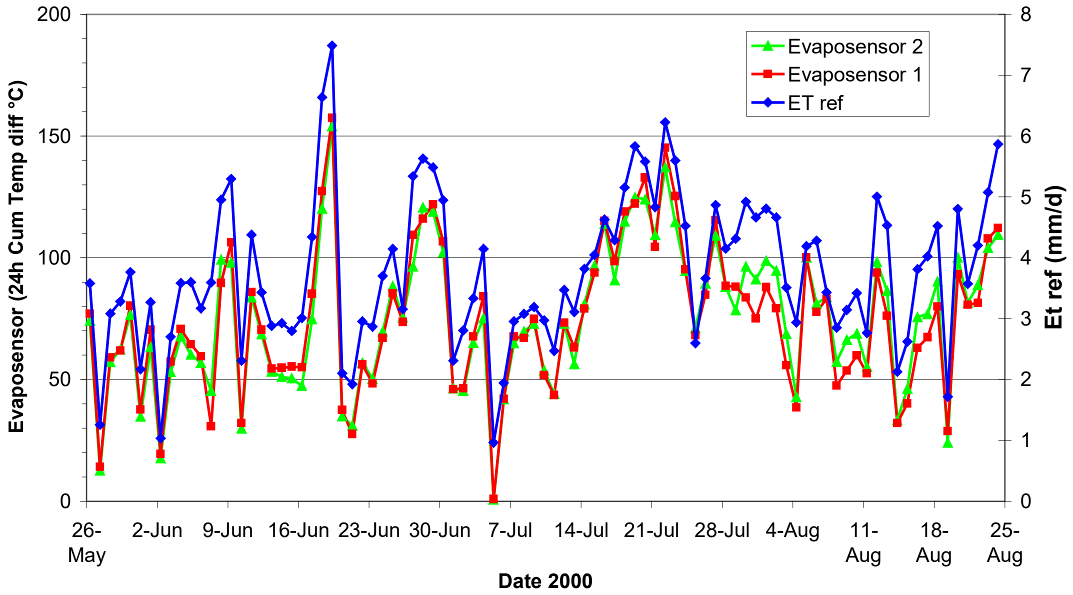


Figure 3.3 Comparison of AWS derived Et_{ref} and Evaposensor cumulative daily totals for 2000 growing season.

The data in Figure 3.3 and 3.4 show a close relationship between Et_{ref} and the Evaposensor data, and close agreement between the two Evaposensors. The slopes and intercepts for data from the two Evaposensors were almost identical (22.57 and 21.51, -9.67 and –9.85 respectively).

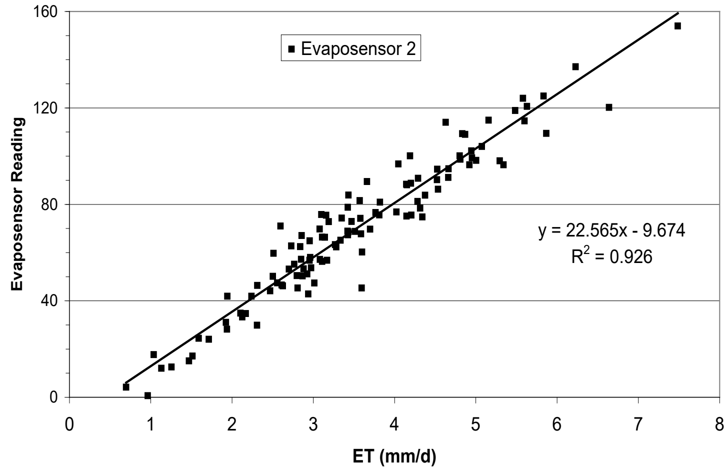


Figure 3.4 Relationship between Evaposensor 2 and $ET_{ref\ daily}$ totals

Overall, the Evaposensor seemed to be able to provide a very good indication of evaporative demand. When compared to the AWS, there are clearly conditions when it is underestimating, and at other times overestimating evaporative demand. The ES response is strongly related to solar radiation and humidity and there are indications that for a given radiation level, the readings are lower if the wind speed is higher.

When the cost of the sensor is taken into account (about £300, including the EvapoMeter), it can be seen to be very cost-effective at producing a reasonable estimate of evaporative demand, when compared to an AWS (cost is about £3000, plus a laptop computer to download data and make the calculations).

ET_{ref} is an estimate of water use of an *idealised* crop. The *actual* water use will depend on the plant size, its leaf area, the species (and cultivar) and the way it responds to the climate, the water availability, and the microclimate to which the particular plant is exposed (e.g. edge of bed or centre). Evaposensors could be used to better "sample" different microclimates because of their small size, compared to an AWS.

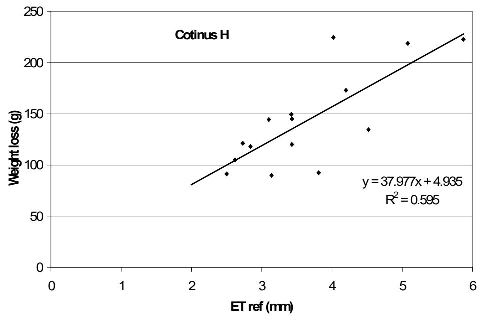


Figure 3.5 Daily weight loss v. ET_{ref}

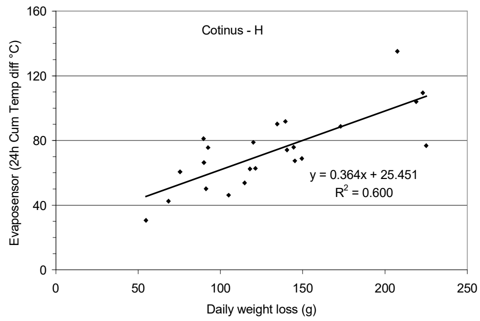


Figure 3.6 Daily weight loss v. ES2

Weight loss of a sample of well watered *Cotinus* containers provided a measure of *actual* water use, which was plotted against Et_{ref} (Figure 3.5) and Evaposensor output (Figure 3.6). The R^2 values were very similar, at about 0.6. The R^2 values for *Forsythia* and *Hydrangea* treatments were somewhat lower, indicating poorer correlation. However, much higher R^2 values, in the range 0.84 - 0.90, have been reported (Harrison-Murray, 1995) and were observed in Experiment 1.1.

The relationship between the ES and ET_{ref} (covering a whole growing season) was very good. The fact that relationships between plant water use and either ES or Etref are not as close strongly indicates that stomatal control is playing an important role in these species, particularly *Hydrangea*, even though they were well watered. The data also indicate that in this study, the ES was a slightly better predictor of water use than Et_{ref}. This is probably because the ES was closer to the plant canopy and better represented the conditions experienced by the plant.

The weight loss data for the different species were compared, and it was noted that these showed a much better relationship than that with the ES, or with individual meteorological variables. Comparing the species, the R^2 were as high as 0.77 indicating that the different plant species are responding in a more similar way to the various environmental factors (wind speed, humidity, solar radiation etc), than the way in which the ES is responding to them.

In conclusion, the correlation between ES readings and actual *water use* is good but not perfect. If used as an indicator of irrigation requirements, the ES may lead to underestimation of requirements on some days, and overestimation on others. Given the large water storage capacity of a 3 L pot, the plants would only suffer stress after several consecutive days of underestimation, starting with pots at pot capacity.

Comparison of soil moisture sensors: Delta-T ThetaProbes and Skye Instruments Mini-tensiometers

Delta-T ThetaProbe

The principle of operation of this type of instrument is described above under 'vi. Soil dielectric'. The ThetaProbe uses an oscillator to generate a single fixed frequency of 100MHz and, as in TDR systems, apply this to a coaxial transmission line that extends into the soil via an array of 4 parallel metal spikes of length 60mm. Soil moisture content is measured from the amplitude of the standing wave which is set up when the reflected AC signal (dependent on soil dielectric) interacts with the generated AC signal.

Measurements are made by pushing the sensing spikes into the soil, or growing medium, to their full 60 mm depth. Using the handheld meter, the ThetaProbe can be used in “roving” mode, where the sensor is pushed into the growing medium, a reading taken, and the sensor withdrawn. This operation takes only a few seconds and readings can be made in several containers within a short time. With a data logger, it is used in “fixed” mode, where the sensor is installed in a single container where it may remain for some time, e.g. a growing season. The output of the ThetaProbe is a voltage, which is measured by the handheld meter or data logger. A calibration is required to convert the voltage into volumetric water content. The HH1 handheld reader unit has two built-in calibrations (one for mineral, and one for organic, soil).

For the 2000 growing season, the fixed ThetaProbes were inserted into the surface of the growing medium to measure the water content in the top 60mm of soil. For 2001 and 2002 all of the probes were sunk a further 35mm into the growing medium so that they were measuring within the central 60mm as shown in Figure 3.7b. This was felt to provide a better representation of pot moisture as it was less affected by the more variable surface and basal effects.

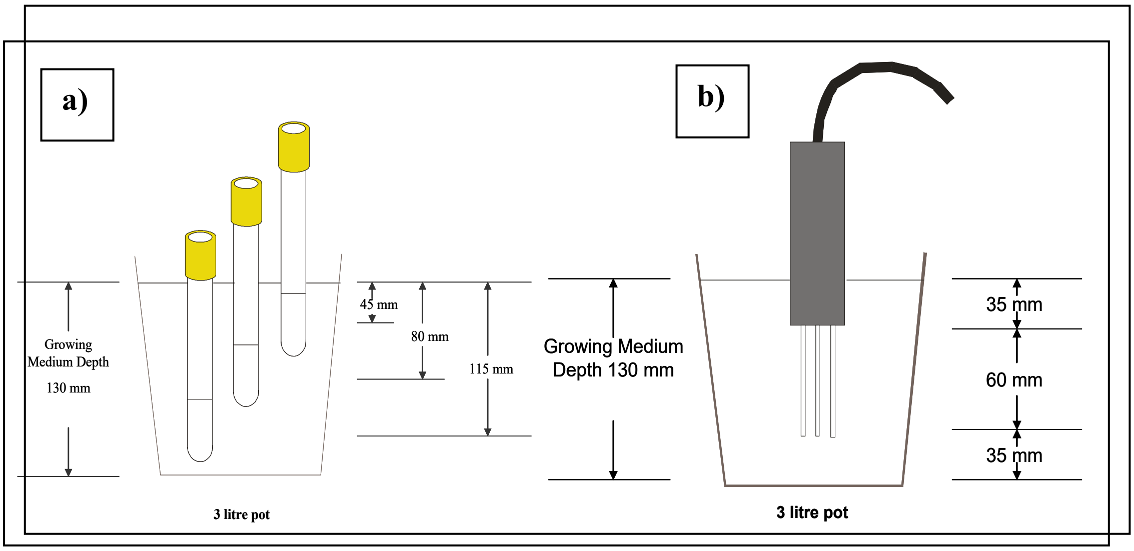


Figure 3.7 Location of a) Mini-tensiometers and b) ThetaProbes in 3 litre pots during the 2001 and 2002 growing seasons.

Figure 3.8 shows the mean pot weights of well watered *Hydrangea*, compared with the mean pot weights estimated from a ThetaProbe installed in similar pot. The changes in plant weights, the density of the compost and the weight of the pot have been taken into account. The two sets of data are for the same bed, but it is important to note that the ThetaProbes were in different pots to those which were weighed. Two ThetaProbe reading per day were plotted, corresponding with the times when pots were weighed.

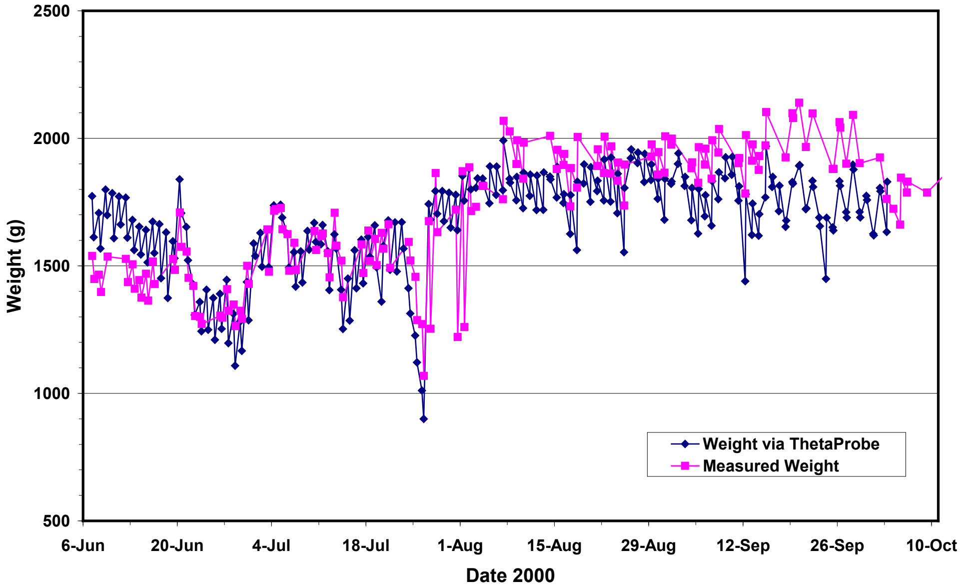


Figure 3.8 Comparison of measured weights of well watered *Hydrangea* containers with weights estimated from ThetaProbe measurements of soil water content.

Estimates based on ThetaProbes in 3 pots matched the mean weight of 4 pots extremely well from June to October despite the need to assume that ThetaProbe reading in the top 6 cm is representative of the whole container. When weight changes are compared (Figure 3.9) a good linear relationship is evident (R^2=0.88), although there appears to be more variability on drydown (weight loss) than on wetting (weight gain).

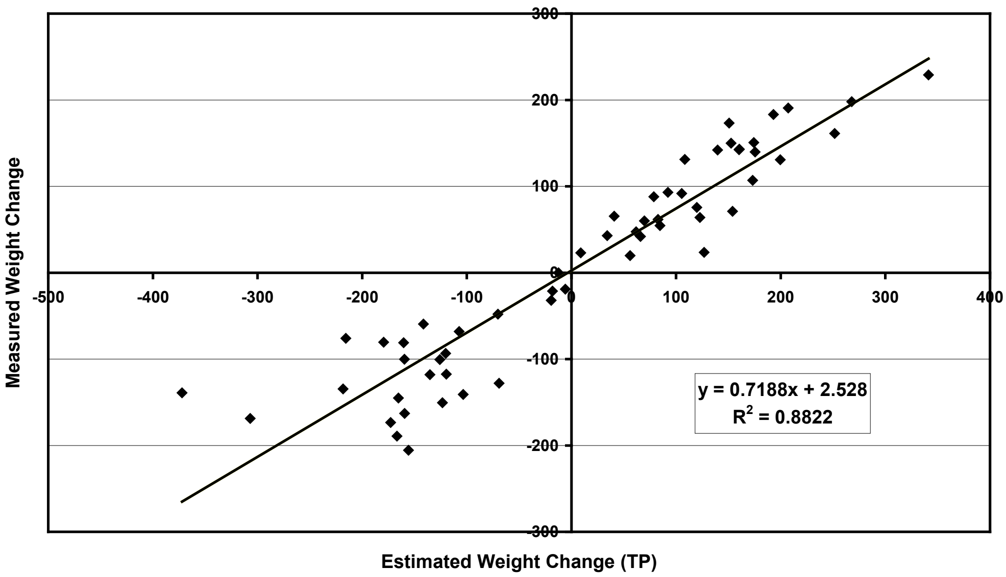


Figure 3.9 Correlation of measured pot weight change and estimated weight change using ThetaProbe for Hydrangea *E treatment.*

Skye Instruments Mini-tensiometers

The method of operation of tensiometers is outlined above under "v. Soil tension".

The tensiometers used in this project are unusual because of their small size. Measuring only 120mm long and 14mm diameter, with a 25mm long ceramic tip, it was possible to easily accommodate 3 mini-tensiometers in a single 3 litre pot to measure soil tension at the top, middle and base of the growing medium as illustrated in Figure 3.7a. This enabled the dynamics of soil moisture distribution within selected pots to be observed over time to better understand the ways in which water enters, disperses and leaves the growing medium.

From Figure 3.10, it can be seen that soil tension is inversely related to water content – as the growing medium dries out, soil tension increases and vice versa. Again, it must be pointed out that the displayed pot weight is the mean value for all the non-instrumented pots in the bed whilst the trace of soil tension comes from the middle (75mm depth) of only a single pot in the same bed. During the wet period from 3-11 July, the soil tension dropped to near zero and it appeared to be rather insensitive to the changes in moisture at the wet end of the moisture 'spectrum'. This reduction in sensitivity is further illustrated in Figure 3.11, which shows the exponential decay of soil tension at high moisture levels.

The loss of sensitivity at high moisture levels suggests that tensiometers might not be suitable for irrigation control if required to maintain high water contents. In contrast, the high sensitivity at low soil moisture content could be an advantage for controlling deficit irrigation (RDI or PRD). However, tensiometers tend to need more frequent topping up under dry conditions.

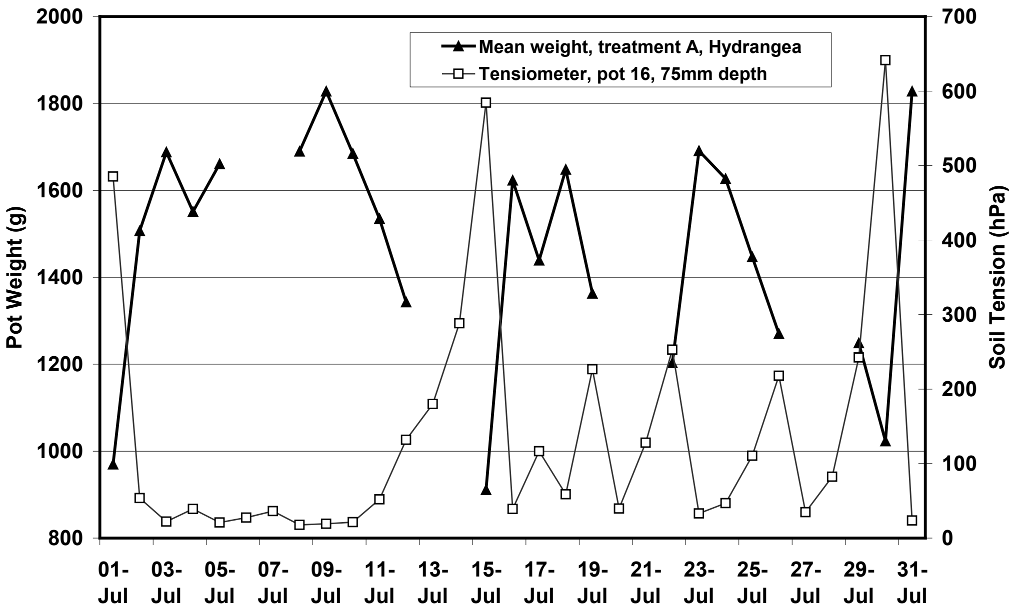


Figure 3.10 Treatment A, sand, 2002 season. Mean pot weight and soil tension for middle of pot 16 showing inverse relationship

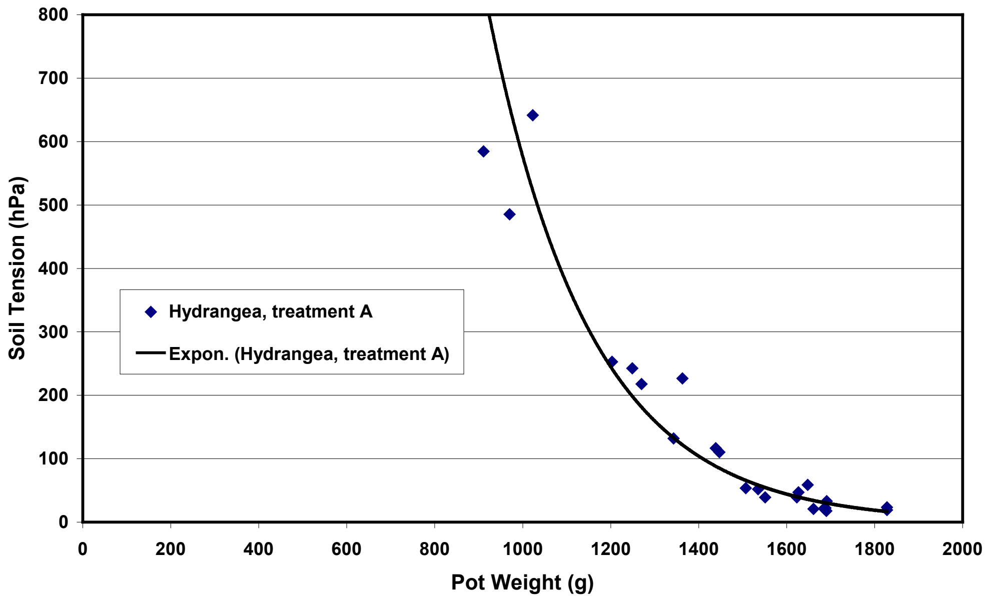


Figure 3.11 Treatment A, sand, 2002 season, showing apparent reduction in sensitivity of Mini-tensiometers to changes of pot weight at high moisture levels

Conclusions

There are a wide range of instruments available for the measurement of soil moisture, but not all are suited to operating in the confines of nursery containers and in the relatively harsh environment of overhead irrigation systems. All of the available instrumentation have been given consideration, both through literature and patent reviews and via the combined experience of the many experts associated with this Horticultural LINK project. This section covered only a small proportion of the accumulated knowledge, but serves to confirm the suitability of the 3 types of instrument which were selected as candidates for development of improved irrigation control for the HONS industry. The main conclusions are:

- The Skye Evaposensor (and EvapoMeter) provides a low cost method of measuring daily evaporative demand but should be used with a rain gauge to determine additional input from rainfall. It provides reference measurement of water use for a whole nursery and requires operator input to make corrections for individual beds according to local factors affecting water use e.g. irrigation application rate, plant size or stage of growth, pot size and spacing, bed construction etc. In its current form, it is an irrigation management tool but it would be feasible to develop it for automatic control.
- The Skye Mini-tensiometer provides a direct measure of soil matric potential (water available to plants) which is independent of the type of growing medium. The small size of the sensor makes it well suited to measurement in containers and profiles of soil moisture have been acquired by using 3 sensors set at different depths. Unlike some larger tensiometers, the response time of the mini-tensiometers is adequate for purpose and, in principle, they could be used for switching an irrigation system. In practice, many of the units were found to run dry when soil moisture tension was > 700hPa. This necessitates regular inspection and maintenance that makes them unsuitable for automatic irrigation control.

- The Delta-T ThetaProbe is one of a number of available sensors measuring soil dielectric constant which, via calibration, can be converted to volumetric soil moisture. For the range of soil moisture required for controlling the irrigation of HONS, a simple linear conversion applies. The 60mm sensor spikes provided a mean measurement of moisture in the central layer of the 3 litre pot, which was found to be the optimum location for irrigation control (see Unit 5). By measuring water content in the pot, the effects of rainfall and plant development are taken into account, but there may still be some seasonal effect due to compaction of the growing medium, which may require adjustment of target water contents. The sensors require no maintenance and are highly reliable; at HRI Efford, 24 ThetaProbes have operated outdoors for 3 growing seasons without any failures or need of attention. Following the first year of field trials, the ThetaProbe was selected as the sensor for the development of an automatic irrigation control system of container-grown HONS.

In Unit 4, data from the above sensors, together with manual measurements are used to illustrate how management protocols can be developed to provide successful control of overhead irrigation systems.

Unit 4: Development of practical means to regulate irrigation according to plant requirements (Objective 5 & 6)

This Unit combines work towards the following scientific objectives:

5. Develop management protocols for non-automated irrigation control.

6. Develop prototype equipment to control and regulate irrigation automatically.

This Unit includes work on improving the uniformity of overhead irrigation, an important component of irrigation efficiency.

Background

This Unit covers the development of practical methods to match irrigation to plant requirement, based on the assessment of alternative technologies presented in Unit 3. It focused on *outdoor* crops under *overhead* irrigation, this being most relevant to current practice in the HNS industry.

From the outset, one problem was clear. A method that matched *average* irrigation amount to *average* plant water requirement (i.e. ETp) was unlikely to be satisfactory because of the wide variations around those averages. That variation would result in many individual plants consistently receiving less water than they needed so that they suffered stress, while others on the same bed did not. To avoid any plant suffering stress, irrigation must be tailored to the driest plant. While this problem is widely recognised, and supplementary irrigation of bed edges often used to reduce it, we identified a need for quantitative data on the degree of non-uniformity. Drawing on techniques developed in Australia, appropriate methods were developed in the course of setting up the irrigation systems for experiments and later applied to assessment of irrigation on some commercial container beds.

Experiments were conducted on semi-commercial scale beds, each equipped with water meters, so that potential water savings of better regulated irrigation could be measured directly. A key objective was to develop and assess the practical feasibility of irrigation scheduling based on the evaposensor or the ThetaProbe. The accurate, but laborious, gravimetric method (i.e. weighing pots) was used as a reference and for calibration of the instruments, particularly the evaposensor.

In this Unit we also report work on the factors affecting the proportion of overhead irrigation that reaches the container, either directly or indirectly through the base, and is absorbed by the medium rather than lost as drainage. These factors clearly have a direct effect on efficiency of water use but are also relevant to the regulation of irrigation using the evaposensor, or any other technique based on evaporative demand. A precise measure of ETp will be of little value if the proportion of the irrigation applied that reaches the plants is unpredictable.

Factors that could be important include the size and structure of the foliage canopy, which varies between species and growth stage, and the type of bed (e.g. a Mypex covered sand or a gravel standing base) which determines the potential for capillary uptake and drainage through the base.

The work described in this Unit was conducted on 12 outdoor beds, each 6.0 m x 1.6 m and separated by concrete access paths, at HRI Efford.

Experiment 4.1: Manual regulation of irrigation based on evaporative demand

Materials and Methods

Irrigation system

In a preliminary experiment in 1999, pin nozzles on a single overhead irrigation line running down the centre of a bed resulted in very uneven irrigation. In 2000, uniformity was improved by having irrigation lines down each side of the bed with 180° arc anvil spray nozzles on 1m tall risers.

Irrigation management treatments

Treatment E	100 % ETp
Treatment H	150 % ETp (taken to be a conservative estimate of the degree of over-irrigation common in the industry).

Gravimetric estimation of ETp

At the start of the project, while equipment was being evaluated, ETp was measured by weighing a sample of pots from within the bed and comparing it to the previously determined weight at 'pot capacity' (i.e. after the pot had been thoroughly wetted and allowed to drain). For a 100% ETp regime, irrigation times were calculated to restore pot capacity. The weight at pot capacity was redetermined periodically to allow for the increase in plant mass and changes in the properties of the medium.

Battery operated kitchen scales, reading in 5 g steps, provided a cheap and effective method of weighing. For regular weighing of the same pot, a wire was fixed across the top of the pot so that it could be weighed *in situ* with a hanging balance.

Evaluation of potential control sensors

Although irrigation was regulated on the basis of the gravimetric data, a variety of possible control sensors were monitored in this experiment to establish their capabilities and operational characteristics. The sensors included evaposensors, mini-tensiometers, and ThetaProbes as well tipping bucket raingauge and other standard meteorological sensors in an automatic weather station.

Quantifying performance of overhead irrigation systems

Irrigation uniformity and application rate was measured with an array of plastic trays (pot saucers) to collect irrigation over a known time interval (usually 20 min.). The volumes of water collected were converted to irrigation catch in mm/h for each dish, and the following parameters, which summarise the performance of an irrigation, were calculated:

$$\textit{Coefficient of Uniformity}\ (CU) = \left(1 - \frac{(\textit{mean deviation from mean catch})}{\textit{mean catch}}\right) \times 100$$

$$Mean\ Application\ Rate\ (MAR) = \frac{total\ catch\ per\ hour\ from\ all\ containers}{number\ of\ catch\ containers}$$

$$Scheduling\ Coefficient\ (SC) = \frac{mean\ catch\ rate}{lowest\ catch\ rate}$$

The scheduling coefficient (SC) indicates by how much the irrigation time must be increased to ensure the driest areas receive the intended (i.e. mean) volume of irrigation.

These calculations were done in a spreadsheet ('Water Distribution Calculator') which facilitated creation of graphs illustrating the distribution pattern. The spreadsheet has been made available to growers following interest expressed at technical workshops.

Results and discussion

The irrigation system

The irrigation system used in 2000 gave the following performance parameters when tested under calm conditions in a glasshouse:

CU 81%
MAR 63 mm/hour
SC 1.6

Guideline standards published by the Nursery Industry Association of Australia (Atkinson, 1997) suggest the following targets:

CU >85%
MAR <15 mm/hour (to avoid exceeding the absorption rate capacity of the growing medium)
SC <1.5

Thus, while the system achieved a much more uniform distribution than the single overhead line used earlier, uniformity (CU) was still poor and application rate (MAR) was too high. Furthermore, the nozzles produced fine droplets which were highly susceptible to wind drift.

Variation in soil moisture

ThetaProbes were installed in 4 pots of each species within each treatment and monitored hourly with a data logger (Delta-T DL2e) as part of the evaluation of equipment for irrigation control. Probes were inserted into the upper surface so that they measured the upper 6 cm depth of the medium. Figure 4.1 shows a typical plot of data from treatment E (100% ETp) during a spell of dry weather. It is evident that soil moisture content (SMC) gradually declined and that it was much more rapid in one replicate (pot 10) than in the others. It was typical to see such variations increase during dry spells and to be greater in treatment E that treatment H.

The ‘spikes’ on the traces in Figure 4.1 represent the increase in SMC following the daily irrigation. The reason for the overall downward trend in SMC was that the spikes were generally not quite as large as the drop from the previous day (i.e. the preceding spike). The size of the spike does not relate closely to the amount of irrigation applied (shown by the grey bars), suggesting that the proportion of irrigation captured in the pots varied substantially from day to day. This suggests that the slight discrepancy between irrigation and water requirement was attributable to shortcomings in the water application system rather than to errors in the estimate of ETp.

It is also evident in Figure 4.1 that a container at a soil moisture content of 0.5 (= 50 % and is roughly pot capacity) held enough water 3 to 4 days of evapotranspiration from Cotinus pots. Using a daily irrigation schedule, little of the water storage capacity of the medium is exploited. This was taken into account in our design of an automatic irrigation control system based on the ThetaProbe

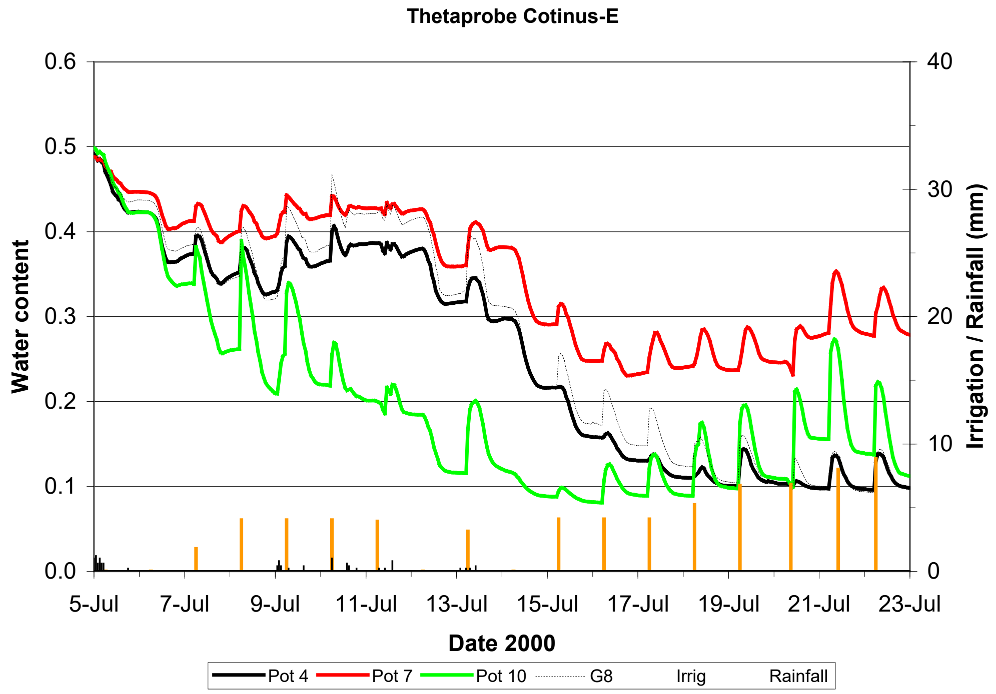


Figure 4.1 Hourly water content data from the 4 ThetaProbes in the Cotinus E treatment, with daily irrigation (thick bars) and hourly rainfall (thin bars).

The irrigation management protocol

Regulating irrigation times based purely on gravimetric measurements of ETp was not entirely satisfactory. Evidence of water deficits developing in some plants necessitated application of supplementary irrigation. The increase in pot weights following irrigation were often much smaller than expected so that pots became progressively drier until generous additional irrigation was given to correct the situation. The high MAR value suggested that this could have been due to substantial 'run-through' (i.e. water draining rapidly through large pores while smaller pores remained unfilled).

This hypothesis was tested at the end of the season using empty 2L pots, lined with a polythene bag, pushed onto the base of 3L pots to collect any run-through (Figure 4.23). Before irrigation, the 3 L containers were on average of 350g below their weight at pot capacity, i.e. with a modest water deficit but not dry enough to have become hydrophobic. Application of an average of 300 ml/pot resulted in 35% - 55% run-through. These substantial losses indicate how important it is to avoid high application rates for efficient use of water, particularly if the irrigation is being regulated on the basis of evaporative demand (whether measured or estimated intuitively).

Water use

The 100% ETp treatment used an average of 3.6 mm/day over the period early June to early October. There was no difference between the species, *Hydrangea macrophylla* 'Blue Wave', *Forsythia x intermedia* 'Lynwood' and *Cotinus coggygria* 'Royal Purple'. The absence of any difference between *Hydrangea*, traditionally regarded as 'thirsty', and *Forsythia*, confirmed observations in the preliminary experiment.

Plant growth

There was no obvious difference in the appearance of plants in the two irrigation regimes and no significant difference in total plant dry weight at the end of the season. This suggests that the transient stress that affected some of the plants in the 100% ETp treatment had no long-term effect.

Main conclusions

- It is essential to maximise the uniformity of delivery of irrigation and avoid high application rates for efficient use of water and for effective regulation of irrigation.
- Gravimetric measurement of ETp is laborious but simple and could be used an irrigation management tool on a small nursery.
- Differences in water use between species are smaller than commonly believed.

Experiment 4.2: ThetaProbe and Evaposensor control of irrigation to 100% and 50% of ETp

By April 2001, initial evaluation of instrumentation was complete, the Skye version of the evaposensor was available and a dedicated meter to integrate evaposensor output was imminent. Experiment 4.1 had identified the need to optimise both distribution and the rate of application if irrigation at 100% ETp was to keep all plants well watered. The foundations were in place for a thorough comparison of alternative means of regulating irrigation to closely match plant requirements. An ambitious experiment was planned in which the evaposensor would be used to estimate ETp, compared with the gravimetric method, and a ThetaProbe would be used as a basis for fully automatic control. In the light of the exciting results with RDI (Unit 1), a 50% ETp treatment was included. The key objectives were:

- Compare regulation of irrigation based on evaposensor estimates of ETp with that based on weighing pots.
- Prove the feasibility of fully automatic irrigation based on a single ThetaProbe.
- Evaluate the effect of 100% and 50% ETp irrigation regimes on plant growth and quality under overhead irrigation outdoors.
- Measure water use under these regimes.

Materials and Methods

Plant material

Hydrangea macrophylla 'Blue Wave', 1-year old, in 3 L pots

Cotinus coggygria 'Royal Purple', 1-year old, in 3 L pots

Wetting agent was added to the medium to improve the consistency of water uptake and retention. Consistent with industry practice, long shoots were pruned back by about half in mid-late July to improve plant shape.

Irrigation management treatments

A Irrigation to 100% of ETp measured by weighing.
B Irrigation to 100% ETp as estimated by the Skye EvapoMeter*.
C Irrigation to 50% of ETp estimated by the Skye EvapoMeter*.
D Automatic irrigation control based on a single ThetaProbe in a representative container.

* i.e. the Skye version of the evaposensor linked to the Skye EvapoMeter, which integrates the output from the evaposensor and displays the results

Layout of beds and sprinklers

Unreplicated irrigation treatment main plots, each with 3 beds, were separated by windbreaks to prevent interference by overspill. Each bed was split into *Hydrangea* and *Cotinus* sub-plots with the 3 beds making up pseudo-replicates within the main irrigation treatment plots. Beds were drained sandbeds covered with 'Mypex' ground cover fabric.

An improved sprinkler layout was designed and installed using Eindor 862 Minicompact sprinklers. Beds were irrigated in blocks of 3 beds to a treatment rather than individually, using 3 lines of 3 sprinklers spaced at 2.0 m in line x 3.5 m between lines. The outside lines ran along the outsides of the north and south row of beds. Windbreak netting was used to prevent overspill and interference between treatment blocks.

This sprinkler system gave very uniform application at close to the designed rate of 10 mm/h, with a high CU and low SC (Figure 4.2).

To determine whether this water distribution can be disturbed by the leaf canopy of the plants, measurements were made in the *Hydrangea* plots once the canopy was well developed. Water deposition was measured as the gain in weight of the containers. Any run-through was collected as described earlier. On average, the capture rate was about 35% greater than the rate of application of water, indicating that the *Hydrangea* foliage was funnelling water into the containers, as might be expected from the upwardly cupped leaf arrangement. However, capture was much less uniform that the water application (compare Figures 4.2 and 4.3), indicating that the effect of the foliage was not consistent. In practice, the variation was reduced when averaged over several irrigation events. Also, this test did not take into account uptake of water that fell between pots and was taken up into the pots before it had drained through the Mypex.

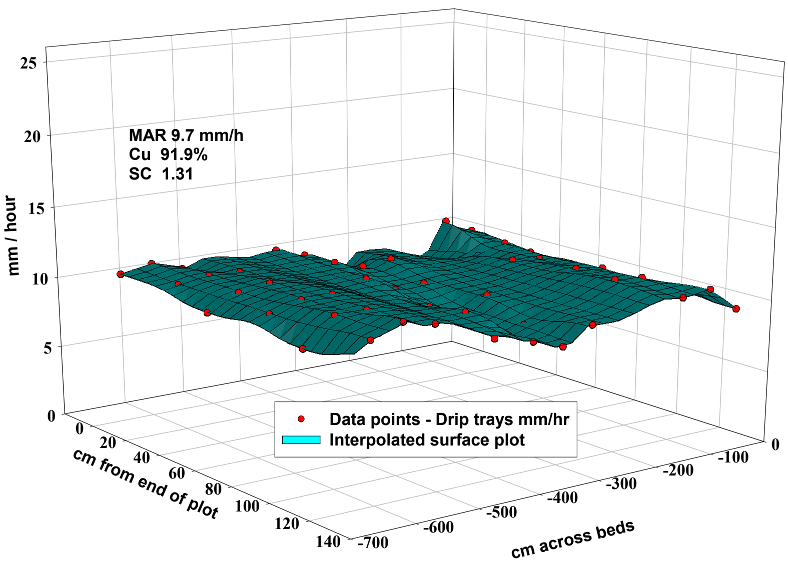


Figure 4.2 Water distribution from the improved sprinklers and layout used in experiments 4.2 and 4.3, measured with pot drip trays before plants were in place.

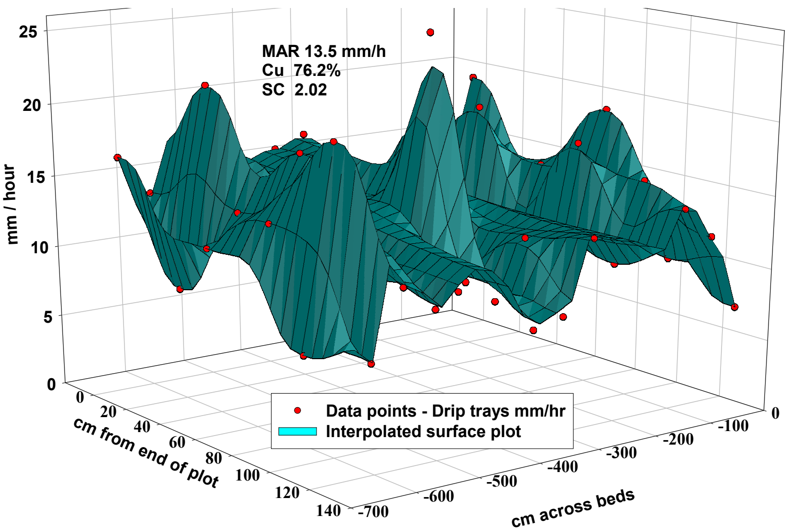


Figure 4.3 Overhead irrigation capture by containers of *Hydrangea* in leaf. Application rate based on pot diameter, and includes any drainage run-through.

Gravimetric ETp

ETp estimates for treatment A were based on weights of *Hydrangea* pots but *Cotinus* pot weights were also monitored.

Using the evaposensor and EvapoMeter

The period from mid May to the end of June was used to calibrate the evaposensor against *Hydrangea* irrigation requirement. Evaposensor output integrated over 24 h (in degree hours) was logged in parallel with gravimetric measurements of ETp from 6 plants per main plot. Also, weight gain during precisely timed irrigation was recorded. Data collected over 16 irrigation cycles were plotted and linear regression was used to fit straight lines to the data. From the regression equations, a lookup table was derived to convert evaposensor integrals to required irrigation time. This approach to calibration combines the calibration of the evaposensor with water use from a particular crop and calibration of the irrigation system in terms of water absorbed by the pots per minute of irrigation. Irrigation pressure and sprinkler output were sufficiently stable for precise control of irrigation by timer.

Skye Instruments delivered the first EvapoMeters (Figure 4.4) in time to be used to regulate irrigations for treatments B & C from July until the end of the experiment. By providing instant access to integrated evaposensor output, the EvapoMeter was much more convenient than the data logger used previously. Daily-adjusted irrigations were applied during weekdays to the Evaposensor treatments and treatment A. Checks were made against pot weights on Friday to ensure containers were heavy enough to last the weekend without further irrigation, and typically heavier irrigations applied on Monday according to accumulated EvapoMeter readings and weight loss. Gains from rainfall were not formally accounted for against irrigation applications in this experiment, although they were recorded. Rainfall events from July to September were either too light or infrequent to make a significant difference, or were obviously heavy enough to bring containers to pot capacity, in which case no irrigation was applied (Figs 4.7 & 4.8).

Automatic control and monitoring

The automatic control by ThetaProbe was achieved by programming a logger (Delta-T DL3000) to switch a relay on and off at specified values of ThetaProbe output. Using the DL3000 programmable logger as a controller provided the flexibility to average the output from 2 or more ThetaProbes but it was decided to test the simplest possible arrangement: control the irrigation from a single probe. When using a single probe, it is imperative that the selected pot is an appropriate of the bed. ThetaProbe data from the 6 instrumented pots connected to the logger were used to select a pot whose SMC was slightly drier than average.

Control set points, i.e. the ThetaProbe output at which irrigation would switch on and switch off, were chosen as follows: on at an SMC of 28 % and off at an SMC of 50 % (corresponding to a ThetaProbe output of 500mV and 850 mV respectively). These were selected with reference to the water-release curve of the growing medium, and ThetaProbe traces collected while setting up the experiment. The ThetaProbes were inserted deeper into the medium than usual so that they measured the water content of the middle 60mm of growing medium (Figure 4.5).

The logic control of the DL300 logger acted as a switch in the power supply between the standard irrigation timing unit and the solenoid valve which controlled the overhead irrigation. The timing unit was set permanently ‘ON’ except for two hours each morning when pot weighing and site maintenance was undertaken. Irrigation therefore took place ‘on demand’ whenever the ThetaProbe value fell below the lower threshold. The measurement interval for the controlling ThetaProbe was set to 1 minute. The precise control that this achieved is illustrated in Figure 4.6.

Figure 4.4 The evaposensor (left) and the EvapoMeter used to integrate and display its readings (right).

Figure 4.5 The ThetaProbe on the bench, pushed into the surface of an empty pot and part-buried in a *Hydrangea* pot to monitor and control water content at mid-depth (35 - 95 mm).

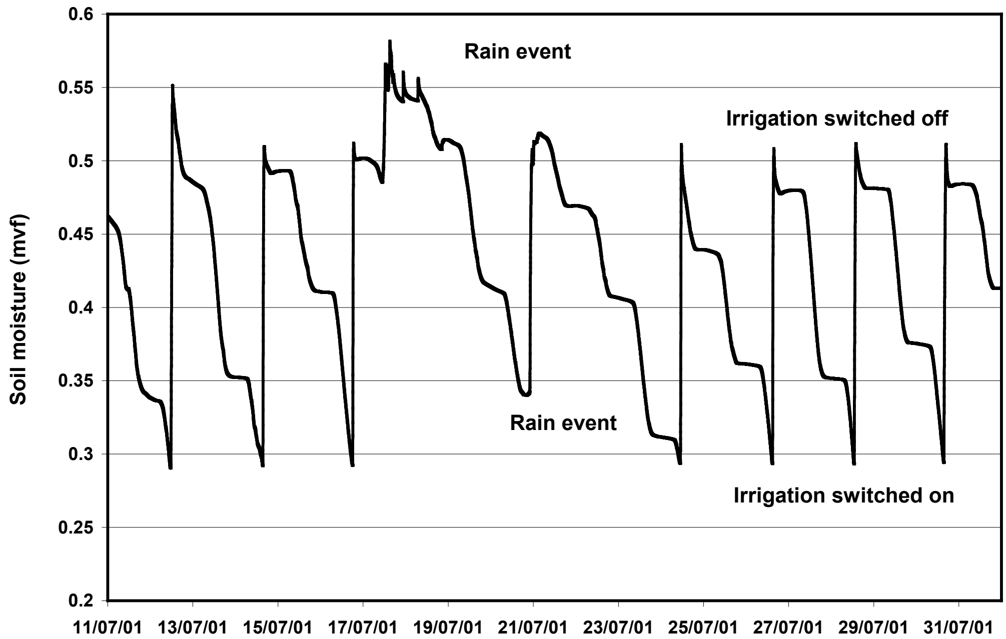


Figure 4.6 In-pot soil moisture variation recorded by the ThetaProbe which triggered irrigation; treatment D, *Hydrangea*, pot 5.

The horizontal parts of the trace shown in Figure 4.6 correspond to overnight periods when water loss is minimal. It can be seen that, in July, irrigation was required every 2-3 days, generally for a period of between 60 and 90 minutes which corresponded to a sprinkler application of around 10-15 mm. The departures from a regular cycle of water content between 0.3 and 0.5 correspond to rainfall events.

The automatic irrigation control in treatment D operated from the beginning of July to the end of the experiment.

Results and discussion

Performance of EvapoMeter and ThetaProbe control, and Water use

The data in Figure 4.7 illustrate how the EvapoMeter readings fluctuated with the weather during the season, with conspicuously low values on rainy days and an overall reduction from summer into autumn.

Hydrangea pot weights remained very similar for treatments A, B and D (Figure 4.8). This shows that Evaposensor control at the 100 % ETp and automatic ThetaProbe control applied similar amounts of irrigation and that this matched closely the gravimetric measurements of ETp (i.e. the amount applied in treatment A).

Pots in treatment C, the 50% ETp regime, were lighter than those in the other treatments almost all the time, but especially during long periods with minimal rain, e.g. late July (Figure 4.8). However, rainfall prevented the establishment of a stable equilibrium weight as seen in the RDI experiments under protection (Unit 1). It can therefore be assumed that the degree of adaptation to water deficit through stomatal closure and reduced leaf growth was much less than occurred in those experiments.

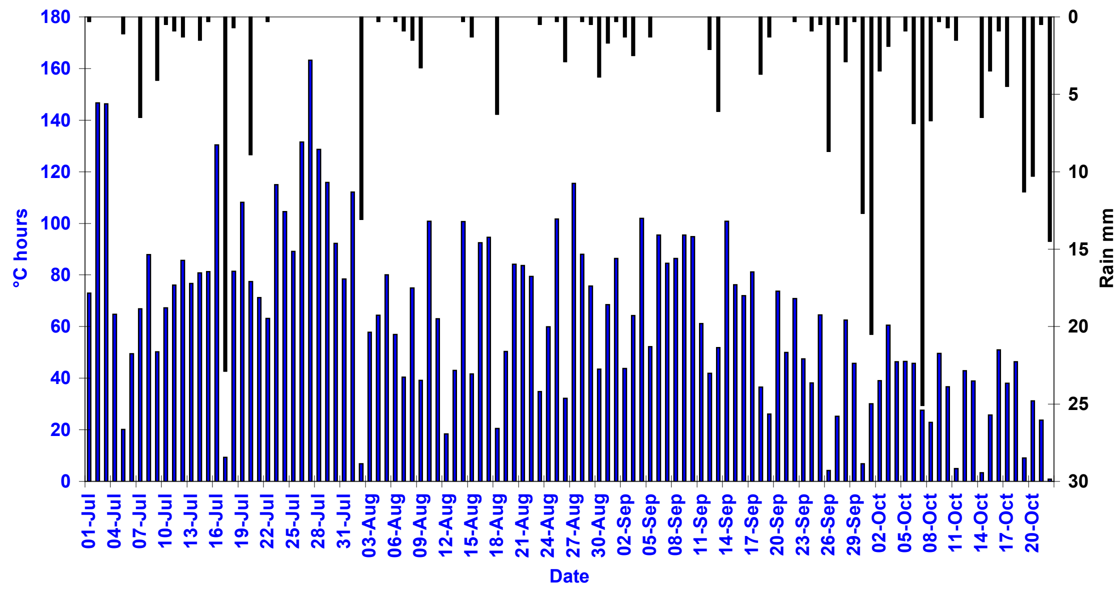


Figure 4.7 Evaposensor 24-hour readings and rainfall

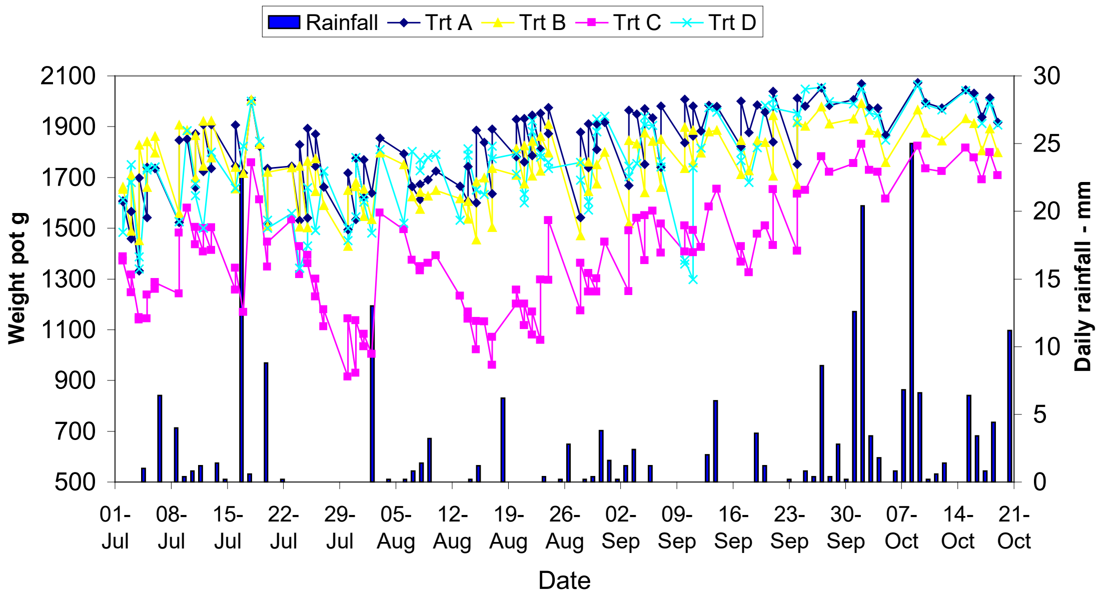


Figure 4.8 Mean pot weights for *Hydrangea* and rainfall

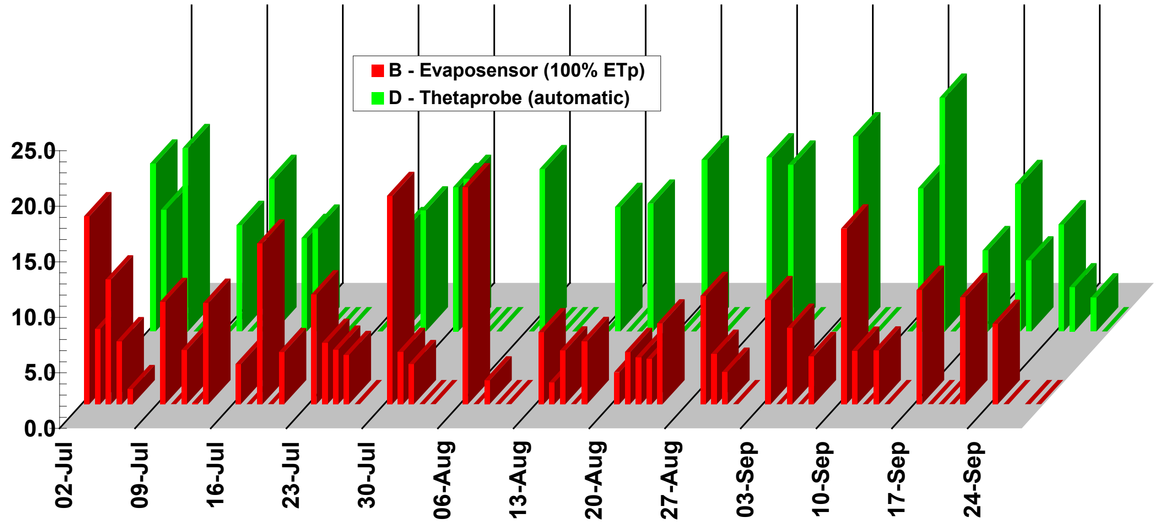


Figure 4.9 Irrigation record showing that applications were heavier, but less frequent, under the ThetaProbe control system than under EvapoMeter-based 100% ETp.

Table 4.1 Water applied to each treatment and rainfall (2001)

Mean mm/day	A	B	C	D	Rainfall
July	5.0	4.4	2.3	4.3	1.6
Aug	3.2	2.7	1.5	2.7	1.1
Sept	2.8	2.4	1.3	3.2	1.2
October	0	0	0	0	4.4
Jul-Sept	3.7	3.2	1.7	3.4	1.3
Jul-Oct	2.8	2.4	1.3	2.5	2.1

Total water use was similar for treatments A, B and D (Table 4.1), but the automatic ThetaProbe control system (treatment D) applied larger volumes of water less frequently - e.g. 2 - 5 day intervals (Figure 4.9). Occasional spot watering by hand of some 'edge plants' was required, particularly on treatment C. Drying of edge plants was observed on central beds as well as the side beds of the main plots. This indicated additional exposure to wind and sun causing accelerated water loss was more of a problem here than inadequate edge coverage from the irrigation system.

The performance of the automatic control system was particularly encouraging. No spot watering was required on this treatment during the trial period from July onwards.

The 50% ETp treatment C received a little more than half the irrigation of treatment B. The extra irrigation arose from two occasions when additional water was applied because pots had dried out so much that they were being blown over and some plants were wilting. It is clear that, for RDI to be practical outdoors, measures to support the plants when the medium dries down are essential. Either the pots must be made heavier, e.g. by a thick layer of gravel mulch, or the pots must be supported in some way (e.g. in a rack).

Soil moisture contents in *Cotinus* pots were generally lower than in the *Hydrangea* pots, which were being used to regulate the irrigation. This contrasts with the similarity in water use of all three species in previous comparisons and may reflect increased sensitivity of the experiment to small differences in water use due to canopy architecture, when high uniformity and precision of water application are achieved. The more open canopy of *Cotinus* means that water loss per unit area is potentially greater because of greater air movement within the canopy (i.e. lower boundary layer resistance). Similarly, the surface of the growing medium is more exposed to sun and wind in a *Cotinus* crop than in a *Hydrangea* crop.

Moisture distribution within pots

Mini-tensiometers at 3 depths (45, 80 and 115 mm) within individual pots provided insights into the distribution and movement of water during irrigation and drying cycles. Figure 4.10 shows tensiometer data from mid-late July (corresponding exactly to the ThetaProbe data in Figure 4.6; note the inversion of the traces because soil suction *increases* as soil moisture *decreases*). The upper layer can be seen to dry more rapidly than the middle and lower layers after each application of irrigation. This was typical for both the *Hydrangea* and *Cotinus* when plant water requirements were being met. However, when the irrigation failed to meet the demand, the situation changes as shown in Figure 4.11. Whilst the irrigation continued to keep the top and bottom of the pot reasonably moist, the middle layer became progressively drier because it was furthest from the points where irrigation could enter the pot and had a high density of roots. The bottom layer also dried out slightly faster than the top, presumably because water uptake through the base was less than direct interception of irrigation at the top of the pot. Root density may also have been greater than in the upper layer. These results support the decision to insert the controlling ThetaProbe deeper than usual, in the middle of the pot.

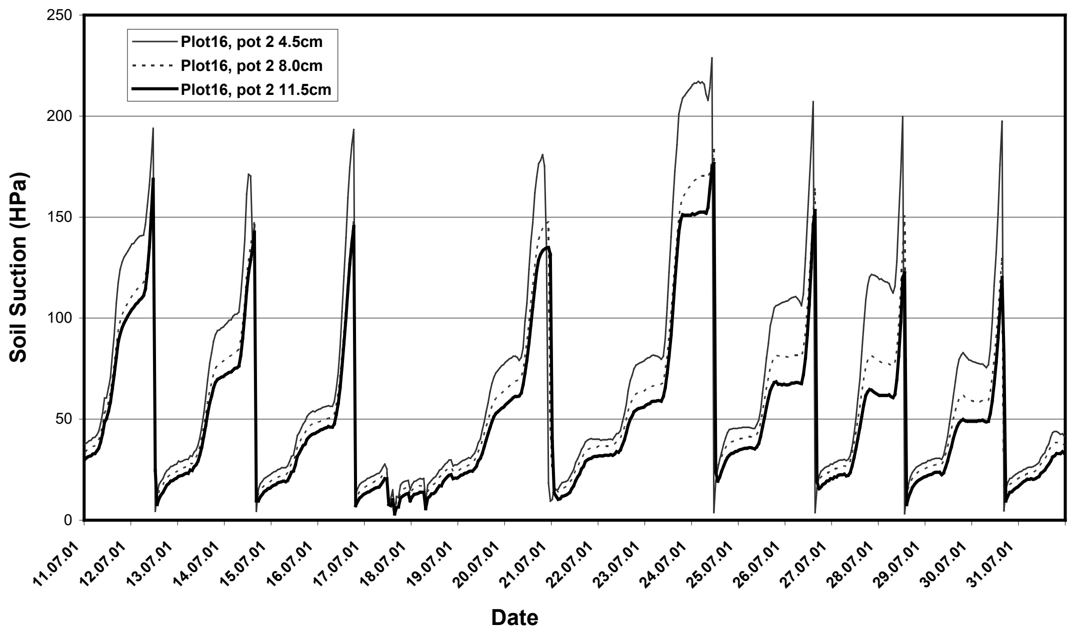


Figure 4.10 Mini-tensiometers at 3 depths, Hydrangea treatment D, Pot 2, during a period of normal irrigation

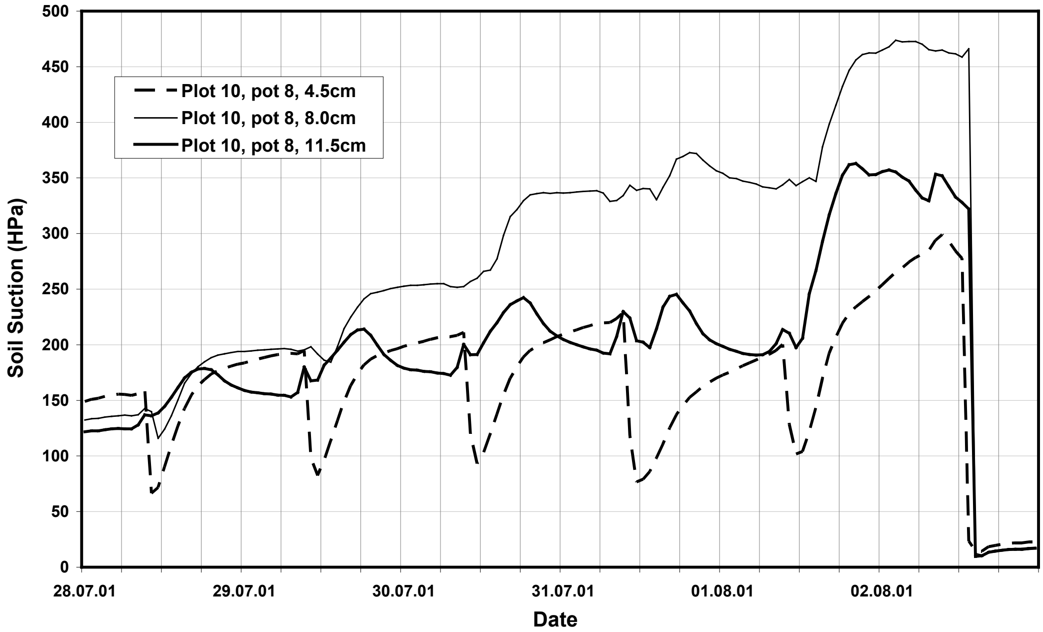


Figure 4.11 Mini-tensiometer traces in *Hydrangea*, treatment A during a period when irrigation failed to match plant water use. Note that the middle layer dried first.

Some water uptake through the base is likely to occur during irrigation, when water accumulates on the standing surface even if it is a water permeable fabric such as Mypex. However, the Mini-tensiometer data provide evidence of long-term capillary uptake *through* the Mypex and point to the likely importance of the standing base on irrigation efficiency. The evidence for capillary uptake lies in the timing of the peaks and troughs in the trace from the 11.5 cm depth tensiometer. The time of daily irrigation is clear from the sharp fall in the 4.5 cm data (dotted line) at around 09:30GMT. Immediately prior to irrigation, the 11.0 cm trace is rising as a result of an early morning increase in water demand. This is reversed only slightly for 1-3 hours after irrigation, after which, it continues to rise to a peak at around 18.00 GMT. Whilst the surface layers continue to dry slightly overnight, the soil suction in the bottom layer drops quite markedly up to midnight and then less slowly for the rest of the night. This suggests strongly that water replenishment of the bottom layer by capillary, gaseous or root uptake from the sand bed through the Mypex was taking place.

These results clearly pointed to the need for further investigation of the importance of bed structure on pathways of water capture by containers and thus on irrigation efficiency.

Plant growth

Greatest growth was recorded under gravimetrically regulated irrigation (treatment A) but differences were small and generally non-significant (Figure 4.12). Final plant height of *Cotinus* was reduced by about 20% in the 50% ETp treatment compared to 100% ETp in treatments A and B, but the effect on *Hydrangea* was small (Figures 4.12 and 4.13). There was also some reduction in growth under the automatic ThetaProbe control system (Figure 4.12), which is probably attributable to the greater drying out of the medium that occurred before irrigation was triggered, compared to the daily irrigation regimes of treatments A & B. The quality of the *Hydrangea* plants under ThetaProbe control was particularly good.

Growth reduction in the 50% ETp treatment was not as marked as in the RDI trials with drip irrigation under protection at HRI East Malling. This is partly because RDI was not started until July, and also because pots were subjected to some rainfall outside. The drying out and occasional wilting of some edge plants in this treatment, and the susceptibility of the dry pots to being blown over, highlighted other practical difficulties of applying RDI treatments outside. Nevertheless, the experiment showed that an irrigation regime running at less than 100% ETp could offer further water saving benefits without loss of plant quality.

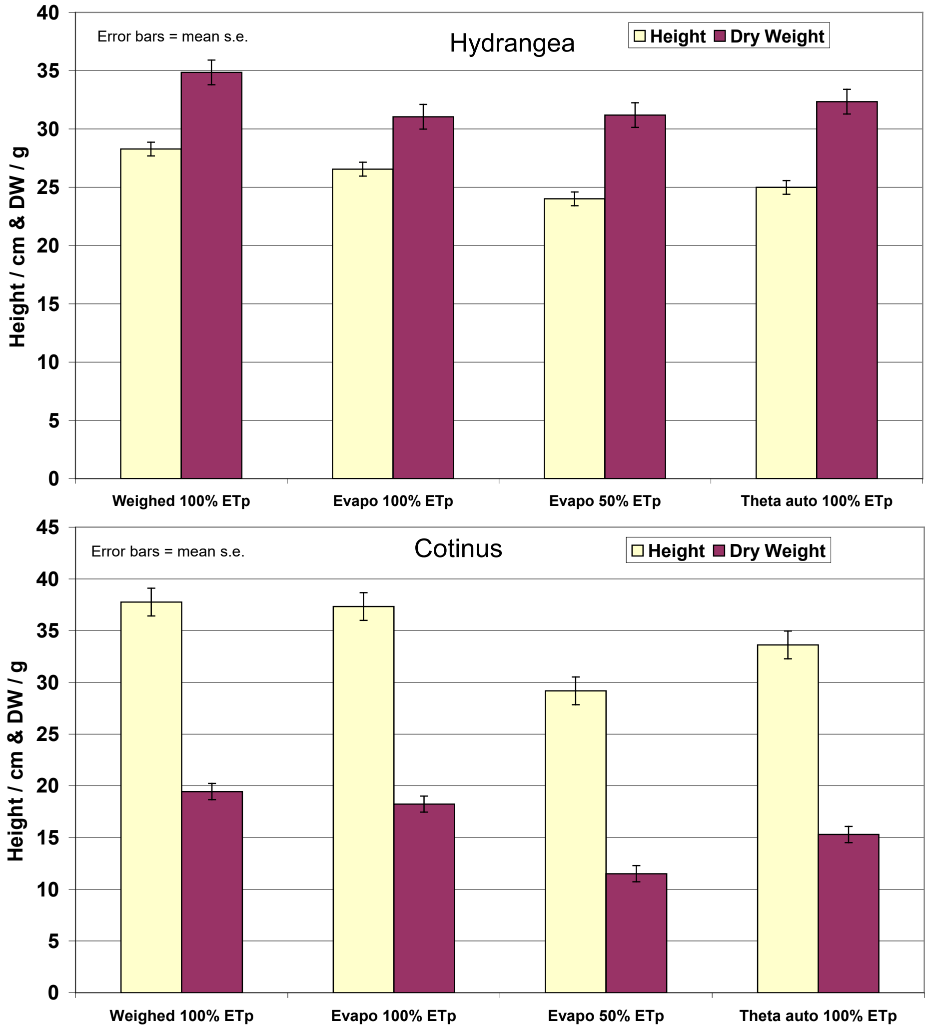


Figure 4.12 Growth of *Hydrangea* and *Cotinus* by the end of the 2001 season

Fig 4.13 *Hydrangea* and *Cotinus* growth by the end of the 2001 season. 100% ETp, treatment A, on the left, 50% ETp, treatment C, on the right.

Main conclusions

- The feasibility was established of automatic irrigation control based on a single ThetaProbe, inserted at appropriate depth into a carefully chosen representative pot.
- Careful design of the irrigation sprinkler system can achieve a high level of uniformity
- Regulation of irrigation to precisely meet plant water requirements is more practicable when the irrigation is applied uniformly.
- Effects of the crop canopy and uptake through the base of the pot can make water capture by containers variable even where the overhead irrigation is uniform.
- The application of less irrigation than required to meet plant requirements (i.e. RDI) on outdoor beds resulted in reduction in growth without leaf scorch
- The severity of RDI was reduced by rainfall so that effects on growth were smaller than have been seen in experiments under protection.
- By allowing pots to become moderately dry before irrigation was triggered, the automatic controller produced high quality plants, showing slight reduction in growth.
- Some drying out of pots occurred in all treatments but occasional rainfall was generally sufficient to correct for this and thus even out differences between plants.

Experiment 4.3: ThetaProbe and Evaposensor control of irrigation on contrasting standing bases

This experiment built on the success of Experiment 4.2, introducing a prototype automatic control unit for the ThetaProbe in place of the programmable logger, and also exploring further the importance of water uptake through the pot base. The main objectives were:

- Evaluate of the use of the EvapoMeter to schedule irrigation when accumulated ETp reaches a threshold value, rather than regulating the amount applied daily.
- Test a prototype electronic 'black box' controller from Delta-T, in place of the expensive DL3000 logger.
- Investigate the influence of standing base (drained sand or gravel) with overhead systems on water use, distribution and uptake by plants.
- Compare water use and irrigation capture of *Hydrangea* and *Forsythia*

Materials and Methods

Plant material

Hydrangea macrophylla 'Blue Wave', 1-year old, in 3 L pots
Forsythia x intermedia 'Lynwood', 1-year old, in 3 L pots

Wetting agent was added to the medium to improve the consistency of water uptake and retention. No summer pruning was applied

Treatment combinations

A	EvapoMeter + Sand
B	EvapoMeter + Gravel
C	ThetaProbe + Sand
D	ThetaProbe + Gravel

EvapoMeter	Irrigation to 100% ETp as estimated by the Skye EvapoMeter, applied when the accumulated total exceeded 300 degree hours
ThetaProbe	Automatic irrigation control based on a single ThetaProbe and a prototype control unit (details below)
Sand	Drained sand bed (single layer of Mypex over sand allowing capillary movement of water in and out of pot.)
Gravel	Gravel (freely drained with no capillary contact across pot base)

Layout of beds and sprinklers

The design and layout of this experiment was similar to that in Experiment 4.2 and is illustrated in Figure 4.14

Figure 4.14 Overview of Experiment 4.3 showing drained sand and gravel standing bases

Use of the EvapoMeter

The results of the previous suggested that there can be advantages in heavier but less frequent irrigation. With 3 litre containers, the water storage capacity typically lasted 2 - 5 days before irrigation was triggered by the ThetaProbe control system. For this experiment, we tried to achieve a similar regime by applying irrigation only when the accumulated ETp registered by the EvapoMeter reached a threshold of about 300 degree hours. A period of calibration at the start of the season was used to find this target level, and check irrigation applications against pot weight gain. The objective was to apply sufficient irrigation to bring containers back to near pot capacity to give maximum moisture reserve, but avoid surplus irrigation to cause wasteful drainage. Then containers were allowed to dry back, before irrigating, to leave some safety margin before wilting occurred, and to accommodate the inevitable pot to pot variation in the crop. In practice a weight of about 900g at the start of the season and 1100 - 1200g by the end of the season were lower limits. Irrigating pots when heavier than about 1700 - 2000g over this period resulted in surplus drainage to waste.

The EvapoMeter was read daily, and the previous 24-hour value recorded. Once an accumulated total exceeded about 300 degree hours, irrigation was applied to match this total and the accumulator was 'reset' to zero. If significant rain wetted up the pots to near 'pot capacity', the EvapoMeter's accumulator was again reset. Otherwise rain was ignored. Irrigation doses were typically 15 - 25 mm (1½ - 2½ hours) in contrast to the smaller daily waterings applied in Experiment 4.2

Prototype automatic irrigation controller

On the basis of the good results obtained with the ThetaProbe control in Experiment 4.2, a meeting in December 2001 identified the main requirements for an electronic control box to take over the function of the expensive DL3000 in the control system. The controller design was quickly evolved and the first prototype was on show at the Consortium Meeting in

March 2002. Subsequently, 5 prototypes were built, of which 4 were installed for testing during the 2002 season: 2 at HRI Efford and 2 at separate commercially run nurseries (further details in Unit 5).

The main objectives in designing the ThetaProbe Irrigation Controller were to achieve the operating requirements whilst:

- keeping the design as simple as possible
- minimising the cost of production

With these points in mind, the main features of the ThetaProbe Irrigation Controller design were:

- take power from existing irrigation solenoid circuit (normally 24v a.c. or d.c.)
- do not incorporate internal clock (cheaper)
- ThetaProbe permanently ‘ON’ when power is supplied via standard irrigation timer. This achieves highest possible temporal resolution and sensitivity for irrigation switching and overcomes need for electronics warm-up timer.
- Use liquid crystal display (LCD) for low power consumption and precision of setting.
- Upper and lower switching points displayed as sensor units (mV) or soil moisture fraction based on organic calibration.

The prototype irrigation control box is shown in Figure 4.15. It would normally be located near to the solenoid control valve which controls water supply to the overhead irrigation nozzles for that bed, preferably under shelter from irrigation and rainfall.
A millivolt signal from the ThetaProbe sensor enters the top of the unit and this is displayed on the LCD either directly in mV or after conversion to an equivalent soil moisture fraction by selection of an internal switch. For the purposes of the field trials, the ThetaProbe signal was also output to a Tinytag solid state data logger where it was recorded at 1 minute intervals, but this would generally not be required when used commercially. Both the electronics for the controller and the ThetaProbe were powered by the 24v a.c. power supply to the solenoid, from the irrigation timer panel. Thus, the settings of existing irrigation timers can be used to prevent irrigation during specific parts of the day, if required.
Depending on the reading of the ThetaProbe, the control unit determined whether power was fed through to the irrigation solenoid valve. To set the threshold values between which the solenoid would be activated, it was necessary to open the front of the control box to gain access to two adjustable potentiometers.

Figure 4.15 Prototype automatic irrigation control unit supplied by Delta-T Devices

The LCD could be set to display either the current ThetaProbe reading or the upper and lower set points by selection of small internal switches. Once the set points had been adjusted to the correct figure, the display was returned to display the ThetaProbe output for normal operation.

Appropriate threshold values can vary according to local conditions (primarily the composition of the growing medium) and growing requirements and they can be determined either systematically or by trial and error at the start of the growing season. The upper threshold (wet end) is the easiest to determine as it is related to maximum water-holding capacity or ‘container-capacity’. The growing medium is brought to saturation, either by prolonged overhead irrigation, by overhead hand watering or by immersion, preferably repeating the operation several times, to ensure that the medium is fully wetted. The containers are then left to drain on a horizontal surface for 20-30 minutes. The reading produced by the ThetaProbe at this point equates to ‘pot-capacity’ and this can either be used directly as the upper threshold or, more likely, a decision made to select a lower value according to plant or water conservation requirements. The rate of moisture increase slows as ‘container capacity’ is approached because water starts to drain from the pot, so the extra irrigation needed to reach ‘container capacity’ is generally not justified.

The lower threshold setting is more difficult to determine at the start of the growing season when the plants are newly potted. Ideally, a water release curve of the growing medium is required to identify the lower limit of ‘readily available’ water, i.e. the water content at a soil moisture suction of 150 cm. However, if the medium is predominantly peat-based, this will normally be in the region of 30% (v/v). This is a reasonable starting point for the lower threshold but if plants show signs of drought stress then the lower threshold should be raised. Furthermore, *it is recommended that the settings are re-assessed 4-6 weeks after* *installation* because consolidation of the growing medium can alter the water release characteristics significantly.

For this experiment, lower and upper thresholds were initially set at 500 and 700 mV respectively (equivalent to approximately 25% and 35% v/v)

Results and discussion

Performance of EvapoMeter

Regular wetting and drying cycles were managed well with the EvapoMeter system from July onwards (Figure 4.16). Some weighing of pots was done after rain, to judge whether or not containers had accumulated sufficient water to justify resetting the EvapoMeter's accumulator to zero. With experience, this assessment could be made without actually weighing pots or it could be judged from rain gauge data.

It was expected that it might be necessary to adjust the calibration of the EvapoMeter during the season as the crop grew. In practice, however, a single calibration held good for the main 'irrigation season' from June to September.

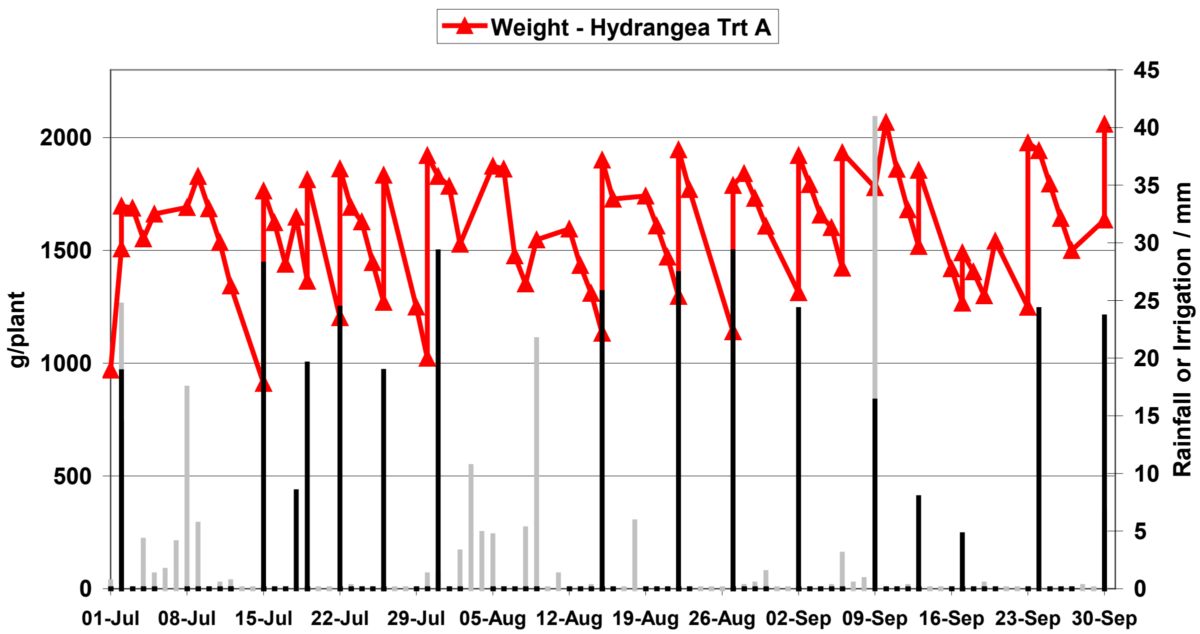


Figure 4.16 Cyclic variation in pot weight associated with irrigation (black bars) and rainfall (grey bars) for *Hydrangea* treatment A.

Performance of the prototype ThetaProbe irrigation control unit

The prototype irrigation controller did not perform with the same precision and reliability as the programmed DL3000 logger had done during 2001. When tested in the laboratory, the controller has worked perfectly, but in nursery conditions there have been many occasions when premature irrigation has occurred before the upper threshold setting has been reached. Although the controller is fitted with electronic filters to reduce the effects of interference on the power supply, it appears that these have not been sufficiently effective to allow unhindered operation in the existing electrical environments. This is a point which has been fully recognised by Delta-T and will be addressed in any future design.

In contrast to the previous experiment, occasional hand watering was required on some *Hydrangea* plants in the beds under automatic irrigation control.

Compaction of the growing medium, combined with the increased volume of the root system, caused a marked loss of air-filled pore space over the course of the season. All of the instrumented containers were brought to 'pot-capacity' at the start and end of the season. Comparison of the results for two occasions showed that 'pot-capacity' increase by approximately 30% over the course of the season. Much of this increase can be accounted for by the water contained in roots, which would have grown mainly through the larger pores that would previously have been air-filled. These data reinforce the need to adjust the threshold settings of the ThetaProbe controller at least once over the course of the year.

Water use

Average water use is shown in Table 4.2. The average over July to September of 3.8 mm/day for treatments A & B was slightly greater than in Experiment 4.2 (3.4 mm/day) and there was also a little more rain over this period. The beds controlled by ThetaProbe (treatment D) used less water than those regulated in accordance with EvapoMeter (treatments A and B). Some of this may have been due to the instability of the prototype controller referred to above, but it is also possible that some of the irrigations applied to treatments A & B were too heavy causing some wastage by drainage.

Table 4.2 Mean water use for each treatment during Year 4 experiment (2002)

Mean mm/day	A	B	C	D	Rainfall
May	1.2	1.5	1.1	0.7	2.6
June	1.9	1.9	2.3	2.3	1.5
July	5.2	5.2	2.8	3.3	2.0
Aug	2.7	2.6	1.7	1.4	1.9
Sept	3.6	3.6	2.2	4.0	1.9
May-Sept	2.9	2.9	2.0	2.3	2.0
Jul-Sept	3.8	3.8	2.3	2.9	2.0

As with *Cotinus* in Year 3, *Forsythia* required hand watering on several occasions indicating that it had a greater irrigation requirement than *Hydrangea*. This could be attributable to the more open canopy of *Forsythia,* as was suggested earlier, in relation to *Cotinus*. Another factor could have been the enhanced capture of irrigation by Hydrangea containers, which was noted in Experiment 4.2. Measurements of water capture by *Hydrangea* and *Forsythia* crops supported that explanation. A heavy irrigation of 25 mm was given to large plants in full leaf on 23 September 2002. Including run-through, *Hydrangea* pots gained on average 1228 ± 39 g / pot compared to 757 ± 42 g / pot for *Forsythia* pots, 38% less than *Hydrangea*. The very different canopy structure that caused this difference is illustrated in Figure 4.17.

Figure 4.17 *Forsythia* and *Hydrangea* plants in early September, 2002

Effect of standing base on water use

There was no overall difference in water use between the drained sand beds (Treatments A and C) and the gravel beds (Treatments B and D). Weight records, following a few irrigation events early in the season, indicated a greater weight gain in pots on sand than in pots on gravel, indicating that some of the water falling between containers was redistributed into the base of the pot. However, once the 'heavier and less frequent' irrigation regimes were established, there was no difference in net weight gain on the different standing bases. For example, in September, 25 mm of irrigation brought about a net weight gain of 651 ± 24.5 g in pots on Mypex covered sand, compared with 619 ± 27.5 g in pots standing on gravel.

The sand bed may contribute to some capillary uptake during irrigation, but following heavy applications that fully wet up the pot, the drained sand bed is expected to draw surplus water out of the growing medium. In pots standing on gravel, this cannot happen and extra water is likely to be held in the medium above a 'perched' water table. The net effect was that water use was very similar in both treatments.

Data from logged ThetaProbes and Mini-tensiometers supported the above interpretation and provided additional insights. For example, Figure 4.18 shows that, during a wet period from 1 to 10 July, the gravel was about 20 % wetter than the sand. During the subsequent dry period there were 17 automatic irrigation cycles recorded on the sand/Mypex plot compared to 12 on the gravel plot. From the high point of 10 July, there was a much more rapid moisture loss from the sand bed than from the gravel. These effects suggest that the sand base is drawing moisture out of the growing medium by capillary pull, reducing the amount available to the plants. It is relevant here that the sand beds were being run as 'drained sandbeds', not as capillary irrigation beds with a maintained water table.

Figure 4.18 also includes evidence of the effects of consolidation of the growing medium as described under Materials and Methods. During the dry period in the latter half of July, the wetting and drying cycles became very short as the quantity of water stored between the initial thresholds was reduced due to changes in water release characteristics. Table 4.3 summarises the adjustments which were made to the upper and lower thresholds to continue to make good use of the water holding capacity of the medium.

Table 4.3 Adjustments made to ThetaProbe irrigation controller threshold settings during 2002 growing season.

Date	Lower Threshold (mvf)	Upper Threshold (mvf)
25 April 2002	0.25	0.35
02 August 2002	0.25	0.40
02 September 2002	0.27	0.43

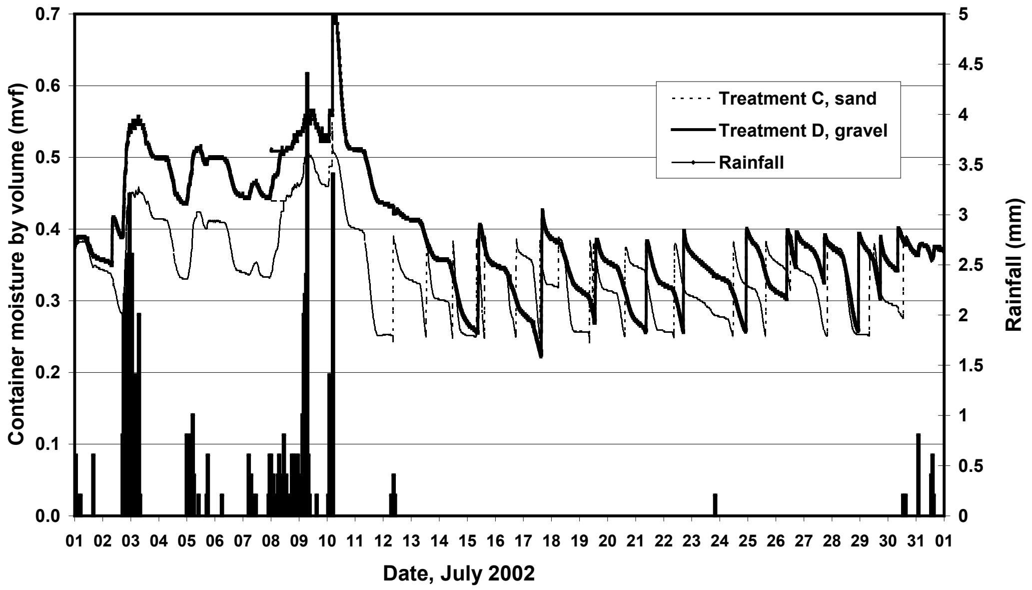


Figure 4.18 Comparison of automatic irrigation cycles on sand and gravel bases during wet and dry periods, based on data from the controlling ThetaProbes.

The mini-tensiometers provided insights into the effect of standing base on the distribution of water within the pots. Figure 4.20 shows data from a pot standing on gravel, with irrigation under ThetaProbe control. Again, the contrast between the wet first half and the dry second half of the month can be clearly seen. Although irrigation took place about every 2 days, it was only effectively wetting the upper and middle layers, with the result that the bottom of the container gradually dried.

A different pattern was seen in pots on a sand base (Figure 4.21). Between 14-19 July, the top and bottom layers behaved similarly and reflect the individual irrigation events. After 19 July, the top layer dried out, but the base continued to respond to irrigation events. As this occurred when the middle layer was dry, the bottom layer must have been taking up water through the base by capillary movement through the Mypex.

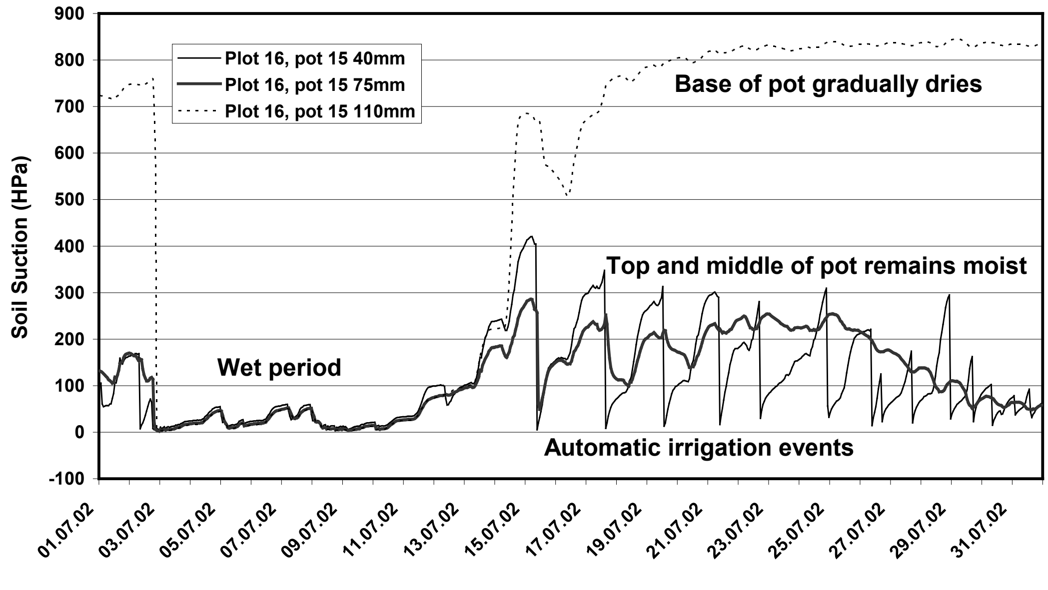


Figure 4.20 In-pot moisture distribution within treatment D, gravel, July 2002

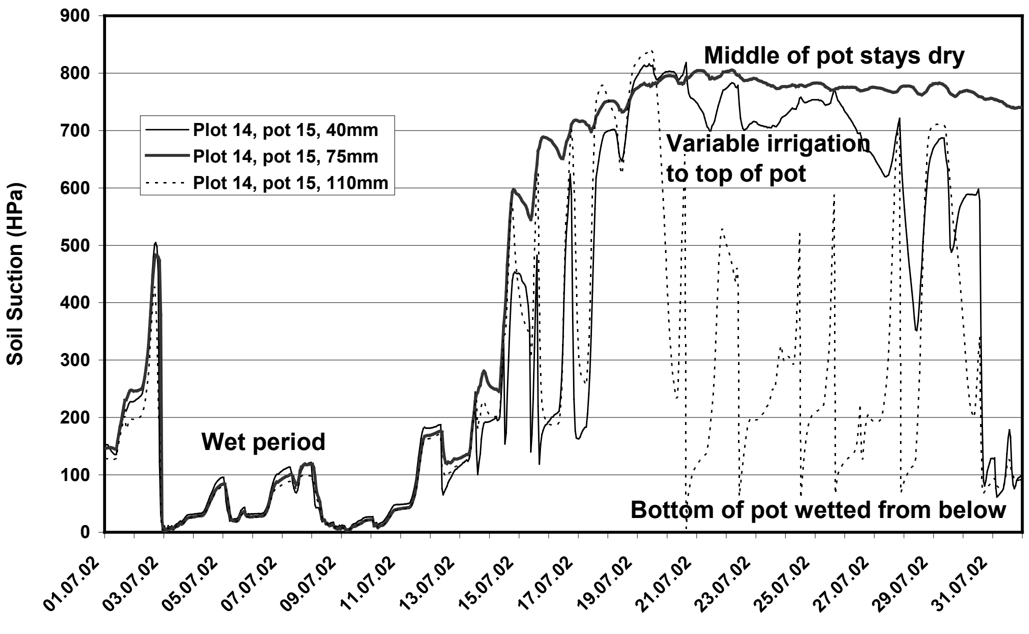


Figure 4.21 In-pot moisture distribution within treatment C, sand, July 2002

Plant growth

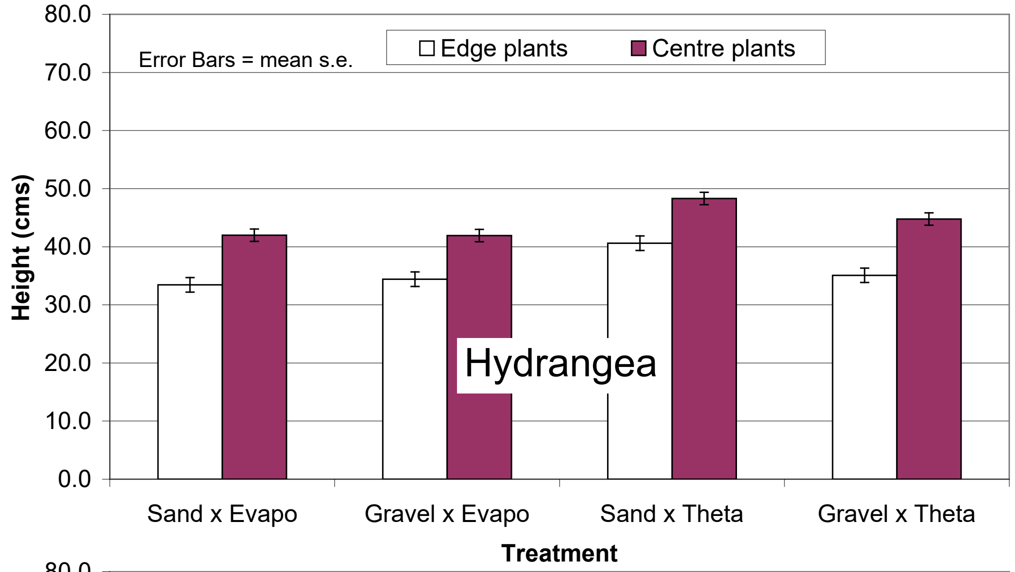
Liners were well branched on arrival in spring, and the initial flush of growth while under protection was further pruned prior to plants being stood on the outdoor beds. This was to even up plant size between species so that initial water requirement would be similar.

In contrast to Experiment 4.2, no summer pruning was undertaken. By the end of the summer neither *Hydrangea* nor *Forsythia* were compact enough for the best quality. It appears that, without RDI or other means of growth control, early spring potted crops of both species require a summer prune even if liner material is well branched

Neither the method of irrigation scheduling, nor the type of standing base had a large influence on final plant size or shoot number. However, there was a significant edge effect on the height of *Hydrangea* plants (Figures 4.22 and 4.24). The perimeter row of plants was noticeably shorter, and developed autumn colour more rapidly. The edge effect was smaller and not significant in *Forsythia*. Since the *Hydrangea* canopy was very dense, low light levels were probably partly responsible for more elongated shoots in the centre of the plots, as well as reduced water loss compared with more exposed plants at the edges.

Figure 4.22 Edge effects clearly visible in *Hydrangea* (left) but not *Forsythia* (right).

Figure 4.23 Centre and edge plants of *Hydrangea* (left). Method of capturing run-through using a polybag lined 2 litre pot under the 3 litre container (right).



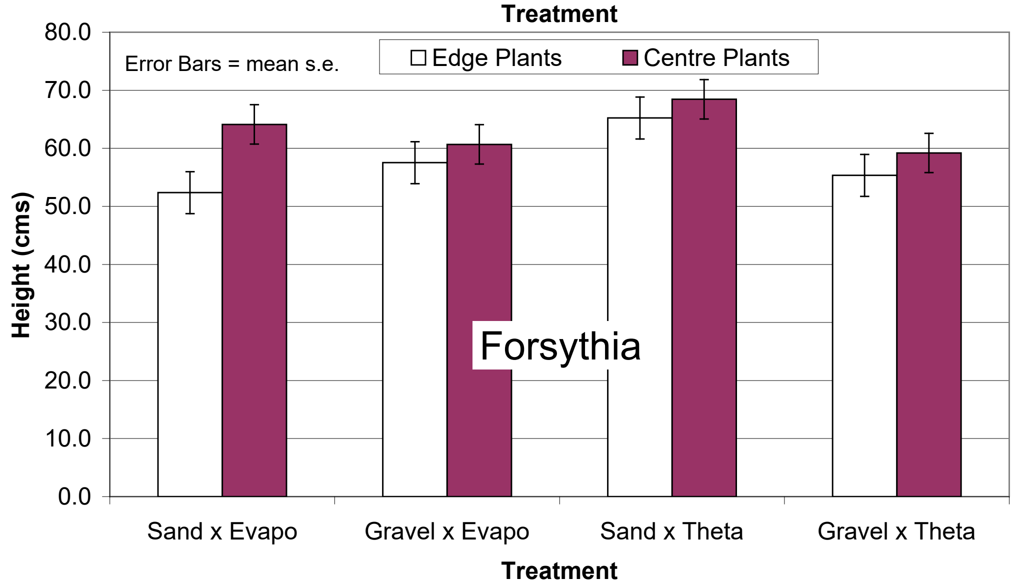


Figure 4.24 Effect of treatments and plant position within plot on Height by end of season

Figure 4.25 Rooting through from undisturbed pots on gravel (left) and Mypex over sand (right) by autumn 2003

'Rooting through'

Containers that were regularly lifted for weighing assessments, did not root out of the container, but undisturbed pots, particularly *Forsythia* on the gravel base, formed a significant amount of root in several cases (Figure 4.25). The Mypex layer on top of the drained sand bed did not prevent roots emerging from the container, but they formed a fine mat underneath the pot rather than penetrating through the Mypex layer into the sand. The presence of a root mat could influence the nature of capillary contact between the pot base and the sand bed for example. The development of roots outside the container further complicates understanding the process of movement of water into and out of containers, which could not be explored within this project.

Conclusions

- Careful design and calibration of overhead irrigation systems to ensure good uniformity and an appropriate application rate is an important step towards saving water.
- A practical method for checking irrigation system performance against standards has been demonstrated in this project. A spreadsheet Water Distribution Calculator has been made available to growers to help with this process.
- Observing 'run-through' is a good indication of excessive irrigation. A smaller pot, lined with a polythene bag, creates a convient reservoir to collect run-through.
- Over 3 years experiments at HRI Efford, July - September water use on an outside crop to meet 100% ETp averaged 3.4 - 3.8 mm/day, with 1.3 - 2.0 mm/day average rainfall with an overhead system on a well drained gravel or sand standing base.
- Further reductions in water use are possible with only small effects on plant growth as shown by the 50% ETp treatment in Year 3.
- There are practical difficulties in applying RDI treatments outside. These include unwanted rainfall, lightweight pots susceptible to blowing over.
- The nature of the foliage canopy can have a significant effect on efficiency of water capture, and water loss through exposure to the growing medium to wind and sun. *Hydrangea* proved not to be any 'thirstier' than *Forsythia* or *Cotinus*.
- The Skye EvapoMeter + Evaposensor has been used to successfully schedule irrigation on a semi-commercial scale outdoor crop in 2 seasons.
- Some calibration by pot weighing is necessary initially, to link weight loss of individual crops to EvapoMeter readings, and weight gain to irrigation times. The EvapoMeter output can be used to guide how long to irrigate (e.g. a daily adjustment of timeclocks), or when to apply a larger fixed dose (irrigating after a °C hour 'trigger alert' total had accumulated).
- A single EvapoMeter + Evaposensor unit could be used to monitor ETp across many cropping areas on the nursery provided they were in a similar environment (e.g. outdoor beds with no shade). Separate calibrations would be needed for areas of different crop type, pot size and irrigation systems for example. However, the unit also has application for nurseries using irrigation controllers where a single % adjustment can be made to many stations simultaneously. Up or down adjustments to baseline timer settings can be readily implemented using EvapoMeter records.
- In the two years experience of scheduling with the EvapoMeter, ignoring rainfall except when it was obvious that sufficient had fallen to wet up pots appreciably was found work satisfactory on our semi-commercial scale experiment. However, recording

rainfall on the nursery is straightforward and inexpensive, and it may be helpful to be guided by rainfall data as well as observation of pots.

- Automatic irrigation control (100% ETp) using the output from a single ThetaProbe in a representative container worked extremely well. The uniformity of the overhead irrigation was good enough for little or no need for spot watering in the *Hydrangea* crop where the probe was located.
- The Delta-T prototype switching device looked promising in 2002, although some further development is needed to solve the occasional erratic performance that occurred in the Efford experiment.
- Further development work is needed to fully evaluate the use of both the Skye EvapoMeter and Delta-T ThetaProbe switching devices for commercial nurseries, including their applicability to different irrigation systems, smaller containers than 2 or 3 litres, and its use with protected crops. Further work is also needed to evaluate these devices to schedule or control RDI regimes where greater precision is needed.
- The type of standing base will affect both drainage of surplus water and the potential for capillary uptake through the base of the container. However, a freely drained capillary standing base, such as a sand bed or even a well drained sandy soil, may not necessarily reduce water consumption compared to a gravel bed when used with overhead irrigation.
- The use of well branched liners, if potted in early spring, does not remove the need for a summer prune in order to obtain compact plants of vigorous species such as *Forsythia, Hydrangea* and *Cotinus*.

Unit 5: Economic evaluation of the costs and benefits of improvements in irrigation control equipment (Objective 8)

This Unit covers work towards the following scientific objective:

8. Provide an economic model to predict the costs and benefits of reducing water use on nurseries in different regions.

Introduction

The first step in evaluating the economics of investment in water saving technologies was to establish the extent of over-irrigation in the industry today and thus quantify the scope for reducing irrigation. An economic model of HONS container production was then constructed as a basis for cost benefit analysis. Finally, the model was used to analyse various scenarios.

Opportunities to reduce water use

The scope for water saving clearly depends on the extent of over-irrigation in the industry at present. Three parts of the project provided relevant data: a survey of water use data on four nurseries, water distribution data on three nurseries, and water savings achieved by the use of the prototype irrigation controller on two nurseries.

The survey

Water use was monitored over two growing seasons on four nurseries, representing different parts of the country (Figure 5.1). Water meters were installed on the supply pipes to at least one outdoor bed and one protected bed on each nursery. The type and size of water meters appropriate to each installation was determined by use of a clamp-on ultrasonic flowmeter and local site data. From this information, a mix of 40mm rotary piston and 50mm Helix meters were selected. Meters were installed during the spring of 2000.

The nurseries were asked to provide a record of water use on a daily basis, measure the rainfall and weather conditions and provide data on the beds being monitored, specifically:

- Bed area
- Sprinkler type and distribution radius;
- Crop data (species, pot size, pot spacing);
- Approximate size of plant on placement onto and removal from bed;
- Media composition.

Data loggers were installed for the 2000 season to confirm that manual recording of water meters would provide a sufficiently detailed and accurate record of irrigation events.

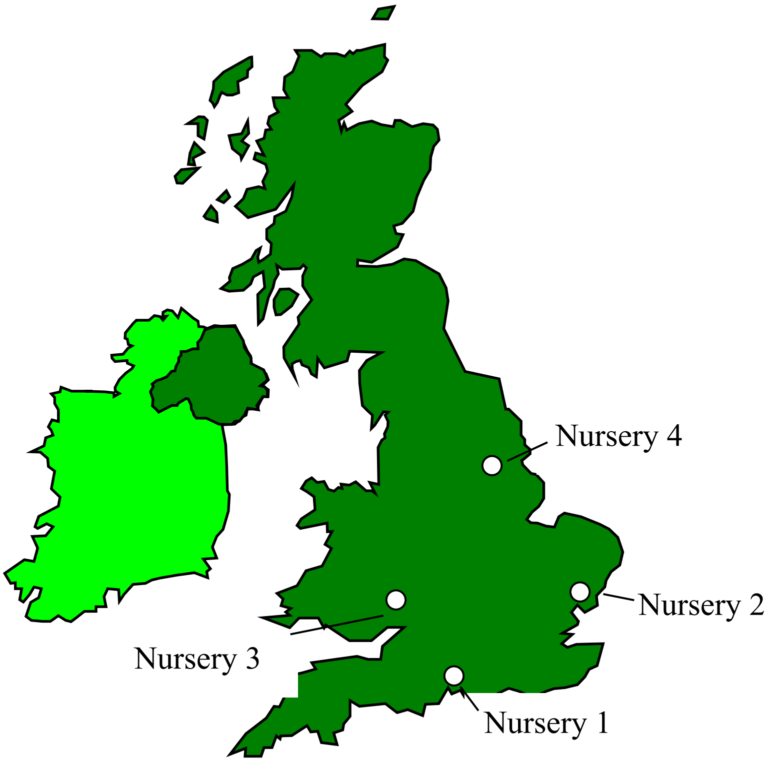


Figure 5.1 Distribution of monitored nurseries

In 2000, full data were obtained from nurseries 3 and 4 and some data from nurseries 1 and 2. In 2001, data were obtained from nurseries 2, 3, and 4 over the full growing season

Data from the loggers showed that the volume of water applied was approximately proportional to the duration of irrigation, which varied from 0 to 40 minutes but was usually between 10 and 20 minutes.

There were some minor discrepancies between manual and logger records. Nurseries were encouraged to read the meters as consistently as possible every day for the 2001 growing season.

Results

Detailed results, along with information about the beds monitored on each nursery in 2001, are provided in Appendix 4. The data showed that the amount of water applied varied between nurseries, often 2-fold and up to 4-fold, suggesting that some nurseries, at least, are over-irrigating substantially.

The irrigation requirement generally peaks in July and August when crops are well developed, and the weather conditions create high evaporative demand. Water use on the outdoor bed averaged 4.88 mm/day in that period, compared with 3.31 mm/day of the beds under protection (Table 5.1). To decide whether that was more than was required and, if so, by how much we have to estimate how much water the plant actually required.

Table 5.1 Water use (mm/day) on the surveyed nurseries on outdoor beds and covered beds (i.e. beds in a glass or polythene house) averaged over the July-August period.

Nursery	Irrigation		Rainfall		Rain + irrigation	
	2000	2001	2000	2001	2000	2001
Outdoor beds						
1	4.3	-	1.1	-	5.4	-
2	3.9	2.3	0.7	3.1	4.6	5.4
3 (bed A)	7.4	6.3	1.0	1.7	8.4	8.0
3 (bed B)	-	3.1	-	1.7	-	4.8
4	5.9	5.8	1.5	2.5	7.4	8.3
Mean	5.38	4.38	1.08	2.25	6.45	6.63
Grand mean	4.88		1.66		6.54	
Covered beds						
1	3.9	-	not applicable		not applicable	
2	3.6	1.9				
3	4.6	4.9				
4	1.2	3.1				
Mean	3.33	3.30				
Grand mean	3.31					

Estimates of potential evapotranspiration based on weather data for those months averaged 3.0 mm/day for the same period (Penman values for East Malling and evaporation pan data for Wellesbourne, 2000 and 2001). That figure applies to a reference crop and would probably be an overestimate for HONS crops. That would suggest that at least 63% and quite possibly 100% more water was applied than the plants used, implying potential water savings of from 39% to 50%

However, we know that not all of the water applied would have reached the plants, largely because of water falling between the pots. If plants are on clean gravel, there is little chance of water falling between pots being taken up through the base instead. In that case, even where plants are pot-thick (i.e. minimum spacing), 21% of water applied will run to waste between the round pots. Most of the nurseries in the survey reported spacing of about 25 cm between centres. That spacing implies a potential wastage of 55% for a 3 L pot (19 cm diameter) and 68% wastage for a 2 L pot (16 cm diameter). To compensate for that wastage, the irrigation required increases by 120 % and 211% for 2 and 3 L pots respectively. In practice, some of the water falling between pots is taken up through the base so that wastage is less than these theoretical predictions would suggest.

An alternative comparison can be drawn between water use on the nurseries in the survey and water use in the experiments at Efford, in which we aimed to match irrigation to plant requirements (Table 5.2). This suggests a much smaller degree of over-irrigation on the nurseries: average irrigation on the nurseries (4.88 mm/day) was 41% greater than the average for Efford (3.46 mm/day). In terms of potential water savings, that amounts to 29%.

Table 5.2 Water use (mm/day) at Efford on beds irrigated to match ETp, estimated in a variety of ways (Experiments 4.2 and 4.3)

	Irrigation		Rainfall		Rain + irrigation	
	2001	2002	2001	2002	2001	2002
Gravimetric	4.1	-	1.3	-	5.4	-
Evapometric	3.5	3.9	1.3	1.9	4.8	5.8
ThetaProbe	3.5	2.3	1.3	1.9	4.8	4.2
Mean	3.70	3.10	1.30	1.90	5.00	5.00
Grand mean	3.46		1.54		5.00	

Evidence from water savings achieved in trials of the automatic controller

The primary purpose of the field trials with the automatic control unit was to get user-feedback from the industry on its ease of use and performance. Additionally, the trials provided estimates of the degree of overwatering of a reference bed that was being controlled in the usual way, i.e. manual setting of a time clock based on intuition, experience and, to a limited extent, weather forecasts.

Trial at Orchard Nurseries

The first unit to be installed (on 09 April 2002) was at Hugh Nunn’s Orchard Nurseries near Evesham (Figure 5.2). One of the design objectives for the irrigation control unit was that it should make use of the power supply to the irrigation solenoid valve. At Hugh Nunn's, the control unit behaved so erratically on this power circuit that it was provided with an independent power supply, which proved more successful.

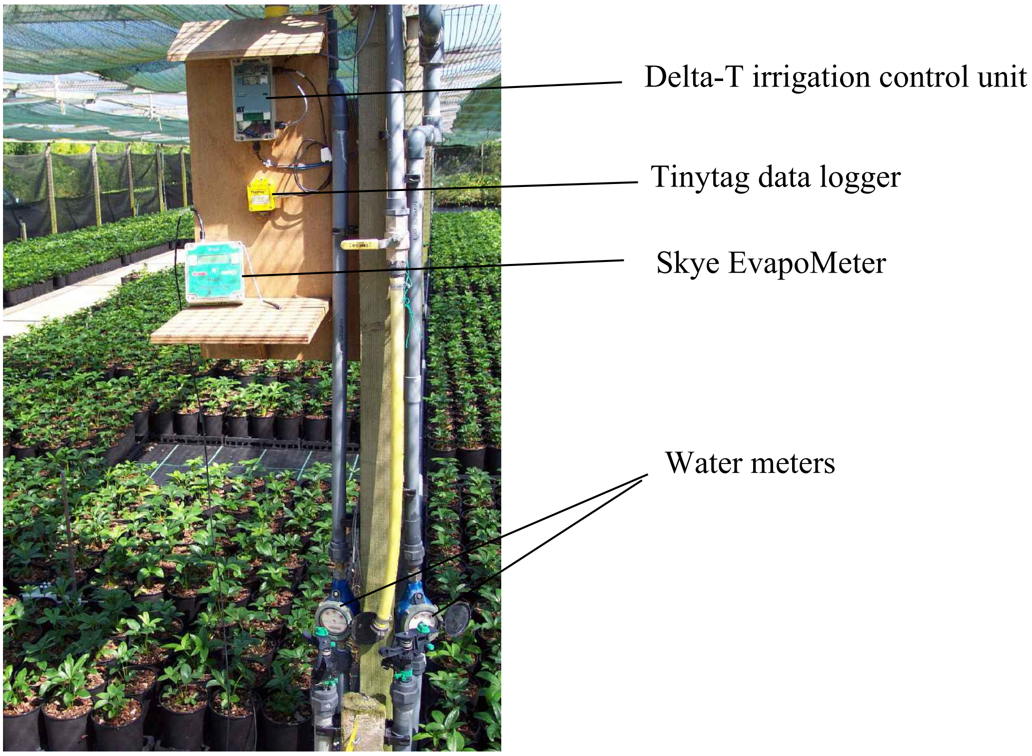


Figure 5.2 Installation at Orchard Nurseries, Evesham showing Delta-T irrigation control unit, Tinytag data logger and Skye EvapoMeter and water meters.

Water meters were installed to enable the automatically irrigated bed to be compared with an identical bed (31m x 8m, of *Hellibores* in 2 L pots) that was irrigated normally.

Irrigation thresholds were initially set to those used in the 2001 field trial at HRI Efford, but were found to be too high because of differences in the growing medium composition. A 'pot-capacity' test provided a more realistic setting. Both upper and lower thresholds were adjusted slightly over time to suit the grower's requirements (Figure 5.3). Orchard Nurseries opted for a fairly narrow range which kept the *Hellibores* moist but not wet and generally resulted in irrigation every 2 days in dry, sheltered conditions.

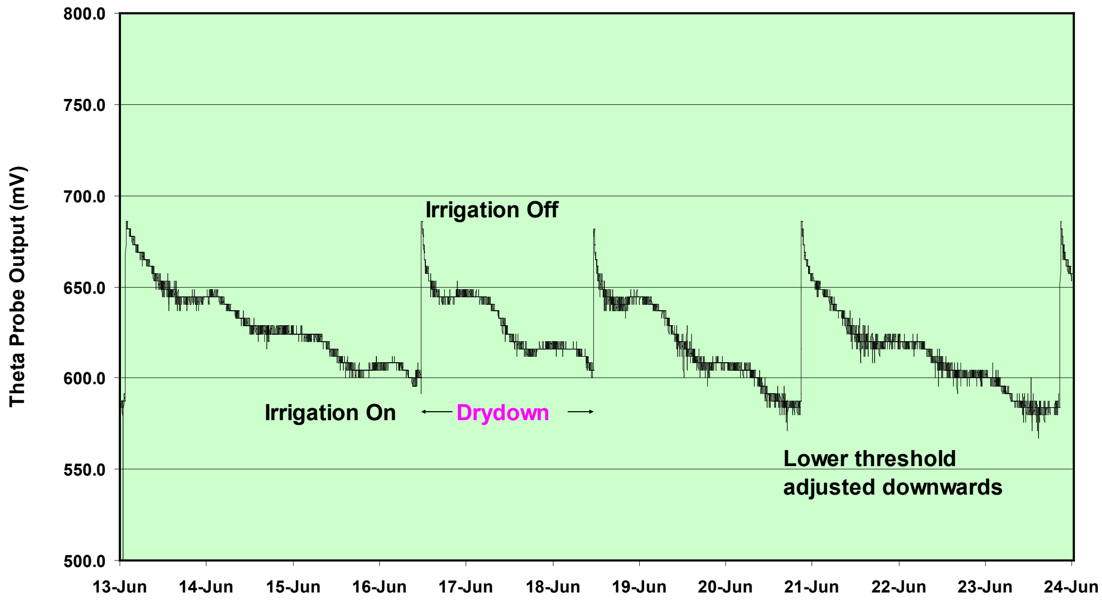


Figure 5.3 Typical irrigation cycles (approx. 2 days) recorded by ThetaProbe output from Orchard Nurseries, Evesham.

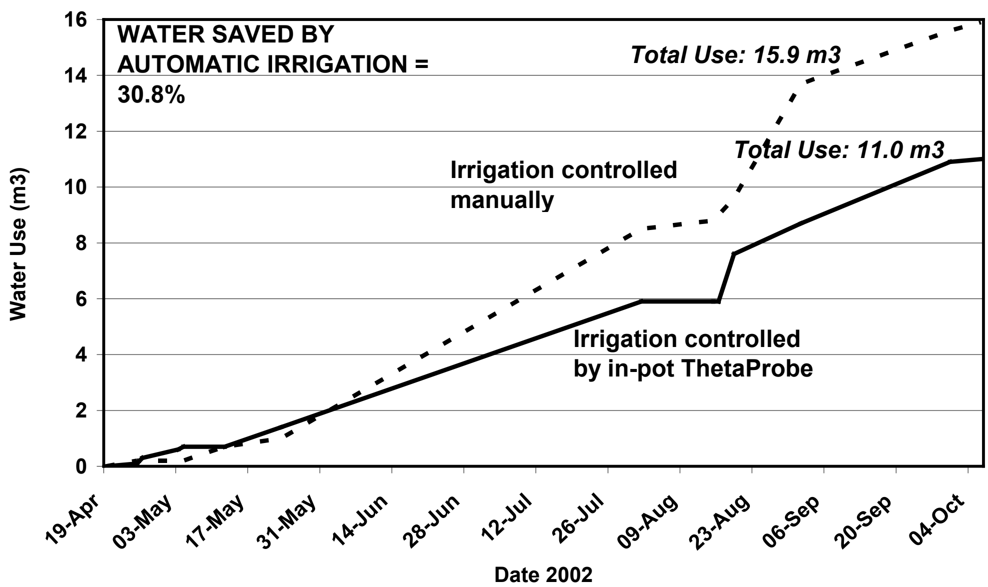


Figure 5.4 Comparison of water use by manual and automatic irrigation control on *Hellibore* beds at Hugh Nunn's Orchard Nursery

The difference in water use between the two beds is shown in Figure 5.4 which shows that the automatically controlled bed used consistently less water. Over the whole season this amounted to a saving in water of 30.8% through the use of an automatic irrigation control designed to meet plant requirements exactly. Expressed in terms of overwatering, the results indicate that manual control overwatered by 45%.

Trial at Notcutts

The second irrigation controller was installed at Notcutts Container Unit at Pettistree on a much larger bed (101m x 13m) of mixed varieties. Because of the large size of the container unit, the opportunity for irrigation was restricted to about 40 minutes in the morning and evening. Consequently, it was not possible to obtain a continuous record of ThetaProbe output from this site. Because irrigation was not available 'on-demand' it was possible, during the intervening period, for the containers to dry to a level below that set by the lower threshold. Once power became available, irrigation would begin immediately and would continue until the upper threshold was reached. In some cases, power may have been switched off after 40 minutes before the upper threshold had been achieved. Nevertheless, the degree of control was still good enough to keep the bed adequately watered throughout the season, and no loss of stock was reported.

Here, the recorded saving in water were even larger at over 40% (Figure 5.5), but it should be noted that the plants on the manually regulated bed were slightly older (due to re-stocking of the automatically controlled bed) and would have had a higher water demand. Allowing for this, a saving of around 30% is probably more realistic.

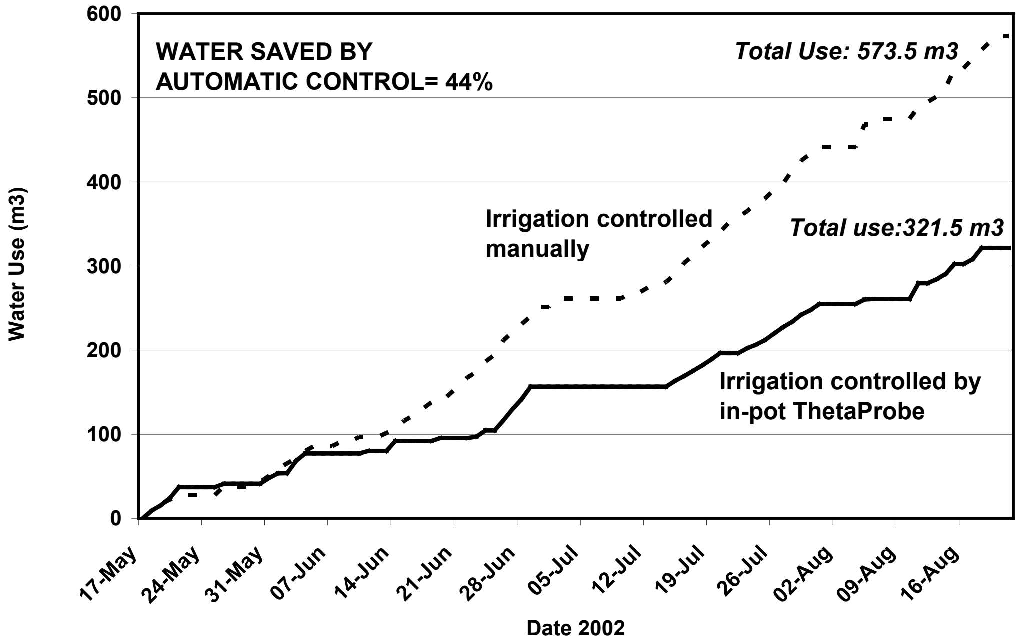


Figure 5.5 Comparison of water use by manual and automatic irrigation control on a bed of mixed varieties at Notcutts Container Unit, Pettistree

Both commercial operators seemed satisfied that the control system was keeping the plants in good condition and would be happy to make use of it on a wider scale. However, both had found it necessary to carry out additional hand watering at certain times and to overcome the inevitable dry spots.

Water distribution on nurseries

Figures 5.6 to 5.8 show beds on which the distribution of water was assessed and the results in the form of a 3D graph. Alongside the graphs, three key parameters are listed: Mean Application Rate (mm/h), Coefficient of Uniformity, and Scheduling Coefficient. Refer to the methods section of Unit 4 for the meaning of these terms and the procedure used to collect the data.

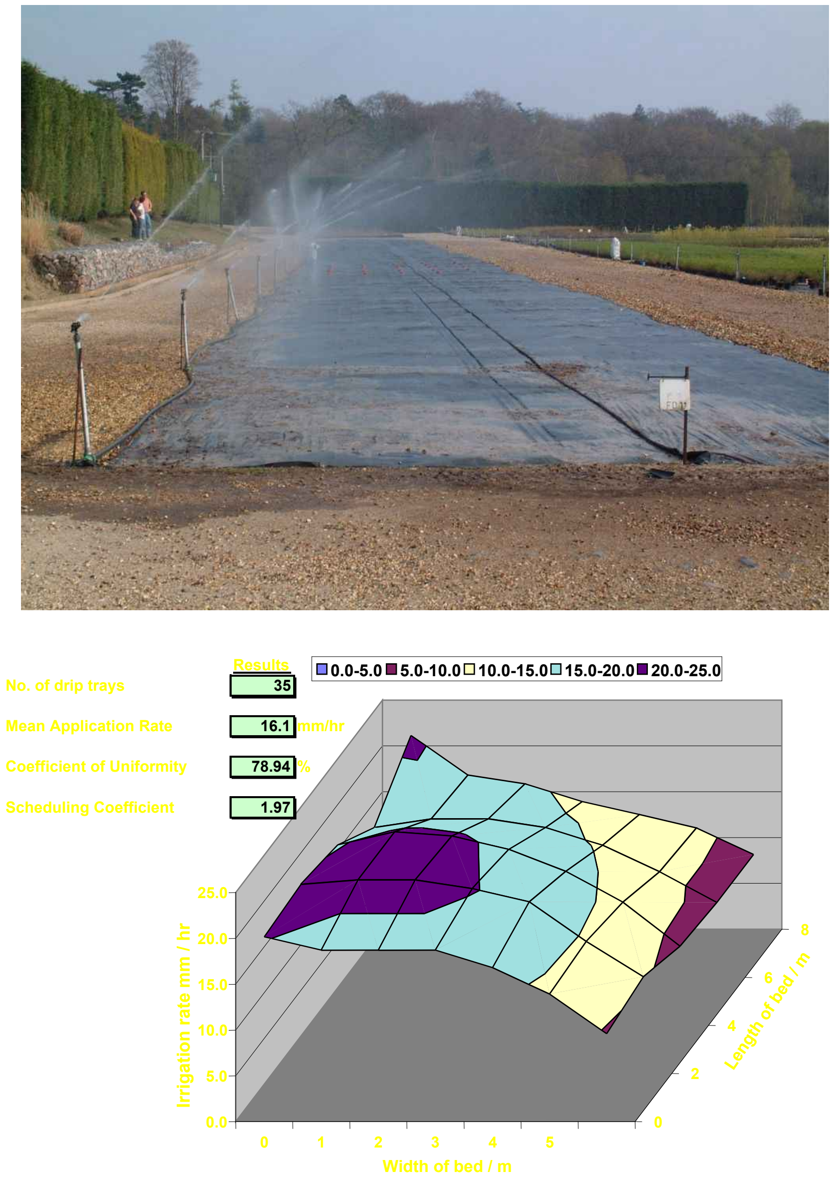


Figure 5.6 Nursery 1: a 'half-bed' equipped with 180 ° impact sprinklers. No wind during measurements

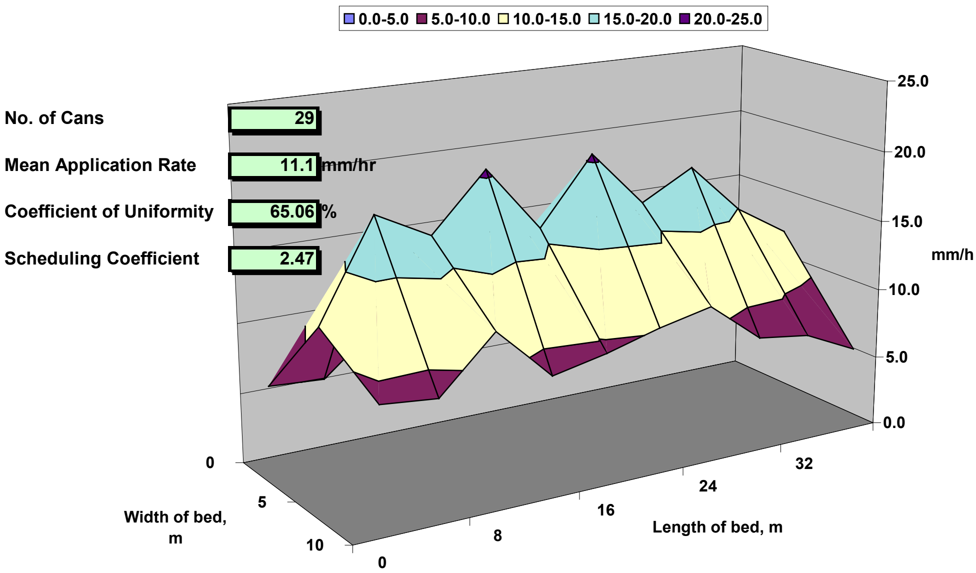


Figure 5.7 Nursery 2: bed used in the water use survey, equipped with 360 ° impact sprinklers. Moderate breeze from the NE (front right).

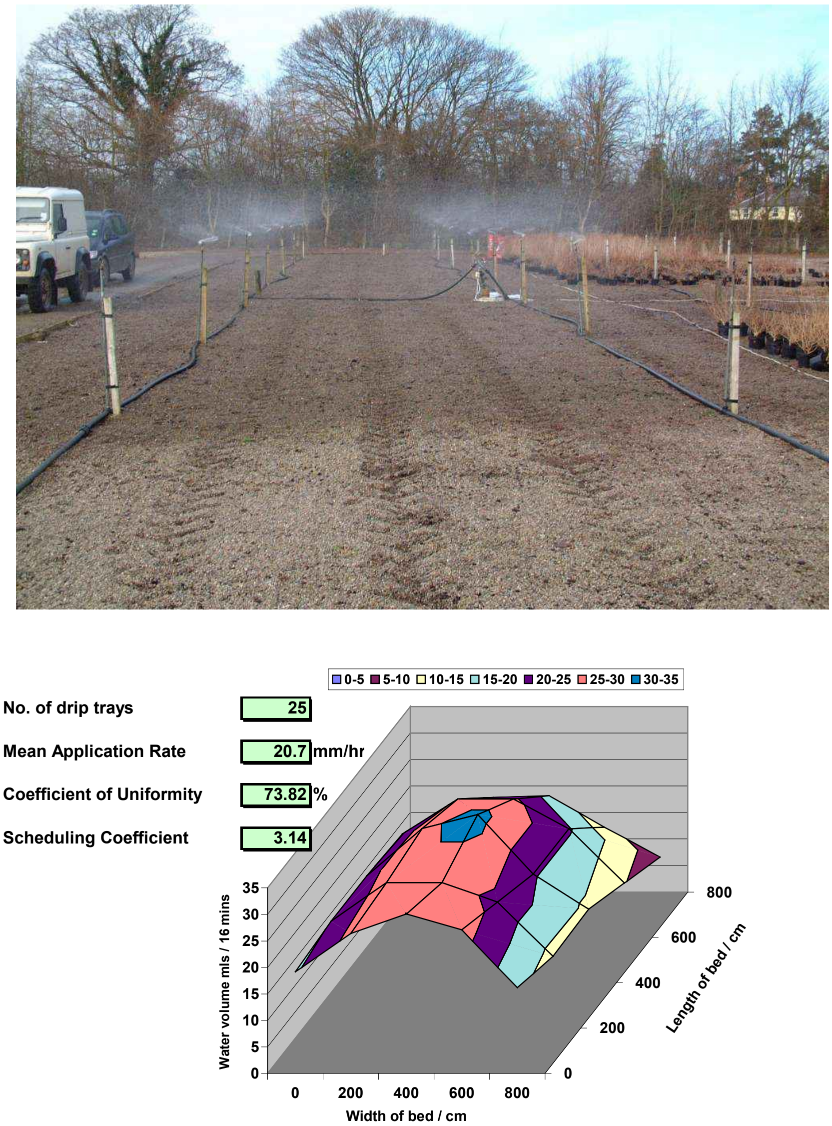


Figure 5.8 Nursery 3: Bed equipped with Rotoframe sprinklers.

These data show that substantial over-irrigation would be needed on all these beds to compensate of uneven application. The scheduling coefficients indicate the average degree of overwatering required to apply the intended amount to the driest part of the bed. On nursery 1 it was 1.97, i.e. 97% over-irrigation would be required. On nursery 3 it was 3.39, i.e. 239% over-irrigation required. In practice, the driest spot would change from day to day with wind direction, or would receive supplementary watering by hand or from a mobile sprinkler. However, large areas of the distribution 'maps' received substantially different rates of watering. For example, on nursery 1, there were substantial areas in both the 10.0-15.0 mm/h and 20.0-25.0 mm/h ranges, with an average difference of 80%.

High rates of application would add further inefficiency, especially on nursery 3, where the mean application rate was 22.4 mm/h, which is well above the target maximum of 15 mm/h.

Conclusions

The unevenness of overhead irrigation creates water wastage. Large areas of the beds have to receive as much as 80% more water than needed, if plants in relatively dry areas are receive exactly what they need. However, depending on the standing base (e.g. gravel vs. Mypex) water may move across the bed from wet to dry zones, and be taken up through the base of pots. Such redistribution will reduce the need to use over-irrigation to compensate for uneven deposition of water.

Assuming that there is some redistribution on most beds, the water savings of 30 to 40 % obtained in the trials with the automatic control system are consistent with the higher estimates suggested by other data. Therefore, **our best estimate of the scope for water saving from better regulation of *existing* irrigation equipment is 30 to 40%**

Beyond that, there is scope for additional water savings of at least 50% through improvements in irrigation equipment that increase the uniformity of application. More uniform application will also make it feasible to adopt RDI as a way to further reduce water applications by as much as 50% of ETp. Combining savings of 30%, 50% and 50% results in a total of 82% saving. Allowing for the fact that RDI will not be applied all the time, and will not be suitable for some crops, it is reasonable to estimate that **total savings of the order of 75% of current water usage should ultimately be possible.**

Economic model

An economic model was developed to investigate the financial implications of investment in water saving ideas. This allows cost-benefit relationships to be examined for various scenarios. To take account of both capital and annual costs a whole life costing approach was adopted.

Costs associated with the irrigation control will include:

- Capital cost of the system
- Ongoing running costs of the system (labour, parts, etc.)
- Additional labour cost attributable to the system (e.g. “bedding in” period)
- Opportunity cost of lost revenue (e.g., if the system uses space which could be allocated to revenue-generating activity, e.g. growing more plants)

Potential benefits accrued from the irrigation control could include:

- Saved water (marginal cost)
- Other system benefits, for example reduced labour (e.g. pruning and watering)
- Increased revenue due to improved plant quality and reduced wastage
- Environmental benefits

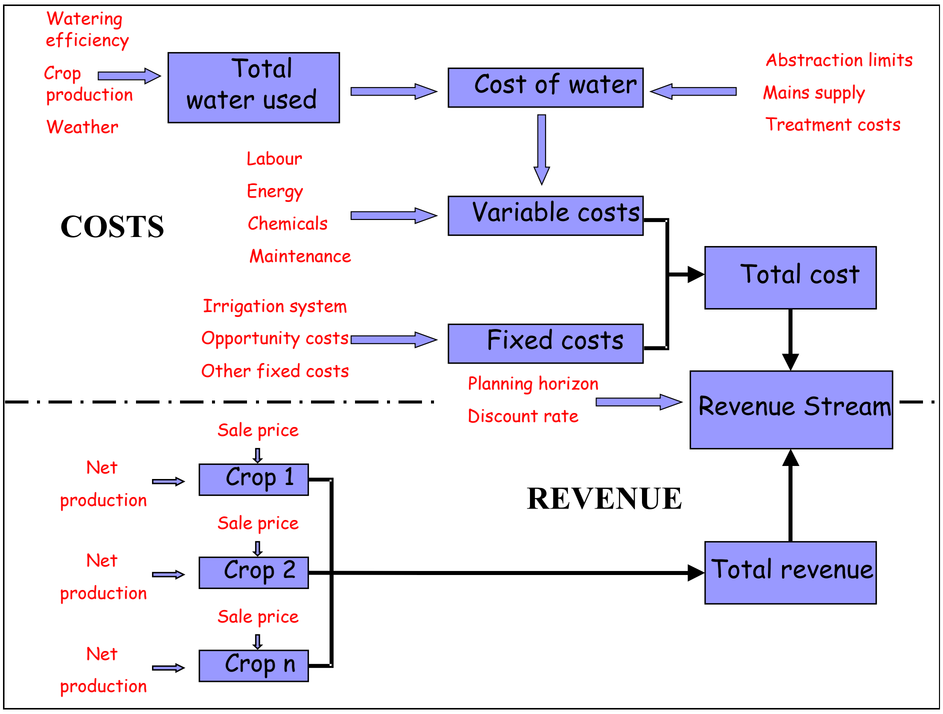


Figure 5.9 Flowchart for full economic model

As can be seen in the flowchart (Figure 5.9), the model includes a number of the factors which are difficult to quantify. The model was therefore simplified to focus on the parameters directly influenced by water use.

Drivers for Investment

Before discussing the cost-benefit analysis, it is informative to consider the various drivers for implementing improved water-use strategies. These include:

i. *Direct cost of water* – the cost of water-use is such that there are (potentially) demonstrable financial benefits associated with saved water. A standard approach to the justification of investment can be used, considering the cost of implementation and the financial benefits thereby accrued.

ii. *Abstraction limits* – abstraction limits restrict (or potentially restrict) operations, either due to expansion of the nursery or a modified abstraction license. A standard approach to the justification of investment can be used except that a surrogate value for the saved water is required, since the unit cost of the abstracted water will not reflect the true value of the water saved. This 'surrogate value' can be modelled as the cost of developing an alternative supply; for example, using estimates of capital and operating costs associated with providing mains supplies.

iii. *Demonstration of 'due diligence'* – the Environment Agency requires (either implicitly or explicitly) nurseries to demonstrate water-use efficiency. If a nursery considers that implementation of improved water-use strategies is essential (due to regulatory drivers), the choice of strategy would be as much an issue of cost-effectiveness as an investment-decision based on the tangible cost-benefits realised.

Cost-Benefit Models

To undertake a cost-benefit analysis, the nursery must estimate the costs of implementing the improved irrigation scheme under consideration and the financial benefits the scheme will accrue.

The present cost of the irrigation improvements (assuming a discount rate 'r') over the useful life of the capital items (the planning horizon 'T') is given by:

$$\text{Present Cost} = C_a + C_b + C_c + \sum_{i=0..T} \frac{(C_d + C_e + C_f + C_g)}{(1+r)^i}$$

Where:

C_a: Capital items (initial cost)
C_b: Installation costs
C_c: Commissioning costs
C_d: Operation/maintenance/repair costs
C_e: Energy cost
C_f: Treatment cost; including sludge disposal (if significant)
C_g: Opportunity costs (land use only)

This cost-model assumes that the nursery will have to reinvest in capital items after time T due to 'wear-out' and/or obsolescence.

The present financial benefit of irrigation improvements over the same period is given by:

$$\text{Present Benefit} = \sum_{i=0..T} \frac{(S_a + S_b + S_c + S_d + S_e)}{(1+r)^i}$$

Where:

S_a: Water savings
S_b: Labour savings (hand watering and pruning)
S_c: Chemical savings
S_d: Improvements in crop revenues (likely to be variable and crop dependent)
S_e: Treatment savings

Cost benefit analysis for various scenarios

Four generic irrigation options have been investigated within the current project. Various issues pertinent to the cost-benefit analysis of these options are outlined below.

Reduced deficit irrigation (RDI) has the potential for reducing crop quality if implemented incorrectly, and the risks associated with this approach must therefore be managed. Nevertheless, RDI can realise a significant saving in water and improve crop quality. RDI is, however, difficult to control with overhead irrigation, although experimental results indicate that running a 'slightly dry' regime can be implemented and be of some benefit.

The cost of implementing full RDI is dominated by the need to install a drip irrigation system. Water savings realised will depend directly on the RDI-regime imposed though other benefits will need to be estimated.

Partial root drying (PRD) is again unlikely to be achievable with overhead irrigation. Furthermore, to obtain the correct root signals it is considered that a significant amount of water must be applied on the well-watered side, so the amount of water saved may not be significant.

The cost of implementing PRD is again dominated by the need to install drip irrigation. Representative costs for such systems are required to allow costs to be assessed, and other benefits need to be estimated.

The project has demonstrated there is scope for improving the precision of water application by:

- Optimising pot spacing;
- Use of more effective spray nozzles;
- Optimising nozzle spacing.

The cost-benefits of this approach depend on the particular configurations used before and after optimisation. Nurseries will need to assess the effectiveness of their initial configurations, the potential for optimisation, and the likely efficiency savings. Estimates of costs involved in the upgrade are also necessary, but will be 'bed-specific' – details of both the existing and 'optimised' system must be considered.

Matching the water application to ETp requirements of some representative plant(s) can save water by providing a better assessment of the plant's needs. This can be achieved by use of either a Theta-Probe or Evaposensor.

Data Requirements

From the preceding discussion, it is clear that to undertake a cost-benefit analysis, nurseries need to collate various data relating to their own commercial activities, including:

- Total bed areas (to which modified irrigation would be applied, although for some options it is possible to calculate cost per unit area or cost per bed);
- Cost of water;
- Abstraction limits with regard to peak demands ('headroom');
- Labour costs;
- Discount rates.

As well as this nursery-specific data, various factors associated with the irrigation options need to be considered. For each option, information is required on:

- Capital items required (plant, equipment, instrumentation, land, etc.) and associated costs;
- Installation and commissioning requirements;
- Useful life of capital items;
- On-going costs (maintenance, energy, treatment);

- Benefits (water saved, labour saved: pruning and hand watering, chemicals saved, crop improvements);
- Opportunity cost (land intensive solutions only, such as storage reservoirs).

Output of Cost-Benefit Analysis

For each irrigation improvement considered, it is necessary to either calculate the payback period (the year 'i' where present benefits exceed the present costs), the net present value of the investment (the present benefits net of present costs), or cost-effectiveness of the scheme. In this context, cost-effectiveness can be expressed as:

$$Cost\ Effectiveness = \frac{Volume\ of\ water\ saved\ (m^3)}{Cost\ of\ solution\ (£)}$$

Where the costs of implementing improved irrigation are small, such as optimisation of scheduling alone, cost-effectiveness (essentially m^3 of water saved per £ spent) will be relatively high if <u>any</u> benefits can be demonstrated.

Issues of Uncertainty

Since model parameters are uncertain, the cost-benefit analysis should ideally assess the impact of this uncertainty on the investment decision. This can be achieved by undertaking either a sensitivity analysis of parameters, or for more complex problems a Monte Carlos analysis (utilising Spreadsheet tools such as @Risk).

Example 1: Increased Precision using Theta-Probes

Assumptions:

One Theta-Probe is required per solenoid valve (bed); capital cost £500 per probe
Planning horizon 10 years (estimated useful life for instrument)
Discount rate of 3% (inflation only)
Initial costs are born at start of year i=0
Benefits are accrued at the end of year 1 and subsequent years
Cost of labour (skilled): £30/hour
Cost of labour (unskilled): £15/hour
The water saving of 44% is applicable to the whole growing season
Labour saving: The research has not demonstrated any significant labour savings but by running more precise regimes, some reduction in pruning is likely. This has been taken as equivalent to 1 day (= 8 hours) per bed over the growing season.
Unit cost of mains water: £0.60/m^3
Unit cost of abstracted water: £0.03/m^3
Recalibration of system as plants grow: 2x during growing season = 1 hour
Maintenance: ½ hour / month

The data used in this example are summarised in Tables 5.3 and 5.4.

Table 5.3 Summary Data for Theta-Probe Trials

Bed details	Outdoor bed 101x13m (outdoor bed, Nursery 2)
Capital Items	1 Probe per bed
Baseline water use	419 m^3 (2001 growing season May to Sept)
Water saving	44% (≈ 185 m^3)
Installation	≈0.5 days
Commissioning	≈0.5 days

Table 5.4 Cost-Benefit Parameters

Parameter	**Value**	**Assumed range[1]**
C_a: Capital items (initial cost)	£500	±10%
C_b: Installation costs	£120	±10%
C_c: Commissioning costs	£120	±10%
C_d: Operation/maintenance/repair costs	£105 p.a.	±10%
C_e: Energy cost	Assumed negligible	na
C_f: Treatment cost	Assumed negligible	na
C_g: Opportunity costs	Assumed negligible	na
S_a: Water savings/yr (mains/abstracted)	£111/ £5.53 p.a.	±20%
S_b: Labour savings	£120 p.a.	±20%
S_c: Chemical savings	Assumed negligible	na
S_d: Improvements in crop revenues	Assumed negligible	na
S_e: Treatment savings	Assumed negligible	na

Note 1: the range assumed for the purposes of sensitivity analysis

The initial costs are £740 with the discounted maintenance and calibration costs shown in Table 5.5 along with the present benefit. The discounted benefit associated with water savings are also given in Table 5.5 for each year, along with the present benefit (PB) of these savings.

Table 5.5 Discounted Benefits (mains supply)

Year(i)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
Discounted cost	740	102	99	96	63	91	88	85	83	80	78	**1636**
Discounted benefit	0	224	217	211	205	199	193	187	182	177	172	**1966**

Taking the mean value for costs and benefits for illustrative purposes, the results of the cost-benefit analysis are:

- NPV = 1966 – 1636 = £330 in general any investment with a positive net present value is justified;
- Payback period = 7 years;
- Cost effectiveness (using the mean water saved over the 10 years) = (10*0.44*419 m^3)/£1636 = 1.13m^3/£ spent.

However, with costs at maximum of range, i.e. as above plus 10% and benefits at minimum of range, i.e. as above less 20%, the NPV is -£217 so the investment would not be justified.

On the basis of the assumptions made here, a Theta-Probe represents a justifiable investment for a nursery using mains water, although the payback period of 7 years makes the investment-decision somewhat marginal.

The NPV would increase, and hence the economic case for investment would be strengthened, if water prices were higher, capital and installation costs were lower or there were other demonstrable benefits. Improved crop revenues, for example, would be very significant. The crop value from this bed for the previous growing season was estimated at £35,000. A 1% increase in this would yield a benefit of £350 p.a. which when discounted over 10 years, increases the present benefit to £4952 and the NPV to £3316 with a payback of 2 years.

The case would be weakened if a higher discount rate was used, which is usually the case for investment decisions. For example, using mean costs and benefits, the NPV of the investment is reduced to £100 if a discount rate of 8% is used.

Given the difference in the price of water, benefits for nurseries using abstracted water would be much lower (£5.53 cf. £111 per year). It is thus clear that any such investment would not be justified where abstracted water was used, under the stated assumptions.

It should, however, be stressed that the cost-effectiveness of this option, compared to capital-intensive schemes, could still make it attractive to nurseries using abstracted water, especially when considered in conjunction with abstraction limits and regulatory drivers.

Example 2 – As above but running an RDI regime with drip irrigation.

Cost for above bed of drip irrigation system: £2500 (20,000 pots x 8p/pot stake and dripper +tubing)
Installation: 2 days unskilled for the drip irrigation plus sensor as above.
Commissioning: as above
Operation and maintenance: 1 day unskilled / month
Water saving: as above +40% through running RDI
Labour: ½ day per month

Table 5.6 shows the discount analysis on this basis. The NPV is substantially negative and hence the investment would not be justified. In order for the investment to be justified costs would need to be significantly lower or benefits higher. A 2% improvement in crop revenue would yield a positive NPV as shown in Table 5.7.

Table 5.6 Discounted Costs and Benefits (mains supply)

year	disc costs p.a.	disc benefit p.a.	Cumulative costs	Cumulative benefits
0	£0	£0	£3,480	£0
1	£699	£495	£4,179	£495
2	£679	£481	£4,858	£976
3	£659	£467	£5,517	£1443
4	£640	£453	£6,156	£1896
5	£621	£440	£6,777	£2336
6	£603	£427	£7,380	£2763
7	£585	£415	£7,966	£3177
8	£568	£403	£8,534	£3580
9	£552	£391	£9,086	£3971
10	£536	£379	£9,622	£4350
	£6,142	£4350		

Table 5.7 Discounted costs and benefits with increase in crop revenue

year	Disc costs p.a.	disc benefit p.a.	Cumulative costs	Cumulative benefits
0	£0	£0	£3,480	£0
1	£699	£1175	£4,179	£1175
2	£679	£1141	£4,858	£2315
3	£659	£1107	£5,517	£3423
4	£640	£1075	£6,156	£4498
5	£621	£1044	£6,777	£5541
6	£603	£1013	£7,380	£6555
7	£585	£984	£7,966	£7539
8	£568	£955	£8,534	£8494
9	£552	£927	£9,086	£9421
10	£536	£900	£9,622	£10322
	£6,142	£10,322		

From Table 5.7, the results of the cost-benefit analysis are:

- NPV = 10322 – 9622 = £700 in general any investment with a positive net present value is justified;
- Payback period = 9 years;

Conclusions

- A cost / benefit model can be constructed to justify investment in water saving techniques. However much of the data, and hence the outcome of any single analysis, will be nursery or bed / crop specific.
- The costs are dominated by the installation of equipment, particularly if a drip irrigation system is to be used.
- It is likely that some benefits from improved crop revenues or greater labour savings will be required in addition to water saving to justify significant investments.

Overall conclusions

Responses to RDI and PRD

- All species tested are able to reduce their water loss to match the reduced irrigation applied, generally over about 2 weeks as SWC decreased from about 50% to 20%. The adaptation involves mainly stomatal adjustment (i.e. reduced g_s) but, in addition, water supply may be improved by an increase root hydraulic conductance. Down to 25% ETp, adaptation prevented visible damage such as leaf scorch, with the exception of *Forsythia* at ≤ 50% ETp. The adaptation process takes time so that slow development of drought helps prevent damage.
- Any degree of RDI is likely to reduce shoot growth. Even at 80% ETp, shoot extension was reduced by 30% and this increased up to 80% under more severe RDI. This growth reduction kept plants well balanced and compact without the need for pruning.
- RDI appears to alter the assimilate allocation in favour of the root system so that root:shoot dry weight ratio is increased significantly. Combined with other adaptive changes, this should favour tolerance water shortage and easy establishment during and after retail.
- With PRD, higher leaf water status was maintained than in treatments in which water was applied more uniformly (e.g. the INT treatment). Drip irrigation, with one dripper per pot placed well to one side of the pot, and irrigating at <100% ETp, provided a simple way to achieve PRD in containers.

Root signals

- In *Forsythia*, the evidence suggests that ABA acts as a signal from roots in drying soil that acts in shoots to reduce g_s and growth. Unexpectedly, xylem sap pH declined in response to soil drying.
- Adding ammonium chloride to the irrigation water, which is reported to reduce the pH and increase ABA concentration in xylem sap, reduced growth and g_s in *Forsythia* (i.e. the same effects as soil drying)
- In *Forsythia*, xylem sap pH does not appear to act as a signal from drying roots but may act locally within the leaf to mediate the response to evaporative demand. A rise in apoplastic pH was associated with high evaporative demand.
- As predicted from the physiological studies, spraying *Forsythia* with a buffer solution at pH 6.7 reduced g_s and leaf growth rate.

Practical means of irrigation control to match plant needs

Two viable means of irrigation control were developed. Each has advantages and disadvantages:

- EvapoMeter: commercially available now, a single unit could regulate many separate irrigation zones but calibration for specific crops and irrigation systems is needed.
- ThetaProbe controller: a fully automatic closed-loop controller, requiring no calibration but a separate sensor will be needed for each bed or irrigation zone, making it relatively expensive.

Scope for saving water and economic evaluation

- Nursery trials with the automatic controller and other evidence suggest that regulating irrigation to match ETp could save at least 30-40% of water applied by current industry practice.

- Non-uniform application is inherently wasteful and is a barrier to the precision required for RDI. If uniform application can be achieved and RDI exploited, total water savings of 75% should be a realistic possibility.
- The cost benefit analysis model provides a tool that growers can use to determine, for their specific circumstances, what type of improvements would be most economically attractive.

TECHNOLOGY TRANSFER

Presentations to growers

Talk at Hortex 2000 (Bill Davies).
Talk at Contact 2000 (Ross Cameron).
HNS Growers Seminars at Efford and Johnson's of Whixley, October, 2000 (Ross Cameron and Chris Burgess)
Presentations at HRI Efford Open Day, 25 & 26 September, 2001 (Ross Cameron and Chris Burgess)
Advances in Water Management workshops sponsored by HDC and HorTips (Ross Cameron, Chris Burgess and Ken Blyth):

- (i) James Coles & Sons, Leicester, 11 September, 2002
- (ii) Johnson's of Whixley, York, 12 September, 2002
- (iii) Hillier Nurseries, Romsey, 26 September, 2002

Presentations at the HDC Propagation Seminars at HRI East Malling, 18 & 19 September, 2002 (Chris Atkinson and Richard Harrison-Murray).
Parts of CPD courses within the Lancaster Plant Sciences for Industry programme (Bill Davies, Sally Wilkinson and Mark Bacon):

- (i) Basic Plant Physiology (PSI 110), April 2002
- (ii) Advanced Plant Physiology (PSI 120), April 2002
- (iii) Biological Interactions in the Root Environment (PSI130) October 2002
- (iv) Biological Interactions in the Aerial Environment (PSI140) November 2002
- (v) Horticultural Water Use in a Changing Environment (PSI 150), May 2001

Technology transfer visits to individual nurseries (e.g. to demonstrate methods for measuring the uniformity of overhead irrigation and use of the ThetaProbe automatic irrigation control unit): Notcutts, Hillier, Wyevale and Hugh Nunn nurseries

Exhibitions and posters

Poster presentation and method/equipment demonstration at the Plant Sciences for Industry (PSI) Conference at the University of Lancaster, October 1999. (Sally Wilkinson and Bill Davies)
HDC stands at Hortex, Four Oaks Show, Southern Growers Show and Scotgrow 2000
Exhibit at GAN Trade show, Christchurch, Dorset, 13 February, 2002 (Chris Burgess)
Exhibit at HRI Efford Public Open Day, 20 July 2002 (Chris Burgess)
Exhibit at HRI East Malling Public Open Day, September 2002 (Chris Atkinson)
Saving water and labour by improved control of irrigation. Poster presented at Horticulture LINK in Focus, 27 February, 2003 (Richard Harrison-Murray)

Popular articles

Less is more. Horticulture Week. 20 May 1999, 20-23. (Ross Cameron)
Water use in container-grown hardy ornamental nursery stock, HDC News 1999 No. 57.
Improving the efficiency of water use in HNS. Publicity leaflet, Hortex 2001 (Ross Cameron and Jim Dean)
More for the pots. *Grower* 137, No. 11, 14-15 (2002) (Chris Burgess)
Efficient water use for container grown nursery stock. HRI Annual Report 2001/2002, p 46.
Improving the efficiency of water use in container-grown hardy ornamental nurserystock. Agriculture Link, 1999 (Ross Cameron)
HDC News 2000 November No 68 – HNS Seminars at Johnson's & Efford
HDC News 2001 February, No 70 – Bill Davis's work on PRD

HDC News 2001 April, No 72 – included in John Woodhead's 'Why I value R&D'
HDC News 2001 August, No75 – highlights from Annual report
HDC News 2001 November, No 78 – Efford Open Days featuring project
HDC News October 2002 No 87 – 'Advances in Water Management'
HDC News November 2002 No 88 – 'Advances in Water Management' – detailed write up

Seminars and conferences

Wilkinson S, Davies WJ (2000). The involvement of xylem sap pH in stomatal closure in Forsythia. Society for experimental Biology Annual Conference, University of Exeter, March 2000

Cameron RWF (2001). Regulation of Water Management and its Efficient Use on a Pot or Bedding plant nursery. Eurogro Seminar, University of Warwick, 18 October 2001.

Davies, WJ (2001). New methods to increase resource use efficiency in Horticulture, International Fertiliser Society, Lisbon, March 2001

Davies, WJ (2001). Stomatal control by chemical signalling and the exploitation of this mechanism to increase water use efficiency in agriculture. New Phytologist Symposium, Birmingham, July 2001

Davies, WJ (2002). Water saving agriculture, Conference University of Xian, China, April 2002

Davies, WJ (2002). Root signals in plants, Physiological basis of increased water use efficiency in Agriculture. Conference, UPM Kuala Lumpur, Malaysia, April 2002

Davies, WJ (2002). Regulation of growth and water use in trees. Long-distance transport in trees. Conference, Harvard University, October 2002

Davies, WJ (2002). Partial root drying as a technique to regulate leaf growth and physiology. Conference on Deficit Irrigation, Adelaide October, 2002

Davies, WJ (2002). Partial root drying in Horticulture. Australian Society for Horticultural Sciences, Sydney October 2002

Cameron, RWF (2002). Regulation of Plant Growth in Container-Grown Ornamentals through the use of Controlled Irrigation. ISHS conference in Toronto, August 2002

Scientific publications

Cameron RWF Wilkinson S, Davies WJ, Harrison-Murray RS, Dunstan D and Burgess C (2002). Regulation of Plant Growth in Container-Grown Ornamentals through the use of Controlled Irrigation. Acta Horticulturae. (in press).

Davies WJ (2002) Hormones as root signals. In: The Encyclopaedia of Plant Physiology, Ed. N.C. Turner. (in press).

Davies WJ (2002) Manipulating the chemical signalling system in plants. In: Ecophysiology of Plants, Ed. M. Regiosa, University of Vigo Press (in press)

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

Wilkinson S, Davies WJ (2000). The involvement of xylem sap pH in stomatal closure in Forsythia. Journal of Experimental Botany 51S: 66 (abstract of SEB presentation).

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

EXPLOITATION PLANS

Industrial relevance

The requirement of a LINK funded project is to provide information or technology at the "pre-competitive" stage, i.e. at a stage requiring some further commercial development before being usable by industry.

Growers have highlighted success in the following areas as particularly relevant to their needs:

1. The project has identified that time-clock controlled overhead irrigation systems, widely used in the HONS sector, often apply water far in excess of the needs of the crops. 50% overwatering is common and 100% exists.

2. The ThetaProbe and EvapoMeter will, with some further development, provide a realistic means of regulating water application much closer to the needs of the crops, thereby reducing water use by 30% or more.

Delta-T is now developing a cheaper version of the Theta Probe and is planning to collaborate with control panel manufacturers to make a system readily available and easy to install on nurseries.

3. Uneven water delivery from overhead irrigation systems has been identified as a major cause of water inefficiency and the various commercially available systems differ greatly in this respect. Software has been developed which will clearly illustrate the uniformity of application from a particular system using easily obtainable data on the nursery.

4. Subjecting some plants to pre-determined levels of water stress causes growth modification resulting in a bushy habit, suited to the marketplace, and without the need for pruning. *Forsythia* and *Cotinus* are good examples of this. Under a "normal" (i.e. excessive) irrigation regime, these plants typically produce two or three very vigorous shoots which require repeated pruning in order to encourage a bushy habit.

It is very likely that restricted water supply could also be used to hold a crop in saleable condition, without the need for pruning to keep it within marketable size.

Further work is required to achieve the required levels of water deficit without risking damage to the crop.

5. Various fertilisers have been shown to affect plant growth in much the same way as a water deficit.

With further work in new proposals, recommendations should soon become available enabling significant savings in the labour required for pruning. They will also enable the industry to realise the beneficial effects of water stress on plants grown outside where rainfall might otherwise prevent the required degree of drought.

6. A economic model has been developed which includes a spreadsheet for use when taking investment decisions relating to irrigation equipment.

Possible constraints on exploitation

- Difficulties in development of a commercially viable version of the ThetaProbe controller
- Time required for user calibration of crops and systems against the EvapoMeter. An alternative, to be explored in future research, is tables from which a calibration factor can be estimated for a given crop, spacing, canopy spread, irrigation rate and nature of standing base.
- Non-uniformity of irrigation. This inherently limits the degree of water efficiency achievable because of the need to irrigate for the driest spots. It will also limit application of RDI because the degree of growth control will vary between different parts of the bed. This problem therefore features prominently in plans for future R&D (see next section).

Future exploitation plans

- Delta-T Devices plans to bring the ThetaProbe controller to the market place by:
  (i) developing a cheaper version of the sensor for control applications
  (ii) collaborating with a manufacturer of irrigation control panels to develop an automated system well suited to installation on nurseries. (Target March, 2004)
- Skye Instruments will promote the use of the EvapoMeter as an irrigation management tool. This requires the development of grower-friendly instructions on how to calibrate against specific crops and irrigation systems. Growers involved in the trials with the EvapoMeter and Richard Harrison-Murray will assist in this process. (Target date March 2004)
- HDC will prepare and publish factsheets. Provisional topics are : (i) Methods and equipment for regulating irrigation, (ii) Methods to measure and improve the distribution of overhead irrigation (iii) Potential to manipulate growth by RDI (Target date March 2004).
- HDC will present the outcome of the project in HDC News articles (e.g. Exploiting RDI in HNS production, New developments in equipment to control irrigation, Improving the performance of overhead irrigation) and will update growers on future developments (e.g. availability of new equipment)
- HDC will organise grower events to follow up on the considerable interest raised by the 'Advances in Water Management workshops' sponsored by HDC and HorTips in the final year of the project. Plans are still under discussion, but it is likely that an HDC-funded demonstration project will be the centrepiece, providing one or more location(s) where growers can see the techniques developed in the project being applied in practice, together with work from related HDC projects (e.g. PC 166). (Target start date January 2004).
- The HDC will provide interested growers, on request, a copy of the cost/benefit analysis spreadsheet
- The HDC will further develop the 'water distribution calculator' spreadsheet and distribute it to growers with user guidelines (target March 2004).
- Chris Burgess and Bill Davies to present papers at the IPPS Conference (International Plant Propagators Society), September 2003. These will be published in the proceedings.
- Further workshops along the lines of the 'Advances in Water Management' will be conducted. (in 2004)

- Presentation by Richard Harrison-Murray at an HDC/EMRA grower's day scheduled for September, 2003
- Feature on HDC stands at trade show, with the factsheets available to 'take home' the message (in 2004)
- The HTA will publicise the opportunities provided by the project in HTA News. (Target date March 2004)
- As techniques become ready for grower uptake, e.g. availability of a commercial version of the ThetaProbe automatic controller, then specialist growers will be approached to test on their nurseries and host demonstration days. The HDC will be approached to provide funding. (Target date September, 2004)
- To hasten uptake of techniques which are not yet fully developed, growers interested in small scale tests, at their own risk, of the novel fertiliser, pH buffer, RDI, or PRD treatments will be offered advice specific to their crops and situation (from HRI and Lancaster University).
- Science partners will submit additional scientific papers to refereed journals so that all information that is not commercially sensitive can be in the public domain and available for development in other ways or for other crops. (Target March 2004)

Exploitation plans of individual grower members of the consortium

Wyevale Nurseries have well advanced plans as follows:

1. They have already made extensive use of the "Water Distribution Calculator" to identify reasons for over irrigation and an explanation for quality variation across beds. They are now using the model to compare irrigation systems and improve layout systematically across the nursery.
2. The demonstration of improved quality under RDI has led them to experiment on running crops drier than in the past. They are running wetter parts of beds to the ideal level and topping up the drier parts by hand. To reduce this labour requirement they are now seeking to achieve greater uniformity of application.
3. If they are satisfied that water distribution is sufficiently uniform, they will be considering use of a ThetaProbe based control system when these become commercially available.
4. If a reliable and easily used calibration for the EvapoMeter becomes available they will consider using it.
5. They perceive that a large amount of capital investment will be taking place for improved water management over the next few years. They believe that the project has demonstrated the potential for improved crop quality, labour saving and water saving but, to achieve this potential, further research is now needed to identify ways to deliver water more uniformly.

The plans of other nurseries are summarised by topic below:

1. Use of simple methods to quantify irrigation practice (e.g. ThetaProbe or weighing) with a view to running beds somewhat drier with confidence (Notcutts, Johnsons, Hugh Nunn)
2. Measurements of water distribution, using the 'Water Distribution Calculator', to direct efforts to improve the uniformity of water application (Notcutts, Hilliers)
3. Use of the EvapoMeter as an irrigation management tool and in a wider context, e.g. monitoring propagation environments (Notcutts)
4. ThetaProbe and/or EvapoSensor controlled irrigation, when commercially available (Hilliers, Notcutts, Hugh Nunn, Johnsons)

5. Use of fertigation and buffer solution treatments to mimic the effects of drought (Hilliers, Notcutts)

All nurseries recognise the need to improve the precision and uniformity of application of irrigation before it will be possible to realise fully the potential of RDI. and, until that time, have no plans to go further than running beds somewhat drier than in the past. This requirement is reflected in a proposal for a new LINK project (see 'Future R&D resulting from this project' section).

NEW R&D RESULTING FROM THIS PROJECT

Additional projects already commissioned

Container HNS: Use of capillary matting under protection. HDC funded project HNS 107.

Improving water management within growing media. HDC funded project HNS 107a which has been examining the use of wetting agents and mulches.

Proposals submitted

Enhancing the quality of HNS and increasing the productivity and sustainability of the industry through novel water-saving and growth-manipulation techniques. A bid for HortLINK funding which has been approved at concept note stage. This proposal focuses on the need for greater precision in the application of water. It includes two approaches: (i) increasing the uniformity achievable by development of existing technology and (ii) development of a gantry mounted 'intelligent' irrigation system which will vary water application according to the water status of individual plants. Remote sensing of plant water status will be achieved by 'thermal imaging' to detect the small rise in leaf temperature which occurs when water stress causes stomata to close. Full proposal currently being developed.

Proposals under development

Partial rootzone drying, a technique to deliver water saving and sustained high quality yield in UK horticulture. Bid being prepared for Defra Open Competition on 'Sustainable Methodologies for Water Use in Horticulture', CTC0301.

Identification of specific traits and markers linked with improved water use efficiency. Bid being prepared for Defra Open Competition on 'Sustainable Methodologies for Water Use in Horticulture', CTC0301.

SUMMARY OF OUTCOME AGAINST MILESTONES

(Primary milestones are marked with * and revised milestones are in italics)

No.	Milestone	Outcome
Objective 1. Test the hypothesis that woody ornamentals can readily adapt to water stress and that transpiration can be reduced by at least 50% in a range of species without loss of horticultural quality.		
1.1	Select three model species with differing water requirements (e.g. *Cotinus*, *Forsythia* and *Hydrangea*) and test their suitability for physiological and biochemical (ABA) measurements. (EM/L)	Achieved.
1.2	Set up drip irrigation under protection for the purpose of imposing RDI treatments to containerised plants of each species. (EM)	Achieved.
1.3	Implement RDI treatments based on daily evaporative demand, i.e. as a percentage of potential evapo-transpiration (% ETp). 150, 80, 60, 50, 40, 20 %. (EM)	Achieved.
1.4	Measure water status of the growing medium (gravimetric and volumetric content) and of the plants (stomatal behaviour, leaf water potential and relative leaf water content) under various degrees of RDI. (EM)	Achieved.
1.5	Measure total growth, internode length and lateral production under the various treatments. Identify growth characteristics of each species and generate plant response curves to RDI. (EM) [31/1/00]	Achieved.
1.6*	Identify the most appropriate severity of RDI for each species. (EM) [31/1/00]	Achieved.
Objective 2. Test the hypothesis that carefully-timed and directed supply of reduced quantities of irrigation water can act as an alternative to pruning, or application of growth regulators, for controlling the plant shape and size.		
2.1	Propagate or purchase plants for the following year (EM/Eff) [28/2/00]	Achieved.
2.2	Implement the propagation or purchase of plants for the following year. (EM/Eff) [30/9/00]	Achieved.
2.3	Set up drip irrigation lines under protection to investigate effect due to time of application of RDI in two of the model species. (EM) [30/4/00]	Achieved.
2.4*	Apply RDI at 4 different stages of growth (precise timings will relate to results in 1.6 but examples may include - (First budbreak, Early primary shoot extension, Late primary shoot extension, Lateral bud break). (EM) [30/9/00]	Additionally, conducted experiment on time required for adaptation to RDI and persistence of effect of rewatering. (Expt.1.3)

2.5	Compare the effects of restricting irrigation on the number and length of internodes, position and numbers of laterals produced, rate of increase in stem diameter and potential injury to foliage. (EM) [31/1/01]	Stem diameter measured only once, at end of season.
2.6	Implement assays for ABA concentrations in xylem sap using plants in 2.4. (L) [31/1/01]	Achieved.
2.7	Implement the propagation or purchase of plants for the following year. (EM/Eff) [30/9/01]	Achieved.
2.8	Refine and re-test most promising RDI treatments from year 2 to control growth in model species. Implement experiments under protected and non-protected situations. (EM) [31/5/01]	Decided to try RDI under overhead irrigation for greater industry relevance Achieved.
2.9*	Set up similar experiments to 2.4 and 2.5 to determine the effect of localised application of water (e.g. via dripper) compared to more uniform application. (EM) [31/5/01]	Used 'split-pot' system for more precise comparison of localised and uniform application. Achieved
2.10	Compare results on plant growth and quality under protected and non-protected situations. (EM) [31/1/02]	Achieved.
2.11	Compare results on plant growth and quality via 'localised' dripper or more uniform application (EM) [28/2/02]	Achieved.
2.12	Identify and implement practical techniques that could be used by industry to implement root signalling responses e.g. effectiveness of cycling regimes of wetting and drying. (EM/L). [31/5/02]	Worked on problems of RDI on overhead irrigation (EM), and fertigation/buffer treatments (L). Achieved
2.13	Record plant response and crop uniformity in practical techniques in inducing root signals. (EM/L) [31/1/03]	Achieved.
2.14	Present results on the effects of reduced irrigation on plant performance to the horticultural and scientific communities. (EM) [31/3/03]	Achieved.

Objective 3. Investigate the effects of naturally-occurring root-generated abscisic acid (ABA) and the influence of possible key co-factors (xylem pH) on growth and functioning of container-grown plants and devise methods to utilise root signalling to reduce transpiration and regulate shoot extension.

3.1*	Establish a means of exposing part of the root system to dry substrate, without imposing shoot water deficit (e.g. a 'split-pot' with separate wet and dry sections). (L) [30/9/00]	Developed 'tipped pot' as more practical alternative to 'split-pot'.
3.2	Implement the technique devised in 3.1 to measure differential ABA signals in the two model species. (L) [30/9/00]	Achieved.

3.3	Determine the effects of ABA *or pH* signals from the roots in the dry section on stomatal conductance and key components of growth in one of the model plants (e.g. internode extension, axillary bud development, stem thickening). (L) [28/2/01]	Achieved for ABA *and* pH.
3.4	Determine whether there are differential effects on the key components outlined in 3.3.(L) [28/2/01]	Achieved.
3.5*	Compare 'split-pot', and conventional drought treatments for strength of ABA *or pH* signals and ability to influence those key components of growth identified in year 2. (L) [30/9/01]	Achieved.
3.6	Investigate the possibility that simple modification of the nutrient status of the substrate will alter xylem sap pH, and thereby increase the strength of the root- generated signal to the shoot. (L) [30/9/01]	Achieved.
3.7	Record responses to key components of growth and analyse samples for ABA in 'split-pot' and conventional drought treatments (L) [28/2/02]	Achieved.
3.8	Record alterations to xylem pH, in relation to ABA concentration and stomatal response. (L) [28/2/02]	Achieved.
3.9	Further evaluate nutritional / pH influences that promote the effectiveness of ABA signals derived from the roots. [30/9/02]	Achieved.
3.10	Present results on root signalling mechanisms to the horticultural and scientific communities. (L) [31/3/03]	Achieved.

Objective 4. Develop a performance specification, and evaluate existing and novel equipment to determine the most appropriate technique for estimating irrigation requirements of container-grown plants.

4.1*	Develop a performance specification for appropriate pieces of equipment for estimating irrigation requirements of container-grown plants. (WRc) [28/2/00]	Achieved.
4.2	Review literature and patent applications to appraise development of novel equipment abroad.(CEH/WRc) [31/12/99]	Achieved.
4.3	Complete evaluation of range of nursery conditions. (CEH) [31/12/99]	Achieved.
4.4	Determine water retention properties of growing medium including conditions for hydrophobicity, growing medium calibration and positions for 'in-container' moisture sensors. (CEH) [31/3/00]	Achieved.
4.5	*Using data collected in Obj 1. compare water requirements estimated using evapo-sensor and in-container moisture sensors, with gravimetric method as a reference. (EM/CEH) [31/3/00]*	Achieved.

4.6	*Set up trials at Efford / CEH, to evaluate equipment to estimate water use in a nursery situation (CEH / Eff) [30/4/00]*	Achieved.
4.7	*Using data from 4.6 circulate preliminary report (CEH) [30/9/00]*	Achieved.
4.8*	Analyse data on comparative methods to estimate water use, i.e. gravimetric measurements of evapo-transpiration (ET) in parallel with estimates of ET from a weather station, soil moisture probes and a evaporation-sensor. Incorporate data gathered from RDI experiment (i.e. 1.4, 4.5). (CEH) [31/12/00]	Achieved.
4.9*	Identify those pieces of equipment that meet the performance specifications and select the most appropriate for (a) an aid to control overhead irrigation, (b) provide the basis for automated irrigation. (CEH) [31/12/00]	Achieved.
4.10	Update information on development of equipment abroad, and refocus workplan on equipment design, or protocols, if required. (CEH/WRc) [31/1/02]	Achieved.
Objective 5. Develop management protocols for non-automated irrigation control.		
5.1	Purchase additional industry-relevant species for trialling at Efford. (Eff)	Achieved.
5.2	Using weight changes in a small group of control plants determine daily evapo-transpiration rates on outdoor container beds. (Eff)	Achieved.
5.3	Compare water use and plant quality in two overhead irrigation regimes controlled by time clocks - one at a commercially-relevant pre-set duration, the other at a variable duration dependant on evapo-transpiration demand. (Eff) [31/1/00]	Achieved.
5.4	Measure water use and assess plant quality under the two regimes. Identify limitations to using evapo-transpiration demand in practice. (Eff) [31/1/00]	Achieved.
*5.5**	*On the basis of preliminary data (from 4.5) select equipment, e.g. thetaprobe or evaposensor, and test as a management aid for regulating overhead irrigation. Compare with conventional control and identify any limitations. (CEH / Eff) [30/9/00]*	Achieved.
5.6	*Compare water use and plant growth characteristics in treatments set out in 5.5 and demonstrate results from this and other milestones at an open day (Eff) [30/9/00]*	Achieved.
5.7	Refine equipment as tools to estimate evaporative demand. (CEH) [31/7/01]	Achieved.

5.8	Develop management protocols for non-automated, overhead irrigation control. (CEH/Eff) [31/12/01]	Achieved.
5.9	Present data on effectiveness of equipment to control overhead irrigation and demonstrate results to industry. (Eff) [30/9/01]	Achieved.
5.10 *	Test management protocols for non-automated, overhead irrigation control (objective 5) on a number of commercial nurseries. (Nurseries) [30/9/02]	Practicality of both non-automated and automated controllers assessed on commercial nurseries
5.11	Evaluate potential savings and the effects on crop quality of using protocols for non-automated irrigation. (Nurseries) [31/1/03]	Evaluation was based on the prototype *automatic* controller.
Objective 6. Develop prototype equipment to control and regulate irrigation automatically.		
6.1	Carry out preliminary tests, in a lab situation, on the effectiveness of equipment for automated control (4.5, 4.6). (CEH) [28/2/01]	Achieved.
6.2	Develop appropriate interface and software for a datalogger and sensors, such that they could act as a prototype automatic irrigation controller. (CEH) [30/9/01]	Achieved.
6.3	Test the most suitable piece of equipment for controlling irrigation (drip) automatically in conjunction with datalogger and appropriate software. (CEH) [28/2/02]	Achieved.
6.4	Identify potential problems of hardware or software in 6.2 and modify as necessary (CEH). [1/5/02]	Achieved.
6.5*	Assess the effectiveness of automated irrigation controller in managing water supply to plants on container beds. (CEH) [28/2/03]	Achieved.
	Provide recommendation on how automated controller could be developed further prior to commercialisation. (CEH) [28/2/03]	Achieved.
Objective 7. Develop strategies for implementing regulated deficit irrigation (RDI) or root signalling techniques over a wider range of ornamental species (i.e. *Choisya*, *Lavandula*, *Cornus*, *Lonicera*) and assess effects on plant quality, water use and agrochemical leaching.		
7.1	Using RDI protocols or root signalling techniques developed, (and possibly prototype equipment for automated drip irrigation control - depending on success in 6.3 and 6.4), set up experiments to assess the feasibility for improving crop quality under protection. (EM) [31/5/02]	Extended range of plants studied by including four new species. Successfully used EvapoMeter to regulate irrigation.
7.2	Test the feasibility of utilising RDI / signalling protocols in a non-protected environment, i.e. on container beds outdoors. (Eff) [30/9/02]	Achieved.

7.3	Using protocols developed (and equipment, if ready) assess results for RDI / root signalling under protection, on plant quality. (EM) [31/1/03]	Achieved.
7.4	*Evaluate water use, irrigation uniformity and plant quality using prototype equipment for non-automatic and automatic overhead irrigation scheduling in combination with containers on two contrasting standing bases. (Eff)* ***[31/1/03].***	Milestone revised in the light of evidence that water uptake through the base of pots can be greater than expected.
Objective 8. Provide an economic model to predict the costs and benefits of reducing water use on nurseries in different regions.		
8.1	Install meters and loggers at selected nurseries in each region (WRc/Nurseries) [31/3/00]	Achieved.
8.2	Summarise and undertake a preliminary analysis of water use from the selected nurseries. (WRc) [31/12/00]	Achieved.
8.3	*Prepare an economic model relating the cost/benefit of water management on nurseries. (WRc) [31/1/02]*	Achieved.
8.4	Collate additional data required for financial cost/benefit analyses of measures to reduce water use against a number of scenarios. *(WRc) [30/9/02]*	Achieved.
8.5*	Present the results of the cost/benefit analyses to nurserymen. (WRc) [31/12/02]	Achieved.

CEH = Centre for Ecology and Hydrology, EM = HRI East Malling, Eff = HRI Efford, L = Lancaster University, WRc = Water Research Centre

ACKNOWLEDGEMENTS

Many scientists and research assistants employed by the scientific partners have contributed to the project including: Mike Fordham, Wendy Oakley, June Taylor, Heather Judd, Angela Leaney, Emily Reid, Mick Martin, Beulah Long, Carrie Hawes, Jim Monaghan, (HRI) and Lionel De Silva (Lancaster)

Guidance on experimental design and statistical analysis was provided by Rodney Edmonson (HRI).

GLOSSARY: terms and abbreviations used

ABA - abscisic acid, a plant hormone. When it appears in square brackets, as [ABA], read 'the concentration of abscisic acid'
bulk density - the density of the medium as a whole, including the pore space, i.e. the mass of a sample of the medium divided by its volume.
evaporative demand - an imprecise term referring to the power of an environment to evaporate water. It differs from humidity in that it takes account of the many other factors that influence evaporation, such as irradiance. For a more precise definition it is necessary to specify a particular evaporative surface e.g. a leaf - see also potential transpiration.
evaposensor - an instrument invented at HRI - East Malling which provides an electrical signal approximately proportional to potential transpiration from a model leaf. As such it is sensitive to the effects of humidity, light, temperature, wind, and leaf wetting. Originally developed for control of mist and fog for propagation. A commercial version is available from Skye Instruments.
ETp - potential evapotranspiration (see below)
g_s - symbol for stomatal conductance
HPa - Hecto-Pascal (=100 Pascal), a unit of pressure equivalent to 1 mb and to 1 cm of water.
leaf water potential (LWP or ψ_l) - leaf water potential, a measure of availability of water in the leaf tissues. It is at a maximum in a fully hydrated leaf which has a water potential of zero and as the leaf dries out the water potential decreases (i.e. it becomes increasingly negative). Some reduction in LWP is necessary to 'pull' water up from the roots, so that, even in well watered plants, LWP is normally negative and tends to decrease in proportion to transpiration rate.
lesion - permanent damage to the plant, primarily death of part or all of the leaf (often referred to as leaf 'scorch' but not necessarily caused overheating) or leaf drop.
LWP - leaf water potential (see above)
MPa - Mega-Pascal (=1 million Pascal), a unit of pressure equivalent to 10 bar. It is the preferred unit for leaf water potentials.
mvf - moisture volume fraction, synonymous with volumetric soil water content except that it is specifically expressed as a fraction not a percentage. To convert from fraction to percentage multiply by 100.
***P* (*P* < 0.05, *P* < 0.01, or *P* < 0.001)** - a statement of the statistical probability (*P*) that the observed differences could have been due to chance. The smaller the value of *P*, the more certain we can be that the result is 'real'. A value of 0.05 is conventionally taken as the threshold for accepting the result, i.e. that an effect is 'statistically significant'.
pH - a measure of acidity. The pH of pure water is 7.0, values below this are acid and values above it are alkaline. Technically it is defined as the negative log of the concentration of hydrogen ions.
potential evapotranspiration (ETp) - the rate at which a crop would lose water under prevailing environmental conditions if water supply was non-limiting. It includes evaporation from the plants (i.e. transpiration) and from the soil. In the context of this report, it includes evaporation from the growing medium in the container but not from the soil or other standing surface.
PPFD - Photosynthetic Photon Flux Density. A measure of irradiance confined to the wavelengths of light that are active in photosynthesis (i.e. 400 to 700 nm) and in the units that relate to its action in photosynthesis (i.e. quantum units).

PRD - 'Partial root-zone drying', a term which covers any irrigation technique that intentionally leads to progressive drying of part of the root system while the remainder remains relatively moist (but not necessarily close to field- or pot-capacity).
RDI - 'Regulated deficit irrigation', a term which covers any irrigation technique in which plants are intentionally subjected to a controlled degree of water deficit by applying less irrigation than is required to balance their potential evapotranspiration.
relative water content (RWC) - the water content of a leaf or other plant part relative to its water content when fully hydrated.
RIA - radio-immunoassay
SC - scheduling coefficient (see below)
scheduling coefficient - a measure of the effect of non-uniformity of irrigation on the degree of over-irrigation required if the driest areas are to receive the intended (i.e. mean) volume of irrigation. It is defined as mean catch rate divided by minimum catch rate
soil water tension - a measure of the capillary forces holding water in the soil (or growing medium), and therefore the force required to remove water from it. It is synonymous with 'soil moisture suction' and numerically equal to the soil matric potential (though of opposite sign). Measured in HPa, which is equivalent to a column of water 1 cm high.
specific leaf area - leaf area per unit dry wt
stomatal conductance (g_s) - A measure of the ease with which water vapour can diffuse out of the lower surface of a leaf, which depends on number of stomata per unit area and the size of the stomatal apertures.
SWC - volumetric soil water content (see below)
volumetric soil water content (SWC or θ_v) - water content of the soil or growing medium expressed as a fraction or percentage of the total volume occupied by water. Its maximum value, when the soil is saturated, depends on the percentage of pore space in the soil, which in peat based growing media is generally about 90%.
water deficit - an imprecise term meaning any reduction in water content below the 'normal range'. It can therefore be applied to both soil and plant. In the present context, the 'normal range' is what applies to a conventionally irrigated plant.
WUE - water use efficiency (see below)
water use efficiency - crop yield per unit of water transpired. Instantaneous WUE measured with by gas exchange is the ratio of CO_2 fixed to water transpired by an individual leaf in a cuvette.
xylem - the water conducting tissue of plants. Water moves mainly through the xylem vessels made up of elongated cells which at maturity are dead and empty of any cell contents so that they form a fine capillary pipework system. End walls between successive cells only partially breakdown, so that they represent constrictions in the pipework that help contain the effect of any damage to the xylem vessels.
[ ] - around the name of a chemical, square brackets indicate 'the concentration of'

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APPENDIX 1: Validation of ABA assay

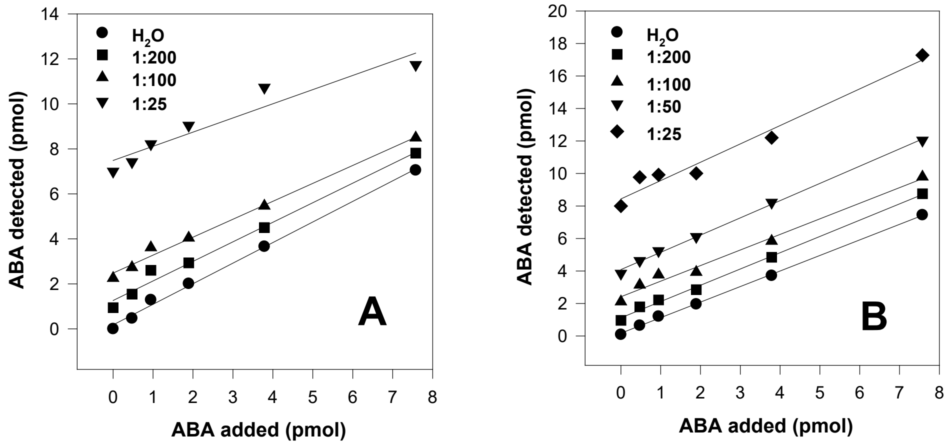


Figure A1.1 Spike dilution test for contaminants of leaf tissue extracts that might interfere with the binding of ABA to its antibody in a radio-immunoassay for ABA (A – *Forsythia*, B – *Hydrangea*). Graphs are pmol ABA added against pmol ABA detected after adding a range of well-watered tissue extract dilutions (g dw freeze-dried tissue:ml H_2O) to the assay tubes. Parallel standard curve regressions indicate the absence of contaminants in the extract.

APPENDIX 2: Standards relating to irrigation systems

Foreword

The specification is a statement of the performance sought from equipment intended for the control of irrigation in container-grown hardy ornamental nursery stock. It is intended as a guide for manufacturers and a basis for procurement by the horticultural industry. The specification focuses on the needs of the measurement and control system and is thus intended to be technology transparent, i.e. not focussed on any single technology but facilitating the development of existing and new technologies. It does not include the valves, pipework and nozzles required for application of the water.

Scope

This specification applies to monitoring and control equipment intended to be semi-permanently installed (i.e. for the duration of a growing season or longer) for the control of irrigation of container grown plants.

Definitions
Controller – The part of an irrigation control system which takes an input from one or more monitors, determines the amount of water to be applied and regulates the delivery of water, via valves and associated actuators. Note in a simple system, the controller and transmitter may be combined in a single unit.

Irrigation Control System – Equipment and operational procedures used to control the irrigation of container grown plants within commercial nurseries.

Measurand – Parameter that is measured by the sensor.

Monitor - The part of an irrigation system that directly or indirectly monitors the water status of the *crop plant*, and provides the signal used by the control equipment. This will generally consist of one or more *sensors* and a *transmitter*, though a sensor and transmitter may be combined in a single unit.

Rated range of use - The minimum to maximum values of any environmental, fluid or electrical parameter within which the equipment is designed to operate without adjustment, whilst continuing to perform to the requirements within this specification.

Sensor – The part of the monitor which takes the measurement.

Transmitter – A device consisting of any mechanical, electrical or pneumatic means of converting the unprocessed signal from the sensor into an output for transmission to the controller. The transmitter includes any built in user interface and signal processing required to set up or programme the monitor.

1. Operational Requirements

1.1 General requirements

Equipment shall be suitable for its intended use taking account of the practical working conditions, and shall not require unreasonable demands of the user in order to maintain its performance within the requirements of this specification. In particular, components of an irrigation control system shall be designed for:

- Simplicity of use;
- Good reliability – an operational use in excess of 5 years;
- Ruggedness for transport, handling, installation, repeated removal and reinstallation elsewhere in a nursery during the growing season;
- Low servicing requirements.

1.2 Measurand

An irrigation control system shall include one or more monitors from which the water needs of the plant may be directly determined.

Informative note: Monitors and their associated sensors tend to fall into 3 main groups. Those which measure:

a) Properties of the growing medium, e.g. water content,
b) Environmental conditions, e.g. temperature, wind speed, evapotranspirative need,
c) Properties of the plant, e.g. leaf water content, stem diameter.

This specification may be applied to any of these approaches.

1.3 Controller

A controller shall take the input from one or more monitors and determine the water needs of the crop against a pre-set regime (e.g. reduced deficit irrigation).

The user shall be able to programme the controller with the required irrigation regime.

Informative note: The irrigation regime to be applied will depend on various factors including the nature of the crop, changing water needs through the crop growth cycle, properties of the growing medium, local topography and geographical location of the nursery. Hence it is essential that a grower shall be able to programme the control system to address those needs. This programming will include a calibration step to determine the response of the monitor or sensor(s) to local conditions which influence water needs.

The controller shall include a clock to allow irrigation to be carried out at pre-set times of the day or night.

The user shall be able to programme the time of day when irrigation is to be applied. The manufacturer shall state how many irrigation events may be set over a 24 hour period.

The controller shall be capable of operating one or more solenoid valves to deliver water to the crop.

Where a controller is used with multiple valves, it shall be possible to stagger the operation of the valves.

1.4 Range

The manufacturer shall specify the operational range of a monitor for a specified uncertainty. The equipment shall continue to operate within the manufacturer's specified limits of accuracy and repeatability throughout this range when all conditions are within their rated ranges of use.

1.5 Accuracy and repeatability

The manufacturer shall specify the accuracy and repeatability of the monitor. The equipment shall continue to operate within these limits when all conditions are within their rated ranges of use, between the manufacturers recommended intervals for maintenance and calibration.

The irrigation control system should ensure sufficient accuracy of water delivery. Where control of irrigation is for water management alone, the accuracy of water delivery should be better than 20%. For other regimes such as Regulated Deficit Irrigation (RDI) the water delivery must be controlled to better than 10% of value.

1.6 Resolution

It shall be possible to set clocks and timers to a resolution of 1 minute or less.

The manufacturer shall state the resolution of the monitor. This shall not be greater than 1% of the range.

1.7 Documentation

Monitoring and control equipment shall be accompanied by documentation, written in English, in accordance with BS EN 61010 Part 1, 5.4 Documentation.

NOTE: This includes documentation to cover the following areas:

- Technical specification.
- Instructions for use.
- Instructions for calibration.
- Manufacturer's details.
- Equipment ratings.
- Equipment mounting and installation.
- Equipment operation.
- Equipment maintenance.

1.8 Security

Controllers and monitors shall be protected against unauthorised use of all controls that affect the performance irrigation control system.

2. Mechanical Requirements

2.1 Modularity

An irrigation control system shall be of a modular construction, with individual modules that are easily removable. It should not be possible, when using reasonable force, to cause damage to the equipment by incorrect insertion of modules. All modules shall be readily accessible and easily replaceable.

2.2 Ruggedness

Components of an irrigation control system shall continue to function within the requirements of this specification after being subjected to the test procedures described in clauses 3.2.1 and 3.2.2 in BS EN 60068 Part 2.31 Basic Environmental Testing Procedures Test Ec Drop and Topple, primarily for equipment-type specimens. It is not necessary for equipment to be operational during the test. Any cables which may interfere with the drop or cushion the impact shall be removed. In each case the height of the drop shall be 50mm.

Any cables linking components of an irrigation control system should be sufficiently robust to prevent damage associated with normal operational procedures within the nursery.

2.3 Identification

All components of an irrigation control system shall be clearly labelled in accordance with BS EN 61010 Part 1, 5.1 Marking, 5.2 Warning Markings, and 5.3 Durability of Markings.

Sensors intended for deployment in the growing medium or crop shall be labelled and clearly visible.

2.4 Size and Weight

The manufacturer shall state the weight and dimensions of components of an irrigation control system. The dimensions of sensors intended for deployment in the growing medium should be commensurate with the size of the growing containers.

2.5 Availability

The monitoring and control equipment shall operate without manual intervention during the period between routine maintenance operations except when undergoing self cleaning or automatic calibration.

The manufacturer shall state recommended intervals for maintenance and calibration that are necessary to maintain operation of the equipment within the requirements of this specification.

2.6 Reliability

Components of an irrigation control system shall have an assessed mean time between failure of greater than 5 years. The maintenance procedures required to achieve the assessed mean time between failures shall be detailed in the routine and long-term maintenance schedules.

The manufacturer shall state the shelf life and storage requirements for the components of an irrigation control system to ensure that its operability is maintained when stored for periods of up to two years.

Electrical Requirements

3.1 Power supply

Equipment should operate from one of the following power supplies, in all cases, the manufacturer shall state the rated range(s) of use for the power supply:

a) 12 or 24V d.c. supply. The manufacturer shall state the voltage range over which the equipment shall function within the performance requirements of this specification. Instruments operating from this supply shall incorporate appropriate protection against accidental reversal of the supply.

b) 110V or 230V a.c. 50Hz supply.

c) dedicated power source, e.g. a battery, or battery which is charged by an associated solar panel. The manufacturer shall state the operating limits of such a supply.

3.2 Battery power

Equipment operating from a battery shall incorporate a method of indicating when the power supply voltage is below its normal operating limits.

Any output should revert to zero on battery failure.

The manufacturer shall state the expected battery life when the equipment is used in normal operating conditions.

Battery powered monitors may incorporate battery conservation measures, such as intermittent activation, provided that:
- Any such measures can be manually over-ridden to provide readings on demand;
- A reading within the specified uncertainty of the instrument is available at least every 15 minutes.

3.3 Loss of Supply

Equipment operating from an external power supply shall have the facility to incorporate an alarm indicating loss of supply.

All pre-set data, including calibration and alarm set points, shall be retained for a minimum period of one week after the disconnection of the power supply.

3.4 Local Indication

Monitors shall have the facility to provide a local indication of the measurand. The local indicator shall match the output signal within 1% reading.

The local indicator shall be easily read over a range of illumination values from 50 to 900 Lux. The measured value shall be readable from a distance of 3m and subsidiary information characters shall be readable from a distance of 1m under similar light conditions.

The provision of a local display unit shall not compromise the environmental protection of the equipment.

The controller shall incorporate a visual display of inputs from monitors, resultant irrigation schedules and status indicators of control valves.

3.5 Output Signal Requirements

Controllers shall incorporate one or more switched outputs to operate solenoid valves. The manufacturer shall state the number of such outputs available and their voltage and current ratings.

Monitors shall incorporate one or more output signals for transmission of signals to the controller, which can be interpreted to provide the value of the measurand within the performance constraints of this specification.

The manufacturer shall state the number and nature of all output signals, which may be:

- 4-20 mA proportional to the operating range such that 4mA refers to the minimum value of the measurand and 20 mA relates to the maximum value. The manufacturer shall state the rated range of use for the signal load impedance.
- Digital. The manufacturer shall state the communication protocol used.
- Frequency or pulses from either volt free contacts rated at 50V d.c. at 3A resistive; or 12V or 24V positive pulse. The pulse per unit measurand (or quantity of measurand per pulse) shall be selectable by the user.

3.6 Electrical Termination

The cable terminations to all components shall be made in a discrete termination section. This shall house terminal blocks that are sized to suit the voltage and current demands of the circuitry.

3.7 Alarms

Where required by the purchaser, monitors and controllers should incorporate a visible alarm indicator, which may be set to operate at any point within the operating range.

4. Environmental Requirements

4.1 Materials of construction

Sensors intended to be placed in pots or in contact with the crop should be made from materials which are chemically inert with respect to the plant and growing medium. There should be no leaching of chemicals from the equipment into the soil or plant which may affect the plant.

Any parts of the equipment likely to come into contact with the growing medium should be resistant to corrosion due to the presence of fertilisers, disease and pest control agents, growth regulators and other chemicals which may be applied to plants and their surroundings within a nursery environment.

Any parts of the equipment likely to come into contact with the growing medium or plant should not adsorb potentially harmful chemicals such as pesticides and herbicides.

Any parts of the equipment likely to come into contact with the growing medium or plant should withstand chemical cleaning and sterilisation. The manufacturer shall state suitable methods of sterilisation.

4.2 Enclosures

Equipment intended to be used in a greenhouse, tunnel or outdoor environment shall be protected from the ingress to water and dust to at least IP65.

Equipment intended to be placed in pots should be protected from the ingress to water and dust to IP68.

Means shall be incorporated in any cabinet which may be opened whilst in its installed position, e.g. for maintenance or calibration, to ensure that any parts exposed whilst the cabinet is open are protected from the effects of high humidity and condensation.

4.3 Ambient conditions

Equipment shall continue to operate without degradation in its performance under the following rated ranges of use for ambient conditions:

Parameter	**Rated range of use**
Temperature	-10 to +55°C
Relative humidity	5% to 95% including condensation
Incident light	1 to 5×10^4 lux
Pressure	70 to 106 kPa
Soil pH	4 to 8

4.4 Lightning protection

Where required by the user, equipment shall be protected from the effects of lightning.

4.5 Depth of Burial

For sensors intended to be inserted directly into the growing medium, the manufacturer shall state the maximum depth of burial. This shall not be less than 100mm.

APPENDIX 3: Results of searches for relevant patents and other information

Soil Moisture Content

Variations in Conductivity/Resistance of the Soil

United States Patent 6,202,479 (Frybarger March 20, 2001) describes a soil moisture monitoring apparatus, system and method for monitoring the soil moisture content of a given volume of soil in which a plant is growing are provided.

United States Patent 6,138,590 (Colburn, Jr. October 31, 2000) describes a real time complex in-situ soil resistivity sensor and prescription agricultural chemical delivery system which includes a plurality of ground-engaging tools in association with individual soil electrode arrays which measure complex solute and matrix resistivity levels.

United States Patent 5,908,045 (Wallace, et al., June 1, 1999) describes an irrigation system that can utilise a conductivity moisture sensor to activate irrigation within separate irrigation zones.

United States Patent 5,861,751 (Anderson, et al. January 19, 1999) describes a method and device for determining the in-situ density of a porous material using a resistivity measuring device.

United States Patent 5,861,750 (Anderson, et al. January 19, 1999) describes a method and device for determining the hydraulic conductivity of porous materials. Other data, such as a formation factor, permeability constants of the porous material, and in-situ moisture content of the porous material may also be derived or measured.

United States Patent 5,847,568 (Stashkiw, et al., December 8, 1998) describes an irrigation control system, the preferred implementation of which uses a resistance based moisture sensor.

United States Patent 5,749,521 (Lattery, May 12, 1998) uses a moisture probe with conductive electrodes in direct contact with the soil medium.

United States Patent 5,570,030 (Wightman, October 29, 1996) uses a transmitter that produces a constant alternating current. The voltage produced within the soil is detected by electrical conductors on a sensor and is then fed to a receiver.

United States Patent 5,207,380 (Harryman, May 4, 1993) describes a system comprising several inputs that sends a current into the soil and measures the resulting resistance.

United States Patent 4,026,467 (Ayme de la Chevreliere, May 31, 1977) uses two single point electrodes to determine the spread of irrigation water through the soil, specifically when used in conjunction with drip irrigation.

Commercial Products

Delta-T Devices' SigmaProbe type EC1 is a sensor for spot readings of pore water conductivity.

Sutron Corporation's 5600-0080, is a solid state, electrical resistance type sensor, which covers the entire soil moisture range required in irrigated agriculture

Remote Measurement Systems' SMR-1 is a small electronics package designed for measuring the AC resistance of probes, whose resistance varies in proportion to a physical parameter such as soil moisture or fluid conductivity.

Dielectric Sensors - Measurement of Capacitance

United States Patent 6,060,889 (Hocker May 9, 2000) describes a phase shift oscillator circuit having a delay line in a feedback loop which is employed to determine soil moisture content and water level.

United States Patent 6,014,029 (Soto, et al. January 11, 2000) describes a device for sensing changes in the permittivity of a sample of a monitored medium.

United States Patent 5,859,536 (Stockton, January 12, 1999) uses a pair of sensing electrodes and appropriate circuitry to produce an output signal that varies in response to a capacitive change.

United States Patent 4,909,070 (Smith, March 20, 1990) again measures soil moisture by changes in capacitance of a capacitance sensing probe.

United States Patent 4,531,087 (Larson, July 23, 1985) uses electrodes embedded in a granular medium separated from the soil by a layer of filter cloth supported by a plastic or metal screen.

Commercial products:

Delta-T Devices Ltd. offer a range of soil moisture equipment. The sensors include the ThetaProbe ML2 for soil water content, tensiometers for soil water potential and the SigmaProbe for pore water conductivity.

Developmental Technologies, who are marketing the Automated Crop Irrigation System (ACIS).

SDEC's HMS9000. A French company that also makes tensiometers.

Sentek Pty Ltd make the Enviroscan RT6 - a fixed system dedicated to continuous monitoring of soil moisture. The Diviner 2000 using the same sensor technology is a portable system allowing quick infield readings of the whole root zone.

Silsoe Research Institute are developing sophisticated systems for irrigation control using sensors to measure soil water potential. These measurements provide input data for a water movement model which can then calculate the amount of irrigation that is needed. An EU funded project is co-ordinated in the Netherlands, with other partners in Germany, Italy and Israel. Silsoe are also involved in developing the sensors, which are based on dielectric sensors developed at IMAG-DLO (Netherlands) mounted on a stable ceramic substrate that equilibrates with the soil water potential.

The "Gopher" system, developed and manufactured in Australia, is a portable capacitance soil moisture profiler. The system comprises a 1.1m length staff, hand held microprocessor, a capacitance sensor head, software and upload cable.

Troxler Sentry 200 AP capacitance probe is distributed in the US by Irrigation Scheduling Methods Inc., as part of their irrigation scheduling/soil monitoring system complete with scheduling software (PRISM - ISS).

Vitel Hydra Soil Moisture Probe operates at a maximum of about 50 MHz, and has a purpose built data logger available, or can be connected to other loggers.

Frequency Domain Reflectometry (FDR)

United States Patent 5,418,466 (Watson, et al., May 23, 1995) measures the moisture/complex dielectric constant of a variety of mediums. The sensor apparatus uses a tuned circuit that oscillates such that the frequency of oscillation is representative of the complex dielectric constant of the medium.

United States Patent 5,341,673 (Burns, et al., August 30, 1994) describes a system for monitoring the moisture content of soil using a timing capacitor. The capacitor has several conductive elements to sense the hydration state capacitance of the soil. A data logger measures the frequency generated by a capacitance-to-frequency converter.

Time Domain Methods

United States Patent 6,215,317 (Siddiqui, et al. April 10, 2001) describes a method and apparatus for measuring in-place soil density and moisture content by measuring the in-place dielectric constant of soil from contact spikes driven into the ground using time domain reflectometry.

United States Patent 5,933,015 (Siddiqui, et al. August 3, 1999) describes a method and apparatus for measuring in-place soil density and moisture content using time domain reflectometry.

United States Patent 5,920,195 (Robichaud, et al. July 6, 1999) describes an apparatus and method for the moisture content measurement of compressible materials using pressure to firmly hold surface probes against the material to be measured. The apparatus uses moisture measurement circuitry employed in frequency domain impedance or time domain reflectometry devices to obtain moisture content readings from materials.

United States Patent 5,726,578 (Hook March 10, 1998) Time Domain Reflectometry methods and apparatus for measuring propagation velocities of RF pulses to determine material liquid contents, moisture profiles, material levels and various dielectric constants.

United States Patent 5,420,517 (Skaling, et al., May 30, 1995) uses a plurality of probes, adapted for use with a Time Domain Reflectometry device. The apparent dielectric of the soil is ascertained from delay times.

United States Patent 4,918,375 (Malicki, et al., April 17, 1990) discloses a meter for measuring water content of soil whereby the dielectric constant is determined using a reflectometric method.

Commercial Products

Aquaflex SE200 Soil Moisture Meter has been designed to overcome the historical problems associated with measuring the soil moisture content at one point only, and in a relatively small amount of soil. Aquaflex measures average moisture over a 3 metre (10 feet) length and in a cylindrical volume of 6 litres (370 cubic inches) of soil. The system uses Time Domain Transmission (TDT) which is similar Time Domain Reflectometry.

Automata Inc. manufacture and supply the AQUA-TEL sensors as well as host of other equipment. "The AQUA-TEL-TDR is similar to the tried and true AQUA-TEL, but reading volumetric free water independent of soil texture. The distributed measurement is averaged over 18". The exposed material is epoxy. Sensor signal of 0-1mA (or optionally, 4-20mA). Another option is to read soil temperature in addition to soil moisture (Model AQUA-TEL-TDR+T).

Campbell Scientific Inc. offer the a) CS615 reflectometer: ready to use sensor can be used with any voltage sensing data logger b) Hydrosense hand held unit with readout and c) TDR Soil Moisture Measurement System that combines Tektronix 1502B Cable Tester with CAMPBELL SCIENTIFIC 21X data logger.

Dynamx TR100 Soil Moisture Probe. They also supply TDR and other equipment
Easy Test, Ltd (licence: Institute of Agrophysics, Polish Academy of Sciences) supply a packaged TDR probe with field and laboratory versions. More advanced models sense temperature and electrical conductivity whilst a miniature version suitable for use in soil columnsor cores. A PC driven suite is available as well as a two data loggers. They also have a conventional matric potential sensor with a ceramic cup, as well as a "redox potential" meter.

GeoTDR Inc. assembles and installs systems using equipment from various manufacturers primarily for geological applications.

Global Water's sells various models based on measuring the dielectric constant.

Meteolabor's "Lumbricus" dielectric permittivity sensor with a claimed 1.5% accuracy at all water contents.

Soilmoisture Equipment Corp. Trase Systems 6050X1 (Cable Tester and data logger in one).

TDR300 by Spectrum Technologies Inc. supplies a push-in type unit, as well as other monitoring equipment.

Trime System of IMKO (Germany) originally developed only soil sensors, but have developed sensors for grain, paper rock and building materials. They also have good definitions of the various methods of expressing soil water content, as well as a comparison of common moisture measurement methods.

Automata produce AQUA-TEL94 capacitance sensors, which average soil moisture measurements over the length of the stainless steel probes.

Streat Instruments' Aquaflex uses Time Domain Transmission (TDT). Aquaflex measures average soil moisture over a 3 meter length and in a cylindrical volume of 6 litres of soil.

Campbell Scientific's Water Content Reflectometer measures the volumetric water content of porous media using time-domain measurement methods.

Environmental Sensors Inc.'s product portfolio include Moisture·Point, a sensor based on Enhanced Time Domain Reflectometry, which offers accuracy within 3% in most soil conditions without calibration, as well as Gro·Point, which uses Time Domain Transmissometry.

Easy Test, Ltd supply a packaged TDR probe with field and laboratory versions.

Delta-T Devices offer the ThetaProbe (type ML2x) which measures volumetric soil moisture content to within 1%. The ThetaProbe measures soil properties using a standing wave measurement technique.

Global Water's AT210 measures soil moisture by sensing the dielectric constant of the soil. The sensor averages moisture over its length when placed vertically, or will measure moisture at a specific depth when placed horizontally.

Adcon's C-Probe has a dynamic range of 0-100% volumetric soil moisture and a resolution of 0.4% volumetric soil moisture. Its repeatability is +/- 0.5%.

SDECFrance's HMS 9000 probe is designed to measure the volumetric water content in soils using the capacitance probe method.

Sentek Pty Ltd's EnviroSCAN is a continuous soil moisture monitoring system, utilising frequency -domain reflectometry sensors. Diviner 2000 is a portable, hand-held soil moisture monitoring device that incorporates the same digital technology.

Variable Resistance in Sensor Materials

United States Patent 4,952,868 (Scherer, III, August 28, 1990) uses a pair of concentrically disposed cylindrical conductors, which are separated by a layer of beads. An electrical circuit measures the variable resistance caused by the level of moisture present in this layer.

Commercial Products

Irrometer Company's Watermark sensor is a granular matrix sensor, which allows an indirect, calibrated method of measuring soil water.

Psychrometry

Wescor Scientific Products' PST-55 is a psychrometer that has been widely used in research programs.

Weight and compaction systems

Patent EP0855135A2 (Gerald Rolfe, 1998) uses a buried pressure sensor, which responds to the changes in pressure due to soil water content. (United States Patent 5,954,450 -- Rolfe September 21, 1999 -- by same inventor has wider claims, referring to any ground condition monitoring sensor located below the surface).

United States Patent 6,234,008 (Sjoblom, et al. May 22, 2001) describes a system whereby the soil moisture content over time can be calculated. As a soil specimen dries out, water is drawn from the pore space, which decreases the amount of water surrounding the soil particles, causing an increase in the pore water tension. The tension draws water from a saturated plate and reservoir, causing a change in the output of a strain gauge or pressure transducer and the change in mass can be measured.

United States Patent 6,161,329 (Spelt December 19, 2000) describes an improved watering device providing automatic watering of one or more potted plants with a predetermined volume or quantity of water, in response to the weight of the potted plant which indicates the moisture content of the plant soil.

United States Patent 6,041,582 (Tiede, et al. March 28, 2000) describes a site-specific farming system for performing work on an agricultural field while soil compaction conditions of the field are being recorded.

United States Patent 5,361,534 (Burns, et al., November 8, 1994) uses a beam and load cell assembly to control the irrigation of horticultural plants or crops grown in containers. Irrigation events are related to differential weight change of the plant media system, which allows for compensation of weight change effects due to other factors such as fruit set, plant weight, pruning, and harvesting.

United States Patent 5,351,437 (Lishman, October 4, 1994) uses the weight of a representative control volume of soil (for example, pot weight) to operate a switch at predetermined levels of dryness (that is, sample weight).

Gas Supply

United States Patent 4,040,436 (Caldwell, August 9, 1977) uses a gas supply feeding a porous body buried near the plant root.

Water Swellable Materials

United States Patent 5,794,848 (Nunn, et al., August 18, 1998) uses a polyamide copolymer (such as polyether block amides), which it is claimed has ‘preferred’ hygroscopic and other properties that can be precisely engineered.

United States Patent 5,329,081 (Jones, July 12, 1994) describes a moisture sensor and switch that utilises a water swellable composition. The change in dimensions moves a piston, the position of which can be used to control irrigation.

United States Patent 4,657,183 (Arkebauer, April 14, 1987) describes a valve which incorporates a block of material whose dimensions change in response to soil moisture content. When the block expands it causes the valve to shut stopping the flow of water.

United States Patent 4,655,076 (Weihe, et al., April 7, 1987) includes a chamber with a water-swellable material within. The sensor is responsive to the volume of the water-swellable material. (The sensor incorporates a magnet that is moved by the water-swellable material.)

United States Patent 4,182,357 (Ornstein, January 8, 1980) A pre-set valve using an enclosed volume of water-swellable material to control the flow of water.

Commercial Products

Irristat International Inc.'s Irristat is a pre-set valve which incorporates a synthetic polyacrylamide gel as the moisture sensing element (United States Patent 4,182,357 above).

Thermal Conductivity

United States Patent 4,845,978 (Whitford, July 11, 1989) uses a probe that incorporates both heating and temperature sensing elements. The heating element is energised for a period of time, and the temperature change of the sensing element is then a function of moisture content.

United States Patent 4,197,866 (Neal, April 15, 1980) compares the heat conductivity of a porous element to a given standard to derive the moisture content of the soil.

Commercial Products

Campbell Scientific's 229 thermal diffusivity sensor is based on the measurement of thermal conductivity.

Nuclear Methods

United States Patent 6,079,433 (Saarem June 27, 2000) an automatic moisture sensing and watering system detects a moisture level within the soil using a radiation source and receiver.

United States Patent 4,614,870 (Morrison, September 30, 1986) describes a miniature, low power consuming, density gauge utilising small artificial and naturally found radioactive sources. A radioactive source is positioned a predetermined distance below the soil surface with detectors approximately at the surface and detector at a depth approximately twice the depth of the source.

Commercial products

Campbell Pacific Nuclear International (CPN) manufacture the 503-DR HYDROPROBE® instrument for use in access tubes, as well as the PORTAPROBE® range for surface use.

Geoquip (Pty) manufacture Waterman neutron probes in South-Africa, to international standards, with datalogging facility as well as a "cycle" facility. this enables the user to set-up the probe at a predetermined depth, say 400mm, and start taking readings at a chosen time rate (between 1 and 60 seconds), for as long as the battery lasts or until the required time is past, without activating the probe every few seconds. These readings will be logged to be downloaded onto the computer.

Troxler Electronics manufacture the Model 4301/02 for use with access tubes, but also have surface moisture and density models, sensors for use with wood chips, asphalt and concrete.

Tensiometers

United States Patent 6,321,487 (Sardanelli, et al. November 27, 2001) describes a growth medium moisture replacement system.

United States Patent 6,263,726 (Hubbell, et al. July 24, 2001) describes a sidewall tensiometer to in-situ determine below-grade soil moisture potential of earthen soil.

United States Patent 6,138,408 (Paternoster, et al. October 31) describes a system and method which provide control for delivering water from a moisturising agent to plant tissue.

United States Patent 5,758,538 (Hubbell, et al. June 2, 1998) describes a tensiometer to in-situ determine below-grade soil moisture, potential of earthen soil.

United States Patent 4,922,945 (Browne, May 8, 1990) describes a tensiometer that includes a pressure-sensitive electrical switch, which acts to control an irrigation system in response to changes in matric water potential.

United States Patent 4,396,149 (Hirsch, August 2, 1983) describes an irrigation control apparatus that incorporates tensiometers from which data is transmitted continuously to a central computer.

Commercial Products

Adcon's Electrotensiometer has a standard ceramic cup, but the signal from the vacuum sensor above the water-filled tube is conditioned to be compatible with Adcon's data acquisition units. Adcon also supply telemetry solutions and have other sensors.

Delta-T Devices Ltd. offer a range of electronic, pressure transducer tensiometers, including miniature and rugged-use models. Typical usage is in multiple arrays, automatically recorded by a field data logger. They measure soil water potential to an accuracy of ±0.2 kPa over the range +100 to -85 kPa. These sensors can also monitor water table height when submerged (and the overburden, if present).

Earth Systems Solutions are the American distributors for various SDEC (French) tensiometers including accessories and electronic transducers for continuous logging.

Irrometer The Original American Suppliers since 1951. They also produce the Watermark sensor.

SDEC's TENSIONICS. A French company that also makes a capacitance sensor. They also have a "Tensimeter" (electronic readout unit) which is designed for use as a portable gauge for use with tensiometers.

SoilMoisture Equipment Corporation supply tensiometers as well as many other devices for monitoring soil and plant water potential.

SDECFrance provide a range of mechanical and electronic tensiometers.

Liquid Tension-Sensitive Gas Valves

United States Patent 4,383,543 (Rawlins, May 17, 1983) describes such a valve.

Environmental Monitoring

Evapotranspiration

United States Patent 6,314,340 (Mecham , et al. November 6, 2001) describes an irrigation controller which collects daily high and low temperature data then processes this collected temperature data in accordance with the Hargreaves equation to determine a reference evapotranspiration value.

United States Patent 6,298,285 (Addink, et al. October 2, 2001) describes an irrigation controller that is capable of making daily adjustment of irrigation duration based upon historical, environmental, and or received information.

United States Patent 6,227,220 (Addink May 8, 2001) describes an irrigation controller which modifies sophisticated irrigation protocols using an extremely simple user control.

United States Patent 6,145,755 (Feltz; Louis V., Nov. 14, 2000) describes an irrigation system that controls the amount of water to be applied based upon specific historical meteorological data including relative humidity, evapotranspiration data and precipitation.

United States Patent 6,088,621 (Woytowitz, et al. July 11, 2000) describes an irrigation control system including an irrigation controller, a portable data shuttle and a personal computer.

United States Patent 5,870,302 (Oliver, February 9, 1999) uses evapotranspiration data and meteorological data to compute irrigation needs.

United States Patent 5,479,339 (Miller, December 26, 1995) describes a system that responds to a signal from an atmometer. (An atmometer's evaporating surface uses water at the same rate as the crop, and is thus a physical model of evapotranspiration.) The signal is produced when a predetermined "threshold" amount of water has been lost to evapotranspiration at or near an irrigation station.

United States Patent 5,421,515 (Rinkewich, June 6, 1995) describes an automatic irrigation device where evapotranspiration needs are inferred from an open-top fluid evaporation pan containing the irrigating fluids.

Commercial Products

Weathermatic’s product portfolio includes ET-WISC a tool for aiding in the development of irrigation schedules using historical evapotranspiration values.
Soil Moisture Monitoring Services’ Etgage is an automated atmometer that uses a covered ceramic evaporator to mimic the solar energy absorption and vapour diffusion resistance of irrigated crops.

Temperature Detection

United States Patent 5,539,637 (Upchurch, et al., July 23, 1996) uses crop canopy temperature, measured with an infrared thermometer, to schedule irrigation.

Rain Detection

United States Patent 5,836,339 (Klever, et al., November 17, 1998) describes a raindrop counter and control system for irrigation systems, which provides the quick detection of the presence, and subsequent absence of precipitation once it has first been detected.

United States Patent 5,355,122 (Erickson, October 11, 1994) describes a rainfall detection and disable control system, which provides detection and a visual display of both a trace level and a variable accumulation level of natural rainfall.

United States Patent 5,321,578 (Morrison, et al., June 14, 1994) describes a rainfall detector for detecting a set amount of rainfall, which then functions to interrupt the normal operation of an irrigation.

United States Patent 4,613,764 (Lobato, September 23, 1986) describes a system which operates in response to the weight of water in a collecting pan.

Multi-parameter Measurement

United States Patent 6,343,255 (Peek, et al. January 29, 2002) describes a method and system for providing weather information over the internet using data supplied through the internet and a wireless cellular data system. A user such as a farmer can also supply the system with his particular field and crop conditions and the system will apply the conditions to the weather information and return customised crop production and control information to the farmer over the Internet.

United States Patent 6,076,740 (Townsend June 20, 2000) describes an irrigation control system for land includes a weather station to measure one or more weather conditions in an area.

United States Patent 6,055,480 (Nevo, et al. April 25, 2000) describes an apparatus and method for monitoring environmental conditions that processes information to create and display information concerning changes in the status of environmental conditions.

United States Patent 4,755,942 (Gardner, et al., July 5, 1988) relates generally to systems and methods for scheduling irrigation by measuring crop water stress using a plurality of sensors including crop canopy and air temperature, and humidity. The parameters are combined into a water stress index within an electronic unit, which then uses that value to trigger or stop irrigation.

Plant Monitoring

Size and Growth

United States Patent 4,638,594 (Huguet, et al., January 27, 1987) involves measuring variations in a specific parameter of a plant size (for example, stem or fruit diameter), to identify when the daily variation is below a certain threshold at which irrigation will be triggered.

Hydration of Plant Parts

United States Patent 5,927,603 (McNabb July 27, 1999) describes an automatic irrigation system includes a movable irrigation device having a fluid delivery nozzle and a fluid manifold positioned along the mobile irrigation device and adapted to receive irrigation fluid from a supply source. The system includes a sensor to detect moisture present within an agricultural field which is configured to detect electromagnetic radiation emanating from plants.

United States Patent 5,224,769 (Holbrook, et al., July 6, 1993) uses a plurality of conductive elements adapted for mounting on a plant part to sense the hydration state capacitance of the plant part; (NB: United States Patent 5,341,673 Burns, et al., August 30, 1994 use a similar approach to measure the moisture in the soil.)

United States Patent 4,380,169 (Graham April 19, 1983) describes a method of measuring leaf water content (Moisture Tension Radiometer) coupled to an irrigation control valve.

Leaf Condition

United States Patent 5,981,958 (Li, et al., November 9, 1999) describes an imaging fluorometer that can be used to obtain images that indicate the physiological state of the leaf (application to irrigation control is not mentioned explicitly).

Leaf Temperature

Tektran Agricultural Research Service in the USA have investigated an automatic irrigation scheduling and control system for drip irrigation of corn and soybean. The system relies on measurements of crop leaf temperature. It assessed crop water stress levels by comparing the leaf temperature to a threshold temperature that was determined for a well-watered, unstressed crop. The automatic system was compared against a manual method that used soil water measurements to assess the amount of water used by the crop each week, so that the next irrigation could apply that amount of water to replenish the soil water reservoir. Over two years with quite different rainfall amounts, corn yield, total water use and water use efficiency (WUE, the amount of yield per inch of water used) were stable for the automatic irrigation treatments. But, corn water use and WUE varied widely over the two years of corn production for the manual treatments. The automatic system was able to respond to low stress levels resulting from good rainfall, and thus, delivered larger irrigation WUE values when rainfall was more plentiful. For soybean, yields and WUE were not more stable for all automatic treatments. It appears that the automatic irrigation system will allow a choice between larger yields or larger water use efficiencies to be achieved for corn, but not for soybean. However for both crops, the automatic system delivered yields as large or larger than those obtained with the manual system in all years, with less management time and effort.

Leaf Thickness

United States Patent 6,185,833 (Bravdo, et al. February 13, 2001) describes a leaf thickness sensing device, in particular to the sensing of changes in leaf thickness, particularly for use in irrigation systems.

Commercial Products

Dynagage's sap flow sensors provide a non-intrusive method for measuring sap flow, and thus the water consumption of plants.

Timer Based Systems

United States Patent 5,853,122 (Caprio, December 29, 1998) uses relative humidity measurement in conjunction with a timer.

United States Patent 4,548,225 (Busalacchi, October 22, 1985) uses a fully automated tensiometer to provide feed back measurements for use in conjunction with a timer (see also EP076014A1, 1983).

Commercial Products

Manufacturers of irrigation controllers include Hardie, Toro, Richdel, K-Rain, Irritrol, Orbit, LR Nelson, Superior, Rain Bird, and Eicon

Miscellaneous Products of Interest

Tucor's' Flowmaster Irrigation Control system is a method of retrofitting existing irrigation systems using "two-wire decoder" technology to control the valves (*see http://www.igin.com/2wire.html for the development history of this two-wire system; see also United States Patent 5,839,658*).

Essential Data Control Systems Inc. provide Irrigation Management Systems (IMS) that include moisture sensors.

Gro·Point™ is a moisture-sensing instrument that provides measurement of soil moisture by volume for most agricultural soils. The Gro·Point™ Soil Moisture Sensor operates on a similar principle to radar. The sensor, which measures the speed of electromagnetic waves is very sensitive to soil moisture surrounding the probe.

United States Patent 5,887,491 (Monson, et al. March 30, 1999) describes a soil analysis system for determining various soil characteristics including moisture content, organic matter content and the presence of nitrogen phosphate, potassium and other elements. A soil testing device adapted for intermittent contact with the soil and including a plurality of functionally different testing assemblies including: one or more reflectance testing assemblies, an electrophoresis testing assembly; and a chromatography testing assembly.

Irrigation Control Systems

United States Patent 6,343,749 (Thom February 5, 2002) describes a mobile drip irrigation system includes an existing mobile irrigation system with the sprinkler heads removed and drip lines connected to the locations of the removed sprinkler heads.

United States Patent 6,142,703 (Wilmot, et al. November 7, 2000) describes an underground fluid exchange system for control of delivery of fertilisation, irrigation and pesticides to and removal from a selected fully encapsulated the turf area of a playing field, including golf course green.

5208855 (Marian, May 4, 1993) describes an irrigation control system using evapotranspiration sensors

Commercial Products

Automata's DATALYNX® line of monitoring and control telemetry equipment provides the link between field conditions and the office computer. Growers concerned with conserving water without endangering their crops can monitor field conditions such as rainfall, soil moisture, ET and crop water stress.

Motorola has been providing solutions for remote control of irrigation systems since the late 1970s, including automated irrigation systems which use two-way radio to communicate among the in-field units and the central site monitor and control computer. Agricultural applications include drip and sprinkler irrigation systems, water distribution systems, and nursery and greenhouse operations. Also, a newly patented "two-wire decoder" technology allows two wires to completely control an irrigation system, removing the need to re-wire when expanding the system.

APPENDIX 4: Detailed results of water use survey

2000 growing season

The water-use data recorded by the water meters was converted to a daily application rate and normalised in terms of bed area; an application rate has therefore been calculated, expressed in litres per meter squared of bed. Figure 5.2 shows the water application rates for the covered beds for the months July to September. (Note: for Nursery 2, the metered bed is in a large glasshouse, rather than a poly-tunnel.)

As noted above, the nurseries also recorded rainfall data, expressed in mm of rain per day, and this has been added to the application rate for the outside beds at each nursery, as shown in Figures 5.3 to 5.6.

Figure 5.2 Water Application Rate for the Covered Beds

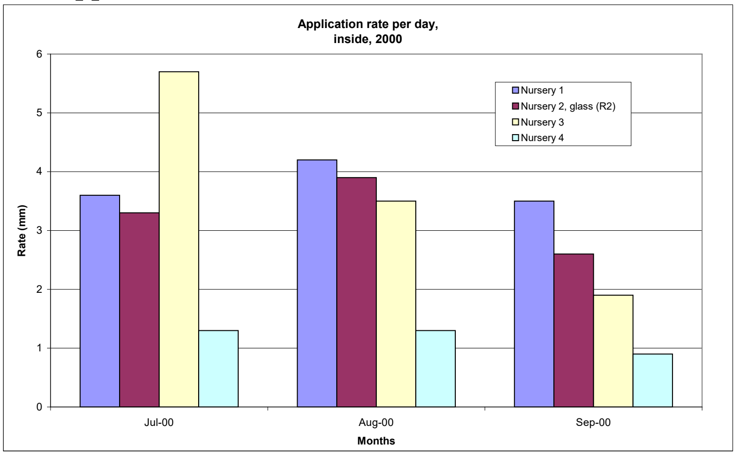


Figure 5.3 Water Application Rate for Outside Beds (Nursery 1)

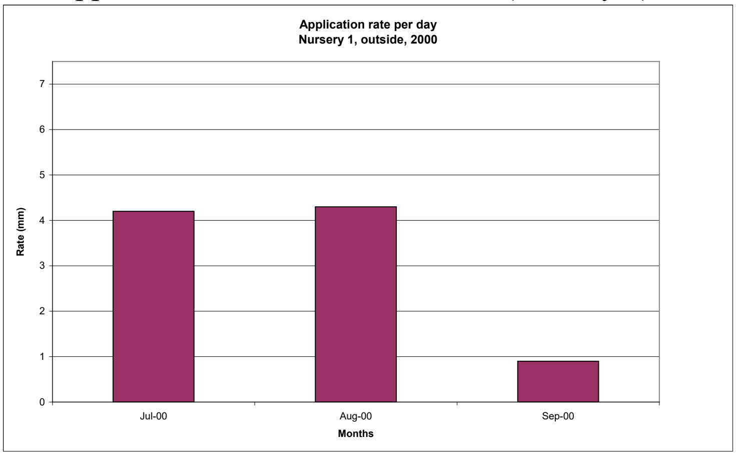


Figure 5.4 Water Application Rate for Outside Beds (Nursery 2)

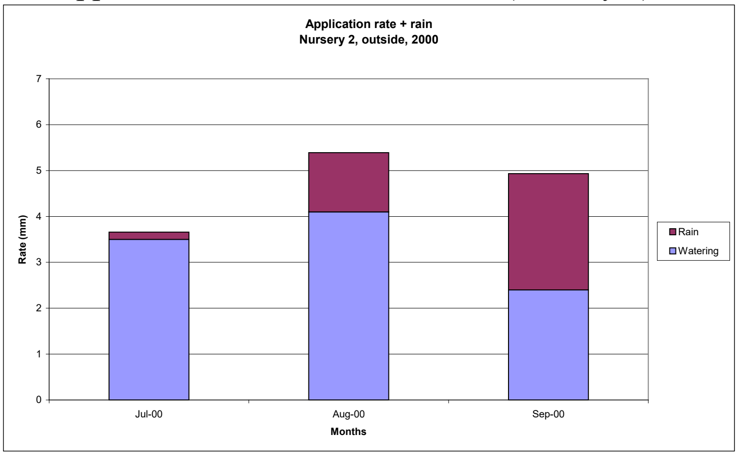


Figure 5.5 Water Application Rate for Outside Beds (Nursery 3)

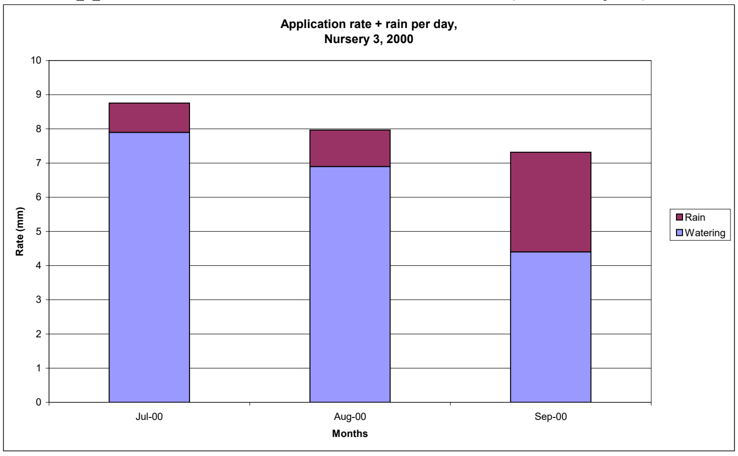
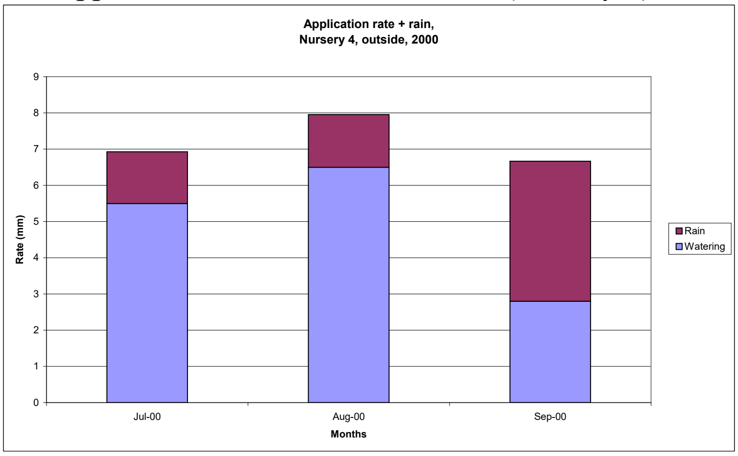
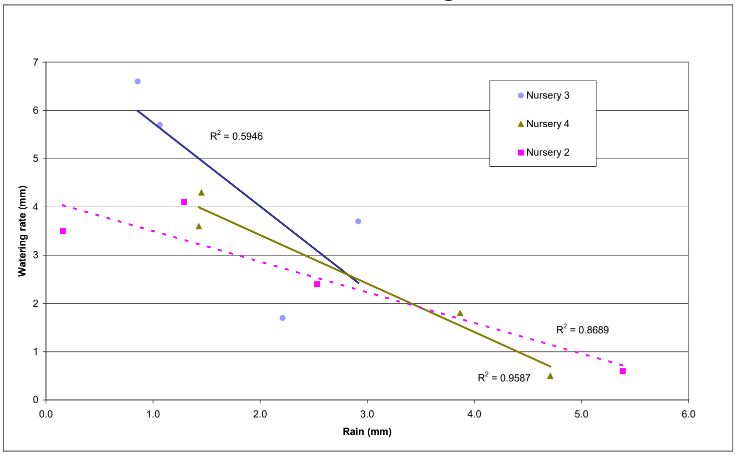


Figure 5.6 Water Application Rate for Outside Beds (Nursery 4)



Analysis was undertaken to determine if there are any strong relationships between the irrigation events and weather. For example, Figure 5.7 shows a plot of irrigation rate against rainfall. As expected there is a tendency for the rate of watering to be reduced as rainfall increases.

Figure 5.7 Correlation between Rainfall and Irrigation



Discussion

From the plots given above, it is clear that there are significant variations in the rates of water application, even though similar crops are being grown. Furthermore, other research partners have noted that the calculated rates are low in comparison to their expectations, based on the evapotranspiration demands of the crop plants. The presence of meters could, of course, modify the decision-making processes of managers, although the nurseries have been asked to ensure that the same watering regime is applied to the metered beds.

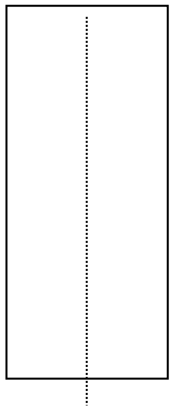
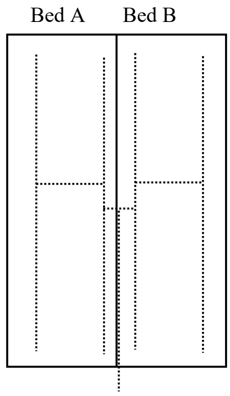
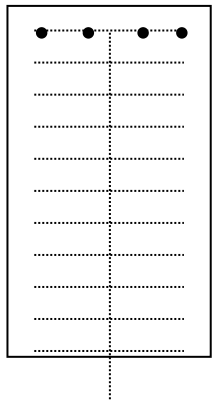
The analysis of water use and weather parameters merely confirmed intuitive expectations; that is, irrigation is positively correlated with temperature and negatively correlated with rainfall. It is again noteworthy, however, that the relationship between weather parameters and irrigation rates varied from nursery to nursery.

2001 Growing season

Three nurseries supplied data for water use in the 2001 growing season, 2, 3 and 4 in Figure 5.1.

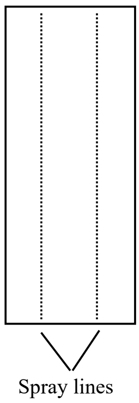
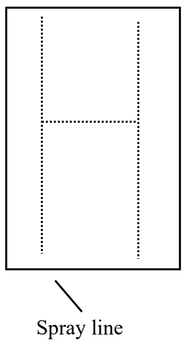
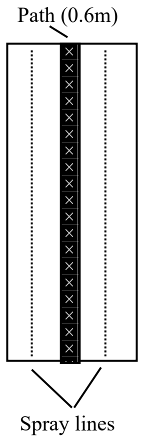
Bed details

Outdoor beds

	Nursery 2	**Nursery 3**	**Nursery 4**
Total area	1313m^2	2 x 440m^2	1014.6m^2
Layout	13 x 101m  Spray line	2 x 8 x 55m (see note)  Spray lines with 4 lines of 7 nozzles	17.8 x 57m  Spray line with 11 rows of 4 nozzles
Number of nozzles	11 in 1 central line	28 in 4 lines of 7 all firing in 180° arc	44 in 11 rows of 4
Distribution radius	22.8m	8m	5.65m
% water lost	63%	<1%	16%
Bed	10/20mm gravel on Mypex	Data not supplied	Gravel
Crops	Mainly Berberis, some currants, gooseberries and physocarpus at various points in the season	Bed A Corylus Bed B Rose	Data not supplied
Pot spacing	Pot size 2/3l spaced at 25 x 25cm pot centres	Majority 2" spacing in 3l pot, some 3" spacing in 2l pot	Data not supplied
Data collected	1 April – 25 Oct	9 Apr – 30 Sept	1 Apr – 13 Nov
Irrigation period	5 May – 14 Oct	A 29 Apr – 30 Sept B 21 May – 30 Sept	11 May – 18 Sept

Note: The outdoor bed of nursery 3 comprised two beds which were irrigated from a common supply but controlled independently. The nature of the site meant that the water meter had to be fitted prior to the split between beds. The timing of the irrigation to each bed was recorded and the total volume recorded was allocated across the beds in the ratio of the timings.

Covered beds

	Nursery 2	Nursery 3	Nursery 4
Total area	259.6m^2	600m^2	222m^2
Layout	5.9 x 44m 	12 x 50m 	6.3 x 35.25m 
Number of nozzles	60 in 2 lines of 30	20 in 2 lines of 10	48 in 2 lines of 24
Distribution radius	5.8m	6m	1m
% water lost	35%a	0	0
Bed	Mypex on gravel	Data not supplied	Gravel
Crops	Magnolias, Camellias, Lavatera, Spireas, Phygelius	Dahlia, Acer, Hydrangea, Fatsia Japonica	Data not supplied
Pot spacing	Mixed crop some plugs in trays not spaced, Magnolias pot thick and Camellias 20 x 20cm pot centres.	Mostly 2” spaced in 2l pot, One crop pot thick, one crop 4” spaced in $l patio pot.	Data not supplied
Data collected	1 April – 25 Oct	9 April – 30 Sept	1 April – 13 Nov
Irrigation period	5 May – 14 Oct	17 Apr – 30 Sept	12 Apr – 11 Oct

Water use summary

Irrigation measurements were made at each nursery by installing a mechanical water meter in the supply pipe immediately before the bed being monitored. The meter reading was recorded manually by nursery staff each day, together with the duration of the watering event. The data supplied has been used to estimate the monthly usage throughout the 2001 growing season. In each data set there were occasional missing or anomalous readings. In such cases, values have been interpolated from the patterns of surrounding information.

The volume of water recorded was converted into millimetres of water applied to each bed by calculating the effective irrigation, i.e. the total volume supplied less the water sprayed outside the bed, divided by the total bed area. For the outdoor beds and the covered bed in nursery 2, the proportion of water lost outside the bed was determined geometrically from the number, arrangement and distribution radius of the spray nozzles as compared with the bed. The distribution of water from each nozzle was assumed to be linear across the radius. For the covered beds in nurseries 3 and 4, losses are constrained by the walls of the tunnel.

It is assumed therefore that all water applied falls onto the bed. In nursery 2, the covered bed is within a much larger glasshouse and so the geometric approach was used.

The monthly average amount of water put onto the outdoor bed by irrigation each watering event was calculated by dividing the total millimetres of water applied by irrigation each month by the number of watering events. These are shown in Table 5.1.

Table 5.1 Monthly average irrigation per watering event

	Nursery 2		Nursery 3			Nursery 4	
	Covered	Outdoor bed	Covered	Outdoor A	Outdoor B	Covered	Outdoor bed
Month	Irrigation (mm)	Irrigation (mm)	Irrigation (mm)	Irrigation (mm)	Irrigation (mm)	Irrigation (mm)	Irrigation (mm)
April	3.6		2.1			4.4	0.0
May	2.7	2.7	2.7	5.2	3.3	20.3[1]	7.8
June	5.0	2.7	4.2	5.5	4.9	7.5	6.0
July	3.6	3.1	5.8	7.6	4.6	9.1	8.5
Aug.	4.5	2.7	4.7	6.7	4.9	6.3	7.2
Sept.	5.0	2.4	3.7	7.0	5.0	4.7	6.0
Oct.	4.5					6.0	

1. The figures for May include one event significantly higher than all others for which no explanation is given.

The daily averages are calculated as the total millimetres of water applied each month, divided by the number of days. For the outdoor beds, rainfall is included. These are shown in Tables 5.2 to 5.4.

Table 5.2 Daily averages for nursery 2

	Covered bed	Outdoor bed		
Month	Irrigation (mm)	Irrigation (mm)	Rainfall (mm)	Total (mm)
April	0.9			
May	1.8	2.2	1.1	3.3
June	2.5	2.7	0.9	3.6
July	1.8	2.4	3.0	5.4
August	1.9	2.2	3.2	5.4
September	1.5	0.9	3.6	4.5
October	0.9			

Table 5.3 Daily averages for nursery 3

	Covered bed	Outdoor bed A			Outdoor bed B		
Month	Irrigation (mm)	Irrigation (mm)	Rainfall (mm)	Total (mm)	Irrigation (mm)	Rainfall (mm)	Total (mm)
April	0.7						
May	2.6	4.4	0.6	5.0	2.8	0.6	3.4
June	4.0	4.4	1.5	5.8	4.2	1.5	5.6
July	5.4	7.3	1.3	8.6	4.4	1.3	5.7
August	4.3	5.4	2.0	7.4	3.9	2.0	6.0
Sept.	3.1	5.8	0.5	6.3	4.3	0.5	4.7

Table 5.4 Daily averages for nursery 4

	Covered bed	Outdoor bed		
Month	Irrigation (mm)	Irrigation (mm)	Rainfall (mm)	Total (mm)
April	0.3		2.9	2.9
May	3.9[1]	2.5	0.8	3.3
June	2.3	4.4	1.6	6.0
July	3.5	7.4	0.7	8.1
August	2.8	4.2	4.2	8.4
September	1.4	2.0	2.7	4.7
October	0.6			

1. The figures for May include one event significantly higher than all others for which no explanation is given.

APPENDIX 5: Additional photographs of responses to RDI

Photographs of Experiment 1.6, taken on 17 July, 4 weeks after the start of the RDI treatments. Left: 200% ETp (Control), centre 50% ETp, right 25% ETp

Forsythia x *intermedia* cv. Lynwood

Cornus alba cv. Elegantissima

Choisya ternata cv. Sundance

Lavandula angustifolia cv. Munstead

Cotinus coggygria cv. Royal Purple

Lonicera periclymenum cv. Belgica

Leaf lesions ('scorch') in the severe RDI treatment (25% ETp)on
Forsythia x intermedia cv. Lynwood

Photographs of Experiment 1.6, taken after the experiment had finished, in January 2003.
Left: 200% ETp (Control), centre 50% ETp, right 25% ETp

Forsythia x intermedia cv. Lynwood

Cornus alba cv. Elegantissima

Choisya ternata cv. Sundance

Lavandula angustifolia cv. Munstead

Cotinus coggygria cv. Royal Purple

Lonicera periclymenum cv. Belgica