Project title: **Improving The Control And Efficiency Of Water Use In Container-Grown Hardy Ornamental Nursery Stock**

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PRACTICAL SECTION FOR GROWERS

Introduction

Water availability is becoming an increasingly important issue across most sectors of the horticulture industry. The increased costs of mains water, the possibilities of restrictions on extraction rights, and the prediction of more irregular rainfall patterns due to climate change have forced nurserymen to think more carefully about their irrigation practices. On most container nursery stock units irrigation is applied by overhead irrigation - often to excess. Although some nurseries are collecting and recycling water, more efficient application in the first place may help reduce overall costs, and provide a mechanism to control plant growth more effectively.

The aim of the project is to match irrigation to the needs of container-grown crops, and in particular, make overhead irrigation more efficient. This will involve evaluating existing and new instruments for monitoring and controlling water use. Combined with this, the project will investigate new irrigation techniques that may help improve plant quality and schedule production, whilst minimising inputs such as labour or chemical growth regulators. Results from year 2 of the project are summarised below:

Water use data

Data on daily water use throughout the growing season was collected by the Water Research Centre from a number of commercial nurseries. Specific beds were identified on each nursery, and water use monitored across similar crop and pot types in each nursery. Interestingly, **water consumption varied by up to 100 % between different nurseries during set periods.** Although these results may to some extent be related to variations in weather patterns in the different locations, it is also apparent that some nurseries are already significantly more efficient in their use of water than others (Figure 1). **This is encouraging, as it suggests that large savings in water use are feasible, even if current 'best practice' guides are followed** and consideration given to factors such as microclimate, sprinkler type and layout etc.

Experiments were implemented at HRI-Efford to determine if it was feasible to irrigate a container crop using evapo-transpiration (ET) demand as the basis for irrigation control. A number of plants were weighed on a daily basis to evaluate the water use of the entire crop (i.e. the ET value for the day). The ET value was then used to calculate the appropriate time period for overhead irrigation to be applied. With this system, plants received more water after hot sunny days, but less after overcast or rain periods. Water use was compared with identical crops irrigated using fixed time controls based on application rates typical of industry. **Results from the experiments showed that by varying the amount of water applied in relation to ET, there was a 30-40% reduction in water use over the entire season.** It was interesting to note that **plants from both treatments were of a similar, relatively good quality by the end of the experiment.** It is hoped that this system will have practical use in the near future, but further evaluations are required to optimise its management. For example, it was apparent that after prolonged dry periods, heavy watering was required to restore container capacity to pots at the edge of the bed, so as to avoid these being blown over. How frequently this is required and how it is best accomplished remain to be determined.

Instrument evaluation

Determining water use (ET) in a crop by manually weighing individual pots is not a practical mechanism, and the project aims to provide alternative techniques to measure ET. Therefore, in parallel with the experiment carried out at HRI-Efford equipment was assessed by the Centre for Ecology and Hydrology for their potential to monitor evaporative demand and control irrigation to container-grown crops. The equipment evaluated fell into two categories:

- Those which measure the water content of the growing medium, ie in situ sensors located in the container. Those tested were:
  - The ThetaProbe, measuring water content (Delta-T Instruments)
  - The mini tensiometer, measuring soil water potential (Skye Instruments)

- Those which make measurements that estimate the "evaporative demand" of the atmosphere. These measurements are not container, or bed specific.
  - An automatic weather station (Delta-T Devices)
  - The "Evaposensor" (Skye Instruments, developed at East Malling)

The two types of sensors lead to two separate approaches to irrigation control with important implications for cost and precision.

The **Evaposensor** gave a very similar estimate for evapo-transpiration to that of the automatic weather station and it appears that the Evaposensor provides a low cost approach to predicting water use. However, the data collected showed that predicted, and actual water use, could vary significantly. This suggests that stomatal control was also influencing total water use in the crop plants. Data from other parts of the project have indicated that stomatal control may be influenced by light intensity or atmospheric humidity, irrespective of water availability at the roots, and such factors may explain the variation between predicted and actual water use. One disadvantage of the Evaposensor is that little account is taken of rainfall and this needs to be measured separately.

The in situ sensors such as the **Thetaprobe** do not require corrections for plant size, and rainfall need not be measured. However, at least one sensor would be required per bed, which make it a much more expensive option. The issue of variability between plants also needs to be addressed to ensure the sensor represented the water use of the crop as a whole. It is probable that the in situ sensor approach would be best used with an irrigation system that provides more uniform application rates than most sprinkler systems in current use.

As both approaches have a number of advantages and drawbacks, **a hybrid approach may have more merit.** The water requirements could be predicted using an Evaposensor, and a roving ThetaProbe would be used on an occasional basis, to check that the irrigation was "on track". If the pots were found to be dry, a remedial irrigation could be carried out. If the pots were very wet, the irrigation inputs could be reduced.

In the longer-term there would appear to be potential for **a completely automatic system.** This would combine an in situ probe with an "intelligent" controller, and would determine, after a number of irrigations, the amount of water to apply for a given change in water content. This would avoid the need for any operator inputs, such as determining pot size, spacing etc. The sensor control unit could be a single channel device for a bed, or a multi-channel device, to accept inputs from perhaps a dozen sensors controlling irrigation on a dozen beds.

Modifying the plant growth habit

Experiments were set up at HRI-East Malling to determine how applying regulated deficit irrigation (RDI) at different stages during the season affected plant growth and habit. *Forsythia* and *Cotinus* plants were placed on irrigation based on 50 % ETp for either the entire growing period, or for eight weeks at various stages during summer. In comparison, other plants were kept well-watered by either being placed on drip irrigation at 150% ETp, or on capillary sand beds, throughout.

Results again showed **it was feasible to reduce water consumption by two-thirds of well-watered controls without inducing plant injury**. **The greatest reduction in shoot vigour was recorded in plants either exposed to 50% ETp in July-August, or throughout the entire summer (50% ETp all).** Plants in these treatments maintained a compact, well-balanced growth habit (Figure 2). The results were particularly encouraging in that relatively good quality plants were obtained with **only minimal pruning** (e.g. *Cotinus* liners, pinched once after rooting, and once in spring prior to RDI treatment). Any requirement for summer pruning to avoid excessive vigour appeared to be negated by the RDI treatment. Providing RDI treatment early in the growth phase of *Cotinus* (June-July), however, was relatively ineffective as rapid re-growth occurred when plants were moved back to a well-watered regime at the end of July.

A second experiment on *Forsythia* demonstrated it was important to apply drought slowly and progressively, to allow plants to adapt most effectively to the reduced water supply. Interestingly, it became apparent that **plants exposed to controlled drought had greater tolerance for later drought episodes**, even after periods of generous watering. This may have important implications for improving plant performance at the retail stage, and aid establishment after planting.

Data from experiments carried out at Lancaster University indicated that the **partial root drying technique (PRD) was equally as good as RDI at regulating shoot vigour.** Plants of *Cotinus* and *Hydrangea* being considerably more compact that equivalent, well-watered specimens. PRD involves applying water to only a section of the root system, leaving the remaining roots exposed to a progressively drying soil. These roots generate signals that close the stomata on the leaves and reduce water use, but do not affect the water content of the plant itself, i.e. leaves and stems remain at full turgor. The **advantage of PRD is that it eliminates any risk of plant injury due to water deficit**, and avoids any unnecessary change in leaf size.

Grower relevant points

For similar sized plants and containers, water requirements over the season were remarkably similar between the species tested where the aim was to apply sufficient, but not excessive, water for maximum growth.

- By correlating irrigation to evapo-transpiration, considerable reductions in water consumption are feasible (up to 40 % reduction)
- Plant quality was similar between plants watered to set times and those watered on the basis of evapo-transpiration data.
- Evaposensors gave a good estimate of evapo-transpiration at relatively limited cost, however, determining real water use in container plants is likely to be more complex.
- Fully-automated ‘intelligent’ systems are likely to provide a feasible mechanism to control irrigation more precisely in future, but are likely to be more expensive
- RDI treatments applied at the appropriate growth phase have great potential to control vigour, and reduce the need for mid-late season pruning.
- To maximise the benefit, the framework of the plant should be built-up to provide a branched liner before the application of RDI.
- The effects of RDI may be relatively long-term (*Hydrangea* plants exposed to < 60% ETp in year 1 maintained a relatively compact habit in year 2, despite heavy watering).
- When drought develops slowly, plants adapt better - reducing chances of damage.
- There may be potential to pre-adapt plants to better tolerate stress at subsequent stages in the production process (e.g. at the garden centre or after the customer plants them)
- Systems involving root signalling (PRD) may also enable shoot growth to be manipulated effectively, but minimise any risk due to water deficits. Practical techniques to implement PRD require development.

Figure 1. Mean water application rates for beds under protection at different nurseries (with similar crop types).

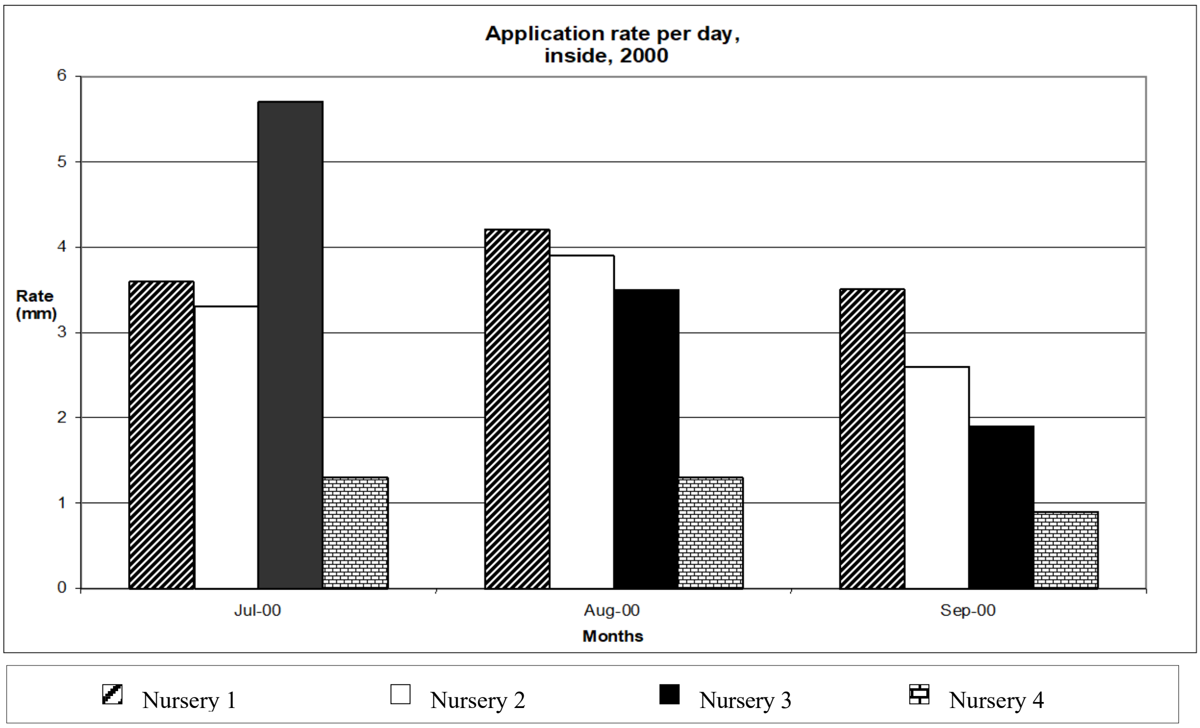
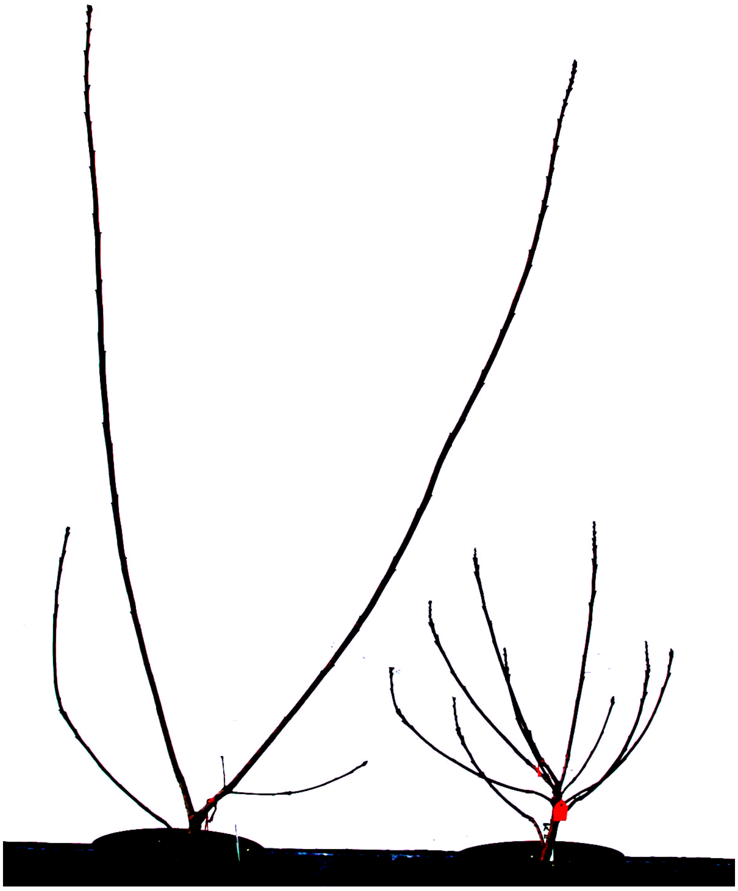


Figure 2. Silhouette photograph of *Cotinus* plants at the end of the growing season after growing under 150 % ETp for the entire summer (left) and 50% ETp during July and August (right). Plant pinched twice as rooted cuttings, with no further pruning.



SCIENCE SECTION

CONTROLLING PLANT GROWTH AND SHAPE THROUGH REGULATED DEFICIT IRRIGATION (RDI)

OBJECTIVE 2

HRI-EAST MALLING

INTRODUCTION

Results from year 1 demonstrated that applying Regulated Deficit Irrigation (RDI) at 50% ETp (potential evapo-transpiration) to a range of container-grown nursery stock was feasible without inducing loss of plant quality. The aim of the research in the second year was to determine how timing of RDI could affect growth rate and habit, and whether there was any potential to reduce the pruning frequency in the crops selected. The use of such controlled irrigation may facilitate more precise scheduling of crops and allow nurserymen to 'hold' crops at the most appropriate stage of growth for marketing. A second, additional component to the work programme was to determine what the longer-term effect of a controlled drought stress was on a plant's tolerance to subsequent stress. The aim in this experiment being to see if crops could be 'pre-programmed' to tolerate water stress during the retail process and after planting in gardens.

EXPERIMENT 1. TIMING OF RDI

MATERIALS AND METHODS

Cotinus coggygria cv. Royal Purple and *Forsythia x intermedia* cv. Lynwood were utilised for evaluating the effects of RDI timing (50% ETp) on shoot growth and development. One-year-old plants were pruned twice during the cutting / liner stage to develop a branched structure. These were potted into a growing medium comprising 100 % premium grade sphagnum peat with 6 g l^{-1} Osmocote Plus 12-14 month controlled release fertiliser, 1.5 g l^{-1} $MgCO_3$ and 0.75 g l^{-1} Suscon Green (chlorpyrifos) during February 2000. Plants were maintained in 2 litre pots for the duration of the experiment with no further pruning treatments being imposed.

Each species was arranged within polythene tunnels in 3 positional blocks and drip-irrigated through pressure compensating nozzles. Drip irrigation commenced in early June and plants were exposed to the following treatments:

150% ETp All - Plants kept well-watered throughout by applying 50% more water than daily evapo-transpiration.
50% ETp June-July - Irrigation reduced to 50% ETp during early primary shoot expansion.
50% ETp July-August - Irrigation reduced to 50% ETp during late primary shoot expansion.
50% ETp August-September - Irrigation reduced to 50% ETp during secondary shoot development and expansion.
50% ETp September-October - Irrigation reduced to 50% ETp during growth cessation (*Cotinus*) or late secondary shoot expansion (*Forsythia*).
50% ETp All - Plants kept on reduced irrigation throughout the entire summer.

Sand – Plants kept on capillary sandbeds throughout the entire summer.

NB. When plants were not on 50% ETp, they were maintained at 150% ETp.
In the 150% ETp All treatment of *Cotinus*, it was noticed there was some drying of the compost in certain plants and the amount applied was altered from 150% to 200% ETp from late July.

There were 10 plants per treatment x block combination, of which 5 were placed with a dripper in a fixed position (fixed). In contrast in the other 5 plants the dripper was moved (moved) to a new location 180° around the pot, every four weeks, in an attempt to discover if changing where the water was applied could generate greater root signalling effects.

As in the previous year, the daily ETp value was calculated using six control plants in each species that were weighed and re-watered every day. The mean weight change equating to the ETp value for the crop. Treated plants were monitored for changes in plant/pot weight, height, shoot length and internode length throughout. Internode length was designated as the distance between one bud on the stem, and the next bud vertically positioned above it. As *Cotinus* has a spiral arrangement of buds up the stem, each internode section represents approximately 4 buds. For the purposes of identifying zones of elongation, mean internode length was calculated from 5 internode sections at a time.

RESULTS

Cotinus

The period in which RDI was imposed had a strong effect over the final size and habit of the plants. In *Cotinus*, greatest overall growth was associated with the plants maintained on the capillary sandbeds throughout (Figure 2.1). These plants were characterised by long, leggy shoots which became bent over with the weight of apical growth. Interestingly, plants in this treatment had significantly more growth that the plants kept on the 150% ETp through drip irrigation. The 50% ETp treatment throughout, reduced growth considerably, but did not stop new shoot growth entirely. Similarly-sized plants were recorded in the treatment where 50% was imposed during July and August. Imposing a 50% ETp during June and July also restricted growth, but shoot growth was very rapid when full watering was restored at the end of July, and the benefit of the earlier restriction was lost.

The variation in growth characteristics between treatments could be accounted for by the number of nodes produced in each shoot, with plants exposed to 50% ETp from July onwards laying down fewer nodes (Figure 2.2). Internode length was also suppressed in those plant kept at 50% ETp throughout (Figure 2.2). Greatest internode length often occurred after approx.5 nodes had been formed on the shoot (Figure 2.3), but the timing this took place varied with treatment. For example, plants on the Sand treatment had laid down 10 nodes per stem by 13 July, whereas those on 50% ETp during June –July had not formed 10 nodes until 4 August. Late growth in all treatments was characterised by compressed node formation and very short internodal sections (Figure 2.3).

Figure 2.1. *Cotinus* cv. Royal Purple. The effect of irrigation treatment on plant height at different times during summer.

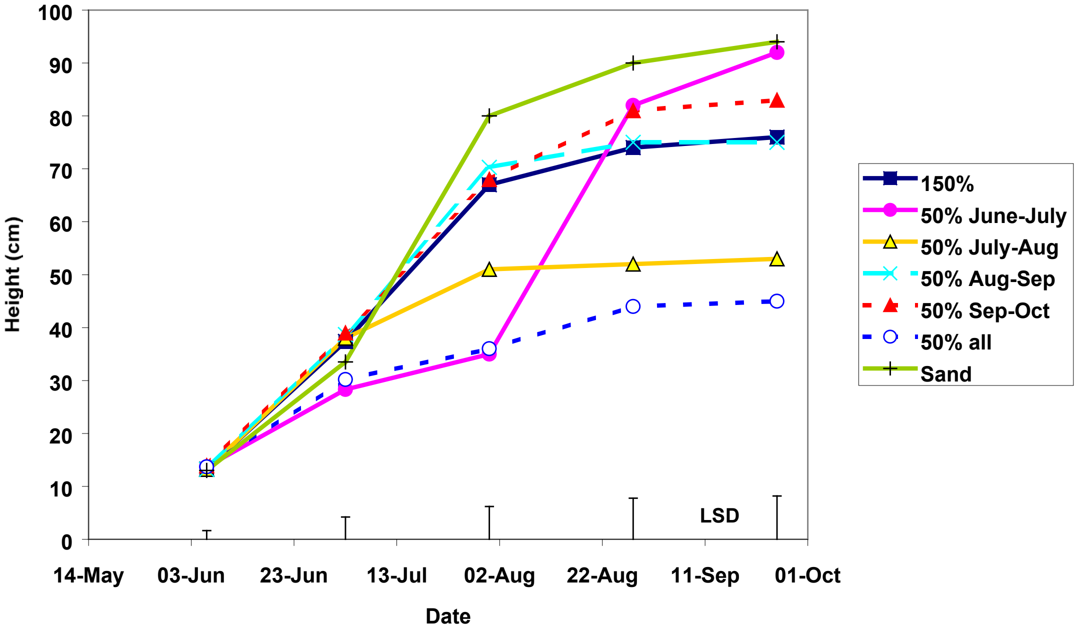


Figure 2.2. *Cotinus* cv. Royal Purple. The effect of irrigation treatment on number of nodes formed and mean internode length.

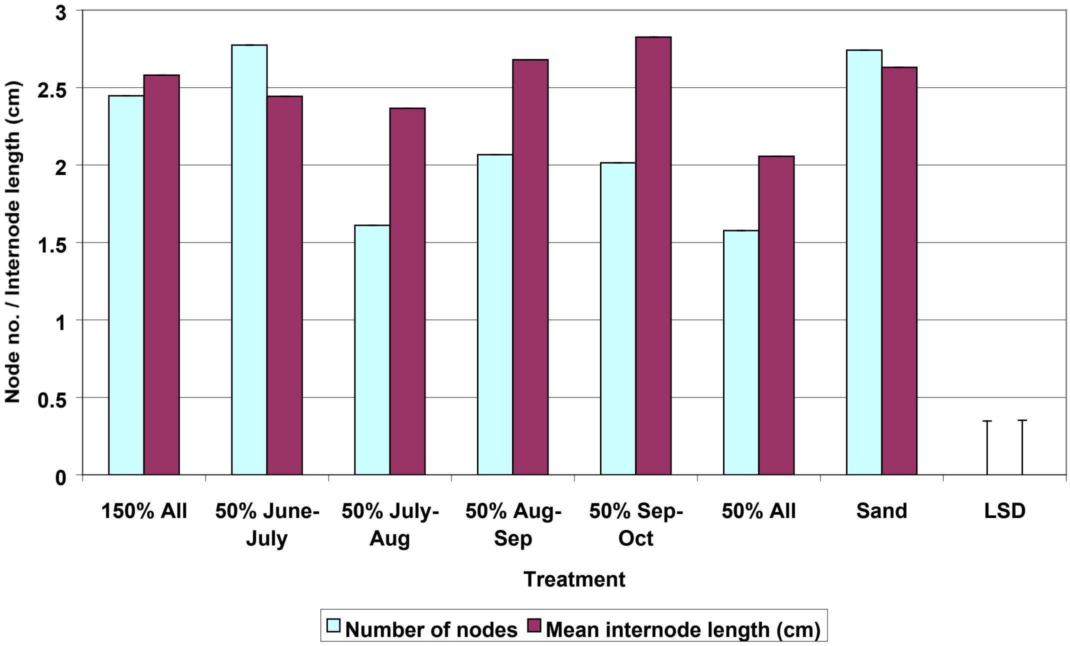
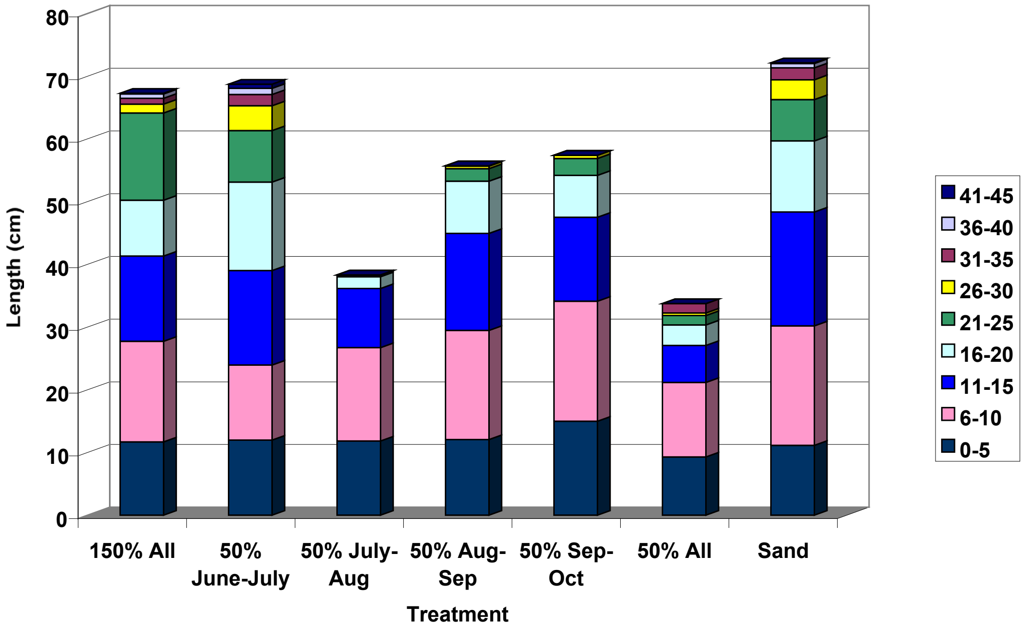


Figure 2.3 *Cotinus* cv. Royal Purple. The effect of irrigation treatment on length of internode sections (e.g. 0-5 = mean value for first five nodes at base of shoot).



Forsythia

Data for *Forsythia* showed similar results to those of *Cotinus* (Figure 2.4). Greatest growth was recorded for plants maintained on the sandbed, with strong apically-dominant shoots being present. In comparison, growth was again significantly less in the 150% ETp All and 50% ETp September-October treatments, although plants were still excessively leggy. As with *Cotinus*, applying reduced irrigation during the most active growth phase in June-July curtailed growth at that time, but on return to full watering, new strong shoot growth was activated. The most compact plants were associated with the 50% ETp continuous and the 50% ETp during July-August treatments.

The number of nodes produced and the mean internode length on shoots were both affected by the treatments imposed (Figure 2.5). Restricting irrigation at any time reduced node number compared to plants maintained on the Sand, and limiting irrigation during June-July, or throughout the entire summer, resulted in significantly shorter internode sections. Shortened internode sections were particularly noted in the 6-10 and 11-15 node regions (Figure 2.6).

Dripper position

The effects due to moving the drippers were not consistent across all treatments and there were no overall statistical significant effects on plant height (Table 2.1). Nevertheless, in some treatments, particularly the 150% ETp All, there was less growth in those plants where the drippers had been moved every 4 weeks, compared to those where the dripper was fixed in the one location.

Water use data for Control plants of *Cotinus* and *Forsythia* was quite similar for both species during the early period of summer (agreeing with results in year 1), but from August onwards water use was generally greater in *Cotinus* (Figure 2.7).

Figure 2.4. *Forsythia* cv. Lynwood. The effect of irrigation treatment on plant height at different times during summer.

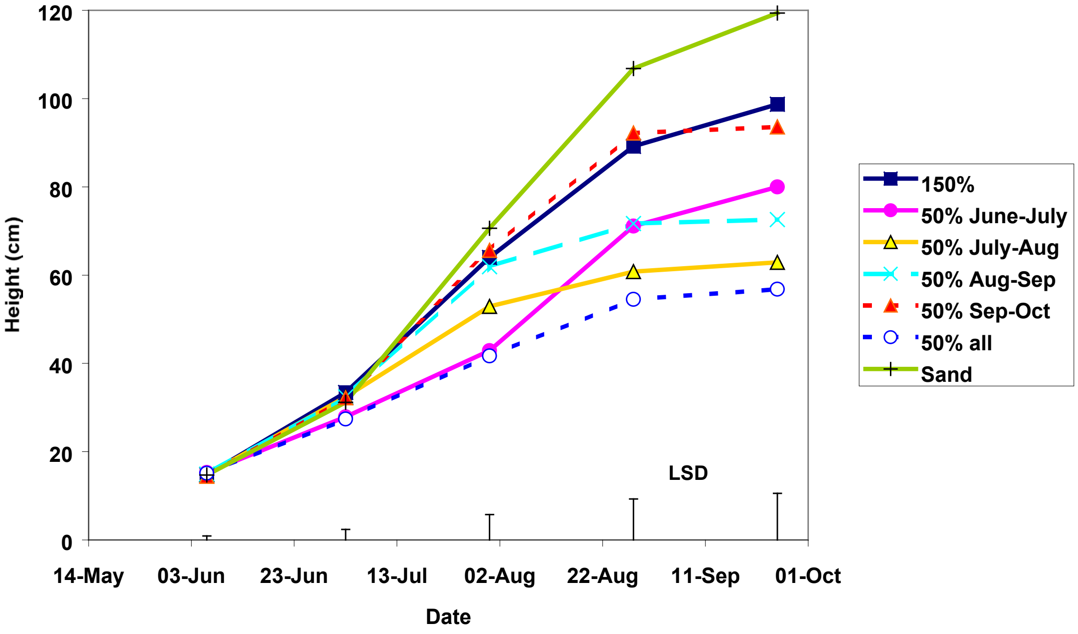


Figure 2.5. *Forsythia* cv. Lynwood. The effect of irrigation treatment on number of nodes formed and mean internode length.

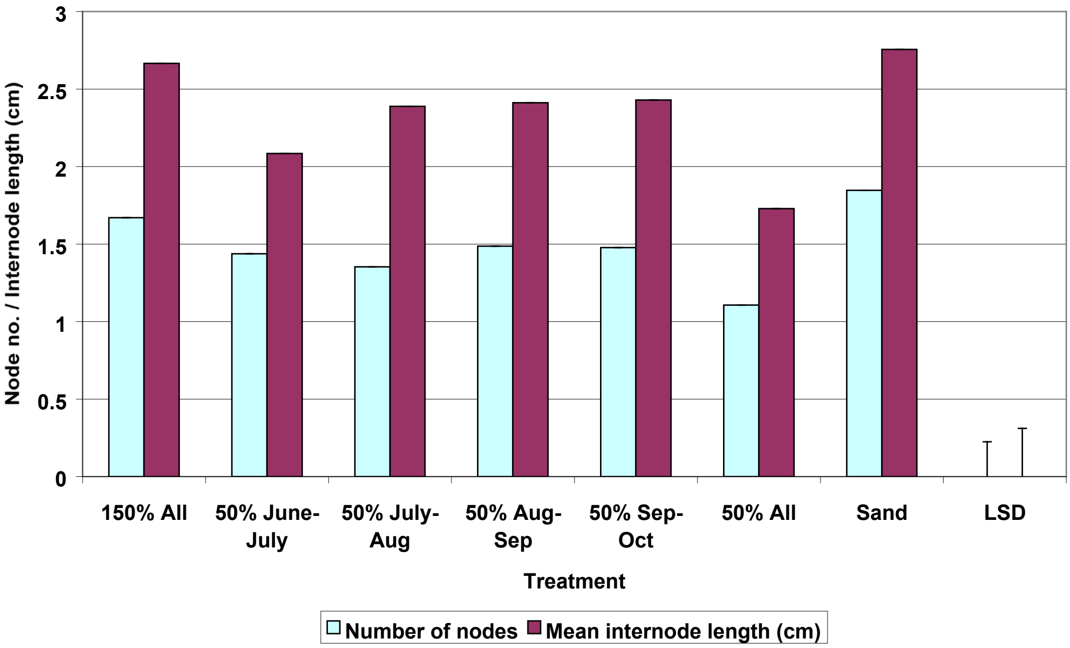


Figure 2.6. *Forsythia* cv. Lynwood. The effect of irrigation treatment on length of internode sections (e.g. 0-5 = mean value for first five nodes at base of shoot).

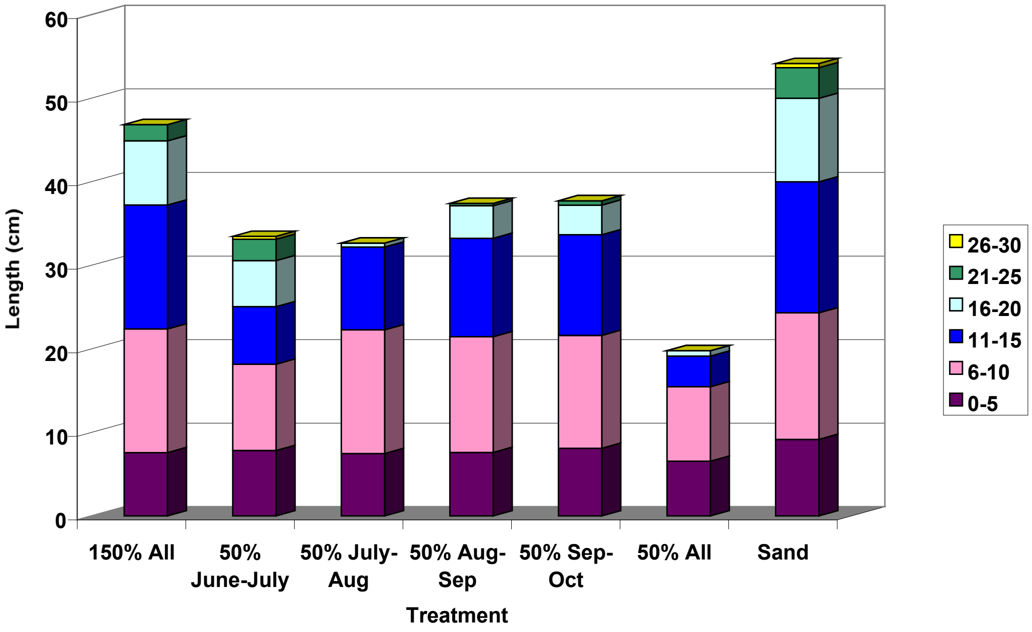
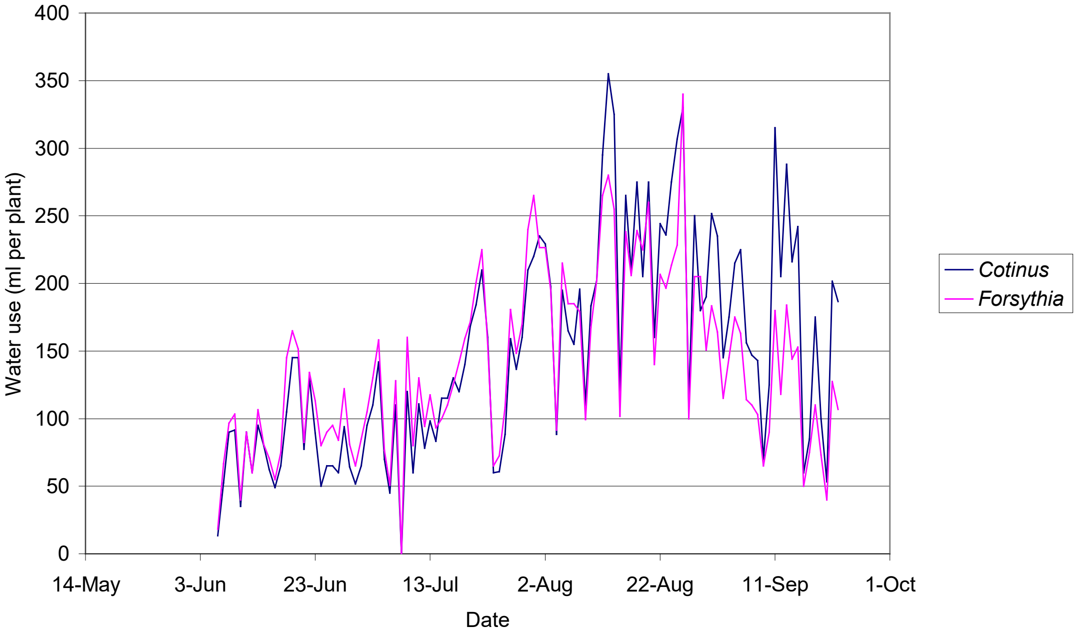


Table 2.1. The effect on plant height on *Cotinus* and *Forsythia* due to drippers being fixed in the one location, or moved every 4 weeks. Data recorded on 25 September 2000.

	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

Figure 2.7. Mean water use per day (ml) in control plants of *Cotinus* and *Forsythia*



EXPERIMENT 2. PRE-CONDITIONING FOR STRESS TOLERANCE

MATERIALS AND METHODS

One of the points raised at a previous Consortium meeting, was how long did the influence of controlled drought stresses last, and what were the implications for plant growth and development over the longer term. Indeed, would plants that had experienced restricted irrigation be more prone or less prone to injury during exposure to environmental stress at a later stage? This question has important commercial implications. For example, could crops grown on the nursery be pre-conditioned to adapt better to stresses that occur at the retail stage, or even after planting in the customer's garden.

A related question is how important is a *gradual reduction* in water availability to the avoidance of damage from RDI. The rate at which the water deficit develops depends on the size of the container relative to the size and spacing of the plants. For example, if the container is relatively small, reducing irrigation to 50% of potential evapotranspiration (50% ETp) could lead to severe water deficit within two or three days, which may well be too short a time for effective adaptation. On the other hand, for small plants in large containers it might be several weeks before the same irrigation regime created sufficient water deficit for stomata to start to close and growth to be reduced. Therefore, it is important to know whether it is acceptable to stop irrigation completely, to quickly achieve the desired soil water deficit, which can then be maintained by irrigating with < 100%ETp. A supplementary experiment was set up during late summer to start to address these questions.

The experiment was designed to answer two main questions –
1/ How does the rate of decrease of soil water content affect a plant's ability to adapt to controlled drought so as to reduce water consumption without visible damage?

2/ How does previous exposure to controlled drought affect a plant's ability to respond to later drought?

Liners of *Forsythia* grown in 1litre pots were used and there were three basic irrigation regimes:

1. **Well Watered Control (WW)**: 200% ETp throughout
2. **Slow onset Drought (SD)**: 50% ETp from day 10
3. **Rapid onset Drought (RD)**: No irrigation from day 15, until θ_v (i.e. soil water content as measured by wt of a sample of pots) equates with treatment 2, then 50% ETp.

There are two drought periods:

Drought Period 1: the above 3 regimes were compared.
Drought Period 2: following a period in which all plants were well watered, a second drought was imposed (RD only) to determine whether the plant's response is modified by previous experience of drought.

The full treatment list was (based on **1st drought - recovery - 2nd drought periods)**

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

RESULTS

It took 14 days for plants in 'slow onset' drought regime (SD), receiving 50%ETp, to restrict their water loss to match the water applied and thus 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 2.8), suggesting that stomatal adjustment reduced water loss to match water supply once the soil water deficit had reached a particular level, irrespective of the speed at which the 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 (ψ_l), and soil water content (θ_v) were then made over the course of 10 days of the first drought during which both treatments were held at 50%ETp. The results confirmed that there were no differences in g_s or θ_v but revealed that ψ_l was significantly lower in the 'rapid onset' treatment (Figure 2.9). Since the leaf area of the plants would have been closely similar, these results imply that the resistance to water uptake from the medium was reduced by exposure to the 'slow onset' drought, compared to the 'rapid onset' drought. This might be due to changes in root membranes associated with the increased production of ABA in roots exposed to dry soil, or perhaps to a shift in resource allocation resulting in slightly greater root development in the 'slow onset' treatment.

Figure 2.8. Changes in weight of *Forsythia* 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).

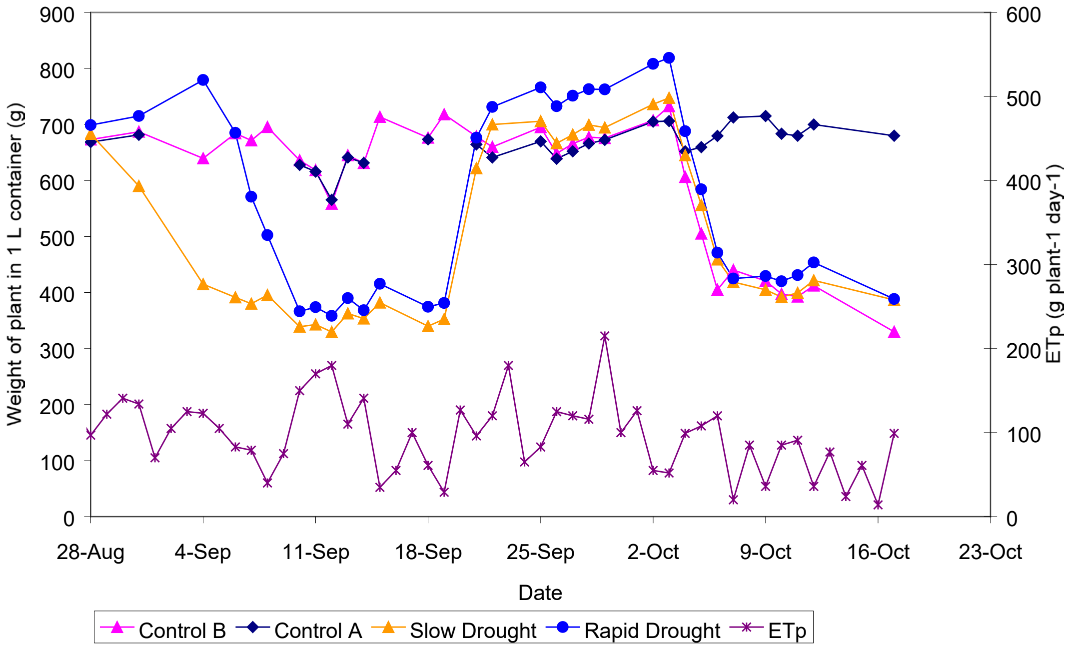
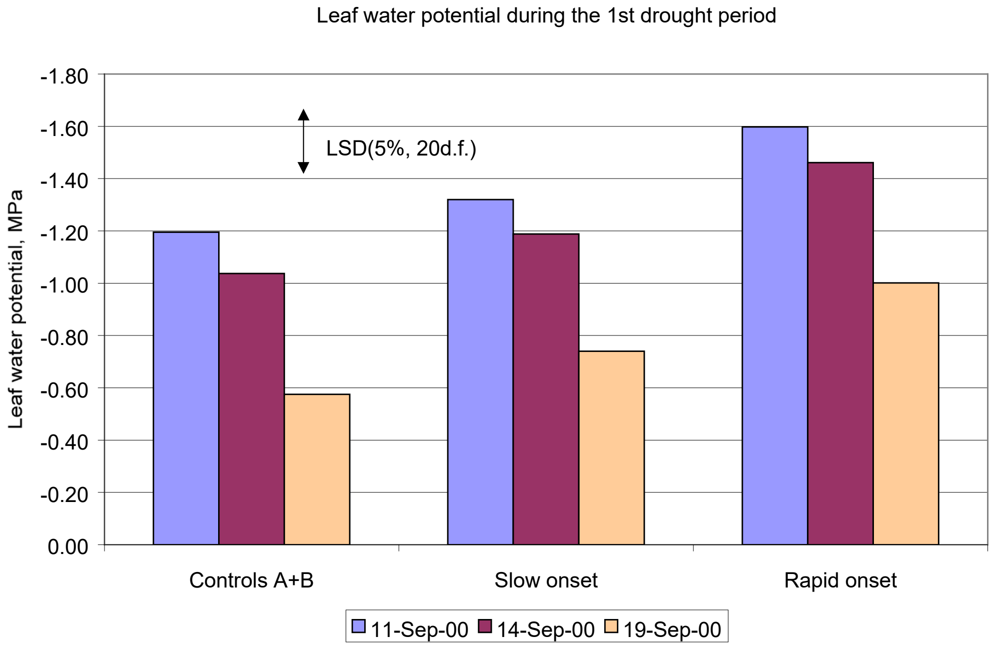


Figure 2.9. Midday leaf water potential on three separate days during the first controlled drought.



After the first drought period all plants were placed back on a well-watered regime for approximately 2 weeks to allow the media to re-hydrate and the plants to regain their full turgor. After which, watering ceased and a second rapid drought was imposed to mimic a very severe stress. Again a group of plants were kept well-watered for comparison (Control A).

The results showed that those plants that had been exposed to a previous drought (both slow and rapid) had greater stomatal conductivity (g_s) and had less negative leaf water potentials (LWP) than plants that had not been stressed before (Figures 2.10 and 2.11). This implies that the previous water stress treatments had allowed a degree of pre-adaptation and that these plants had retained an ability to tolerate subsequent rapid drought stress. Further research is required to verify these findings, but if the results are valid, then this may have important implications for improving the shelf-life of container ornamentals.

Figure 2.10. Stomatal conductance (g_s) of *Forsythia* cv. Lynwood plants during the second rapid drought.

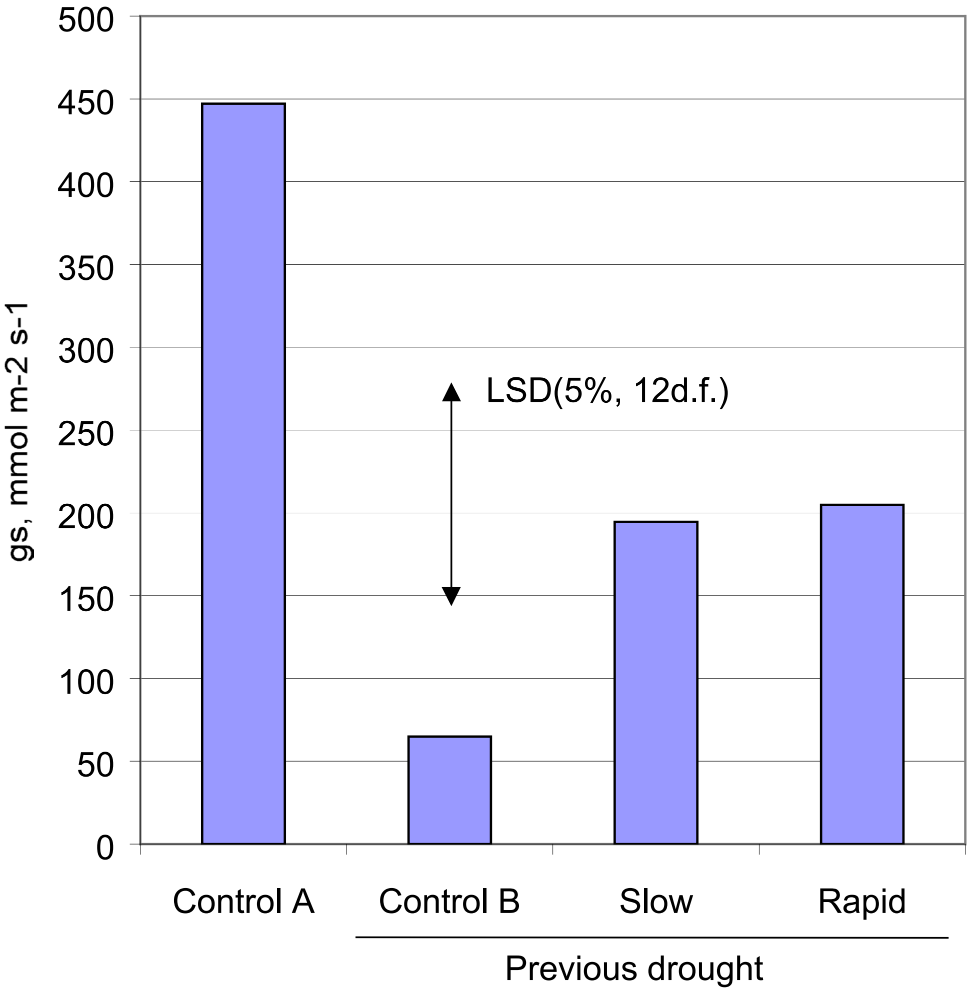
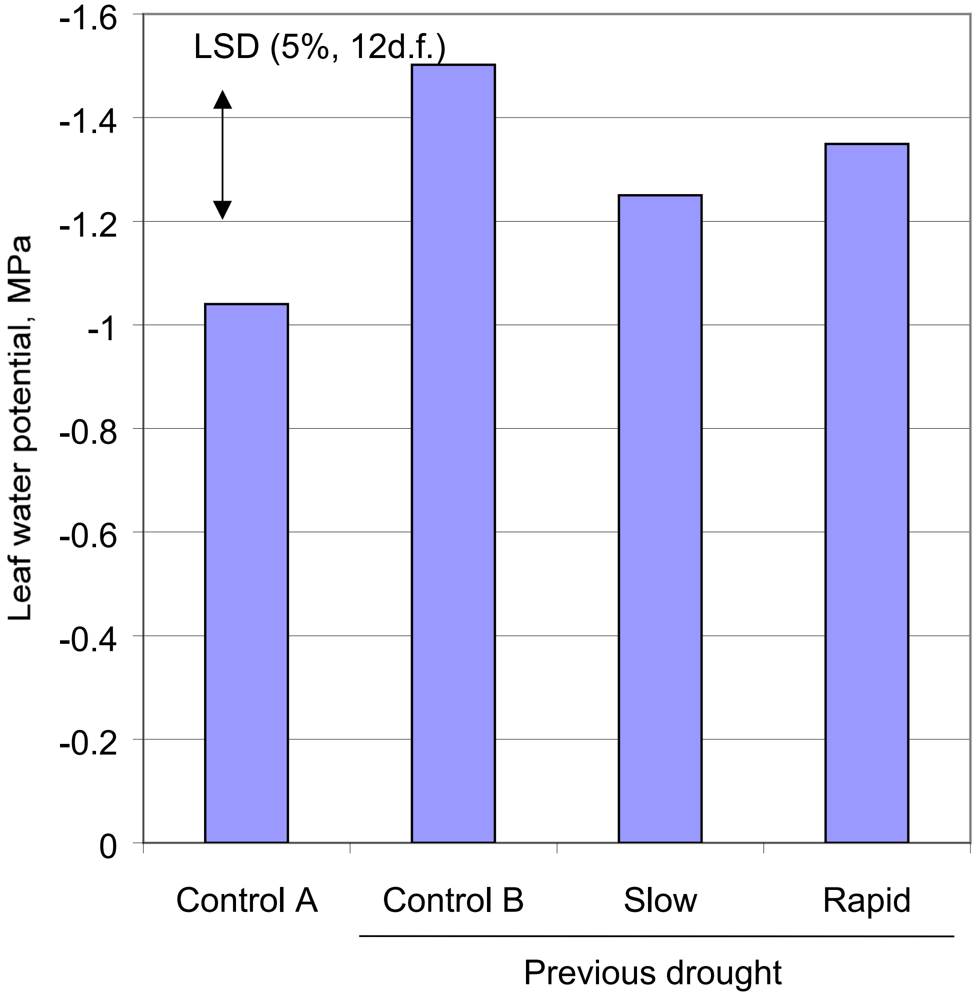


Figure 2.11. Leaf water potential (LWP) of *Forsythia* cv. Lynwood plants during the second rapid drought.



CONCLUSIONS

A number of very important points have been highlighted from this year's results, and the project is beginning to elucidate the extent to which plant growth can be manipulated through the use of appropriate degree and timing of regulated irrigation. In addition, some of the results imply there may be mechanisms to improve the plant shelf-life, and aid establishment in the garden. The main findings can be summarised as follows:

- **RDI treatments applied at the appropriate time in the growth phase have great potential to control vigour, and reduce the need for mid-late season pruning.**

- **Timing of RDI should coincide with the period of rapid shoot expansion that occurs shortly after budbreak, to curtail excessive vegetative growth.**
- **The framework of the plant should be built-up before the application of RDI (use of 'designer-liner technology' ?) to maximise the benefit.**

- **RDI influences shoot expansion by both reducing the number of nodes laid down and internode length.**

- **RDI may need to be imposed for periods longer than 4 weeks for species that have a long growing season.**

- **The effects of RDI may be relatively long-term (*Hydrangea* plants exposed to < 60% ETp in year 1 maintained a relatively compact habit in year 2, despite heavy watering).**

- **When drought develops slowly, plants adapt better - reducing chances of damage.**

- **Therefore RDI protocols must be designed to develop a water deficit slowly and progressively.**

- **Slow drought promotes adaptive changes in the root system that increase the hydraulic conductance of the root system, L_{rs}.**

- **Little evidence that rate of onset of drought influenced adaptation of stomata. In both treatments transpiration declined as volumetric water content (θ_v) approached 20%.**

- **The adaptive changes protected plants from later drought, even after two weeks of generous watering.**

TO INVESTIGATE THE EFFECTS OF ROOT-GENERATED ABA AND CO-FACTORS (XYLEM pH) ON GROWTH AND FUNCTIONING OF CONTAINER-GROWN PLANTS

OBJECTIVE 3

LANCASTER UNIVERSITY

INTRODUCTION

The broad aims of this aspect of the project are a) to identify strategies that reduce water use in container nursery stock production, b) to control excessive vegetative vigour in order to reduce pruning costs, and c) to produce more compact plants with greater retail desirability.

As described in report 1 (HL0132LHN / HNS 97) we have been searching for mechanisms whereby signals from roots that induce shoot water retention can be made more intense or to occur earlier in a soil drying cycle. In year 1 we determined that a technique called partial root drying (PRD – for ideology behind technique see Materials and Methods section) could successfully maintain the turgidity of *Forsythia* shoots (by reducing stomatal conductance) in plants provided with half the volume of water given to a well-watered control group. At the same time vegetative growth (both leaf and internode extension rate) was restricted, but the final leaf size attained was unchanged. Increases in foliar ABA and a novel root-sourced signal, namely a *reduction* in xylem sap pH, may have been involved in improving *Forsythia* water use efficiency and slowing vegetative extension growth. In year 2 we aimed to test whether the same technique, namely PRD, could reduce water use without imposing a shoot water deficit in two additional hardy ornamental species: *Hydrangea* and *Cotinus*. We also aimed to examine any ABA or pH signals sent from roots in drying soil to the shoots.

In addition we determined in year 1 that at least in the afternoon in *Forsythia*, greater control was exerted over stomatal aperture by the pervading aerial environment than by the imposed soil drying treatments. It is therefore important to examine the signals that control water loss in response to changes in, for example PPFD and humidity, in the hope that we may also be able to manipulate these. Indeed Year 1 results provided evidence that leaf apoplastic pH and [ABA] may also be the signals that control stomatal aperture in response to PPFD, and that signals from roots in drying soil and from leaves responding to current PPFD may interact. We aimed in Year 2 to examine whether such mechanisms also occur in *Hydrangea* and *Cotinus*.

MATERIALS AND METHODS

An automatic irrigation system was set up in two polytunnels, one containing *Hydrangea* and one containing *Cotinus*, both in 3 litre pots. For both species an experiment was set up to test the effects of imposing a soil water deficit on several physiological and biochemical parameters. For each species, 30 plants (arranged in 3 blocks of 10 to compensate for any tunnel-position-dependent variables) were kept at well-watered soil moisture levels (between 0.65 and 0.9 Volts as measured using the theta probe), by supplying water through centrally placed 4l/hr drippers (volume of water given per day governed by pervading aerial environment). Another 30 plants were supplied with exactly half the well-watered volume through centrally-placed 2l/hr drippers. Another 30 were also supplied with half the well-watered volume through 2l/hr drippers placed on one side of each pot which was tipped forwards (see Year 1 report), such that one half of the root system was maintained in wet soil, whilst the other upper side was allowed to dry. It was necessary to change the dripper to the dry side and tip the pot the opposite way to create a new dry side after the first 21 days. Our three treatments were therefore well-watered (WW), regulated deficit irrigation (RDI), and partial root drying (PRD); where PRD is effectively a "split-root" treatment, without physically dividing the root system of each plant. The ideology behind the experiment is that some of the roots in the PRD treatment will be influenced by soil dry enough to induce chemical signalling to the shoots that causes stomatal closure and retardation of shoot extension growth (and potentially removes apical dominance to induce "bushiness"). Less water will be lost from these plants, whilst the roots in the wet side provide enough water to keep the shoot turgid. RDI plants will not experience such dry soil due to the symmetrical application of the same reduced volume of water, so that chemical signals sent to the shoot may not be intense enough to close stomata and inhibit growth without a simultaneous loss of turgidity.

The following parameters were measured in July and August 2000 in *Hydrangea* and *Cotinus* to determine their suitability as candidates for commercial production under PRD, and to study the chemical signals sent to their shoots, which could be manipulated to potentially improve their commercial value:

a) Non-destructive measurements carried out every other day (6 replicates):
  - soil moisture potential (theta probe).
  - morning and afternoon stomatal conductance (gs) of mature and immature leaves (using a porometer).
  - leaf and internode expansion and extension rates.
  - light intensity (PPFD) incident on each leaf (porometric); leaf temperature (porometric) and aerial humidity.

b) Destructive measurements carried out approx. every 6 days (3 replicates):
  - leaf collection for tissue [ABA] determination by radioimmunoassay (RIA – *Hydrangea* only; *Cotinus* tissue [ABA] can only be measured using gas-chromatography mass-spectrometry for which there is no facility at Lancaster).
  - leaf relative water content (RWC - experimental leaf weight as a % of fully turgid leaf weight once dry weights have been subtracted).
  - shoot water potential (Scholander pressure bomb).
  - xylem sap pH determination using a microelectrode after extraction using the pressure bomb at 2 and approx. 8 bars over balancing presssure (hereafter called initial and high pressure sap pH respectively).
  - xylem sap collection for future [ABA] determination using RIA (for protocol see Year 1 report).

RESULTS

Soil water stress tolerance.

Figure 3.1 shows the effect of each irrigation treatment on soil moisture content over the course of the experiment. Both the RDI and the PRD treatments resulted in the exposure of some (PRD) or all (RDI) of the roots of both species (3.1A – *Hydrangea*; 3.1B – *Cotinus*) to dry soil. The PRD treatment could be successfully achieved without physically separating the wet and dry halves of the soil – there was no movement of water into the dry side from the watered side. It is of note, however, that in both species the "wet" side of the PRD treatment was considerably drier than the soil of well-watered plants. This may be due to increased soil moisture uptake from the "wet" side to compensate for the lack in the "dry" side. There would have been plenty of time for this to occur, the soil having been irrigated 18 hours before measurement of soil water potential. In year 3 it may be necessary to measure soil water status nearer to the time of irrigation to ensure that PRD "wet" sides have the same initial water potentials as the soil in the well-watered individuals.

Figure 3.2 shows the effect of soil drying treatments on *Hydrangea* stomatal conductance (gs) over time in relation to the well-watered controls, in the morning (A) and in the afternoon (B). The most pronounced effect of soil moisture on gs was in immature leaves in the afternoon. There was no difference in the extent of reduction in gs between the RDI and the PRD treatments. Figure 3.3 shows the effect of soil drying treatments on *Cotinus* gs over time, again in the morning (A) and in the afternoon (B). In this species soil drying reduced gs to the greatest extent in mature leaves in the morning, but also significantly reduced plant water loss in mature leaves in the afternoon. There was no consistent effect of soil drying on water loss from immature leaves. Again there seemed to be no difference between the extent to which RDI and PRD reduced gs in comparison to the well-watered controls.

Figure 3.4 shows the effect of soil drying on leaf relative water content (RWC). In *Hydrangea* (Figure 3.4A) both mature and immature leaf RWC was very variable over the course of the experiment, even in well-watered plants. Only on day 14 did the PRD treatment reduce mature leaf turgidity significantly in comparison to the well-watered plants, and not at all in immature leaves. The RDI treatment reduced leaf RWC on days 14 and 22 in mature leaves, and on day 22 in immature leaves. These results indicate that under PRD *Hydrangea* was able to maintain shoot water status to a greater extent than under RDI, although shoots were not always as turgid as those of well-watered controls. This conclusion was borne out by measurements of shoot water status using the Scholander pressure bomb (results not shown). Figure 3.4B shows that mature *Cotinus* leaves exhibited a much tighter control of mature leaf RWC in all 3 treatments, although both RDI and PRD significantly reduced RWC in comparison to well-watered controls, and this occurred to a greater extent under RDI than under PRD. The RWC of immature *Cotinus* leaves was more variable in all 3 treatments, and during the first half of the experiment both soil water deficit treatments reduced leaf RWC to the same extent. Turgidity was maintained more successfully during the second half of the experiment in both species, presumably because by this time both leaf and internode growth would have slowed to reduce the leaf area from which water loss can occur. It is also of note that under both PRD and RDI, shoots were actually more turgid than under well-watered conditions (results not shown).

Figure 3.1A. The effect of soil watering regime on the soil moisture potential around the roots of potted *Hydrangea* plants. RDI plants were centrally irrigated with 50% of the water given to well-watered plants, but soil moisture was measured on both sides of the pots to detect any asymmetry in this parameter. PRD plants were asymmetrically irrigated with the same volume as the RDI treatment to create a “dry side” and a “wet side” of the pot (n=6).

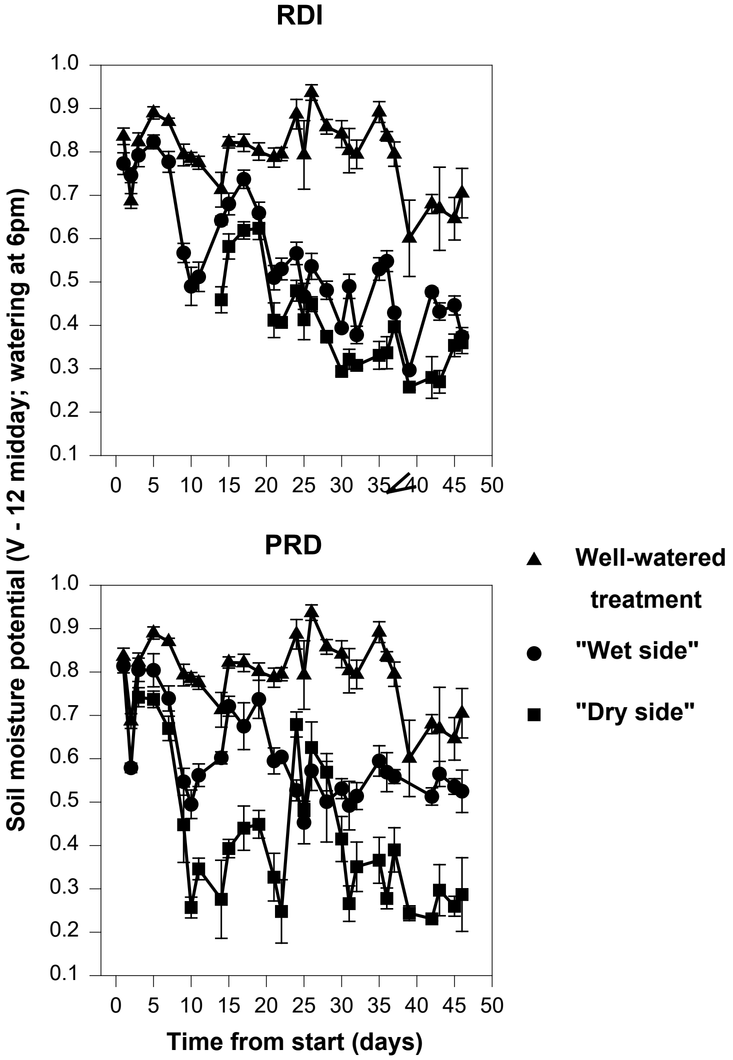


Figure 3.1B. The effect of soil watering regime on the soil moisture potential around the roots of potted *Cotinus* plants. RDI plants were centrally irrigated with 50% of the water given to well-watered plants, but soil moisture was measured on both sides of the pots to detect any asymmetry in this parameter. PRD plants were asymmetrically irrigated with the same volume as the RDI treatment to create a “dry side” and a “wet side” of the pot (n=6).

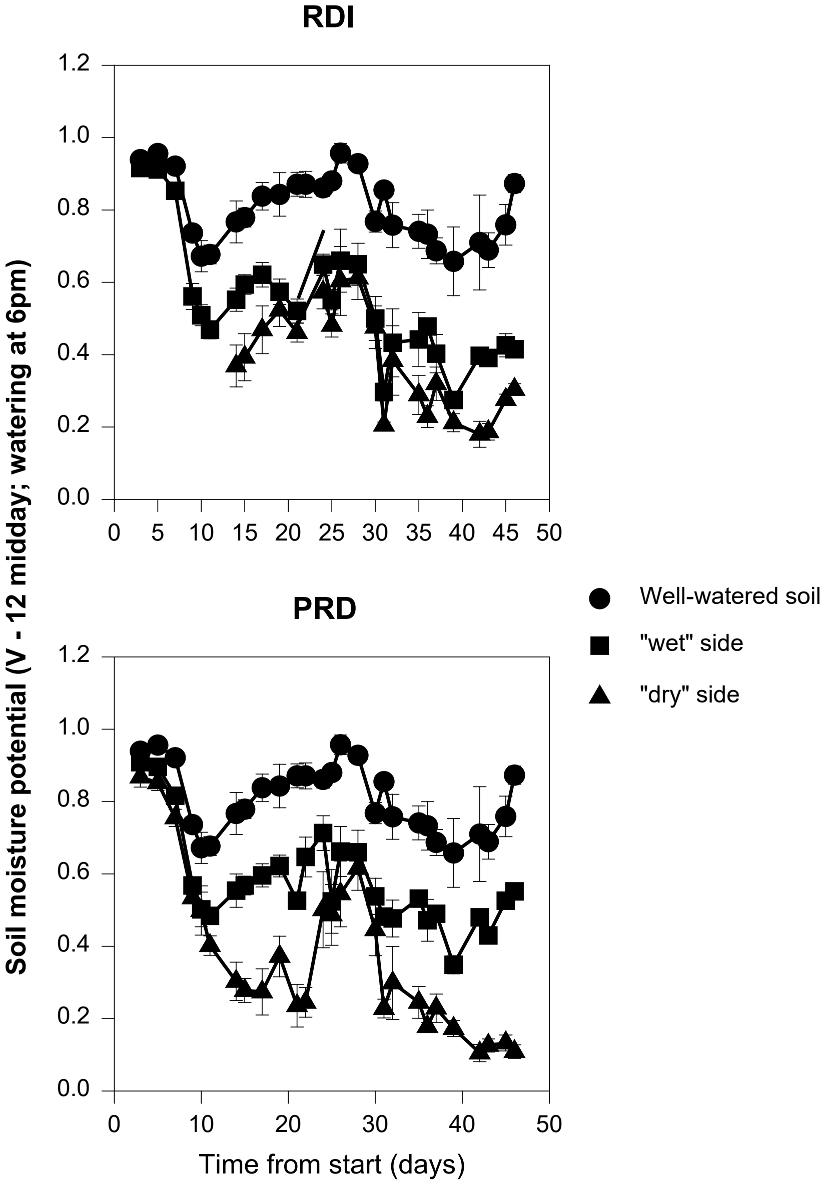


Figure 3.2A. The effect of soil watering regime on the stomatal conductance (gs) of mature and immature *Hydrangea* leaves in the morning. Stomatal conductance is expressed as a percentage of that of the well-watered treatment to account for day-to-day fluctuations in gs caused by the aerial environment (n=6).

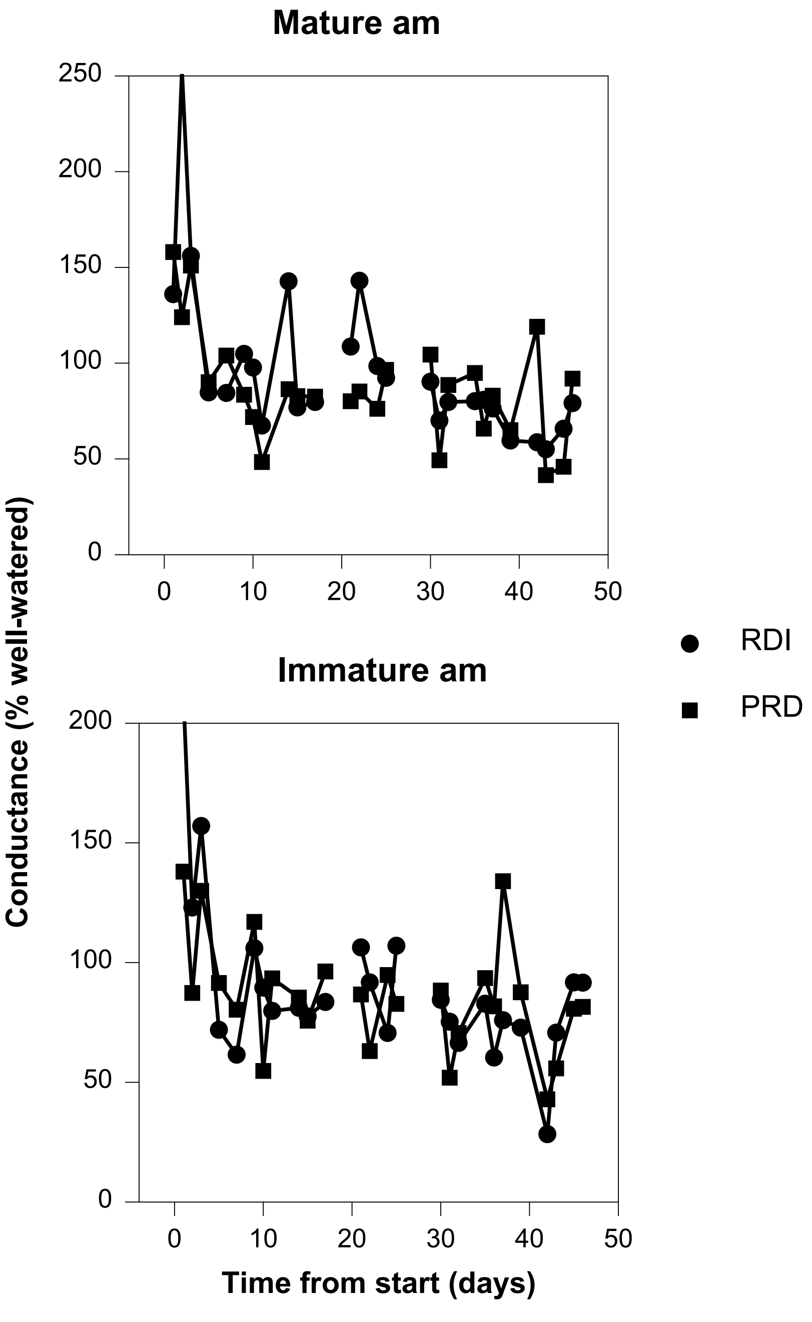


Figure 3.2B. The effect of soil watering regime on the stomatal conductance (gs) of mature and immature *Hydrangea* leaves in the afternoon. Stomatal conductance is expressed as a percentage of that of the well-watered treatment to account for day-to-day fluctuations in gs caused by the aerial environment (n=6).

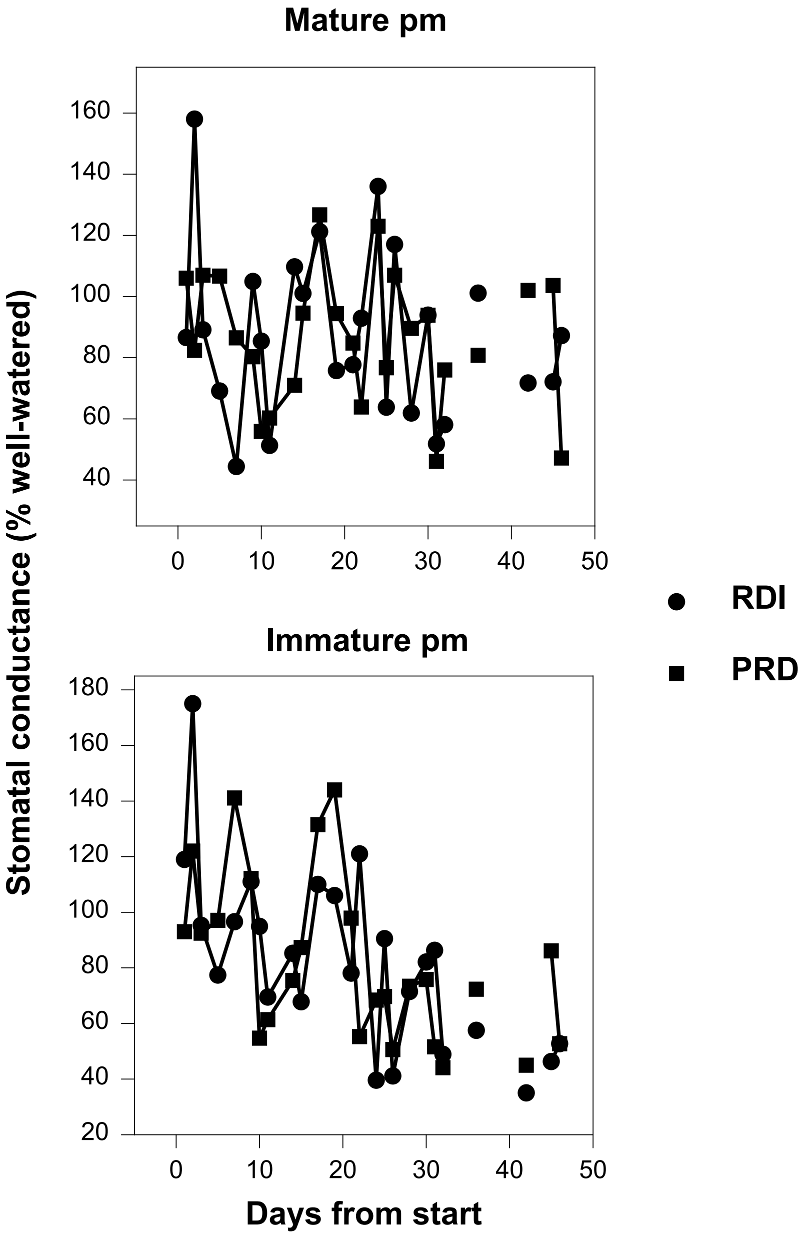


Figure 3.3A. The effect of soil watering regime on the stomatal conductance (expressed as a % of the well-watered reading) of mature and immature *Cotinus* leaves in the morning (n=6).

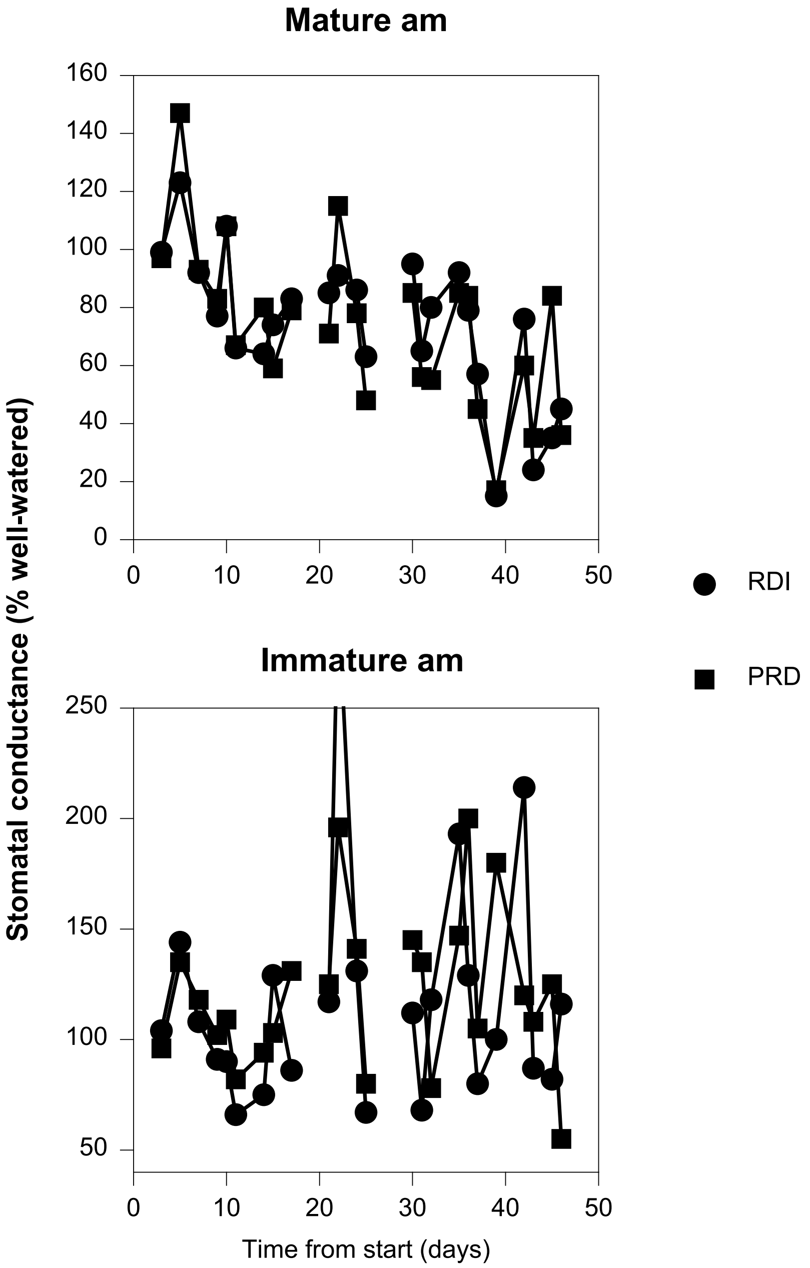


Figure 3.3B. The effect of soil watering regime on the stomatal conductance (expressed as a % of the well-watered reading) of mature and immature *Cotinus* leaves in the afternoon (n=6).

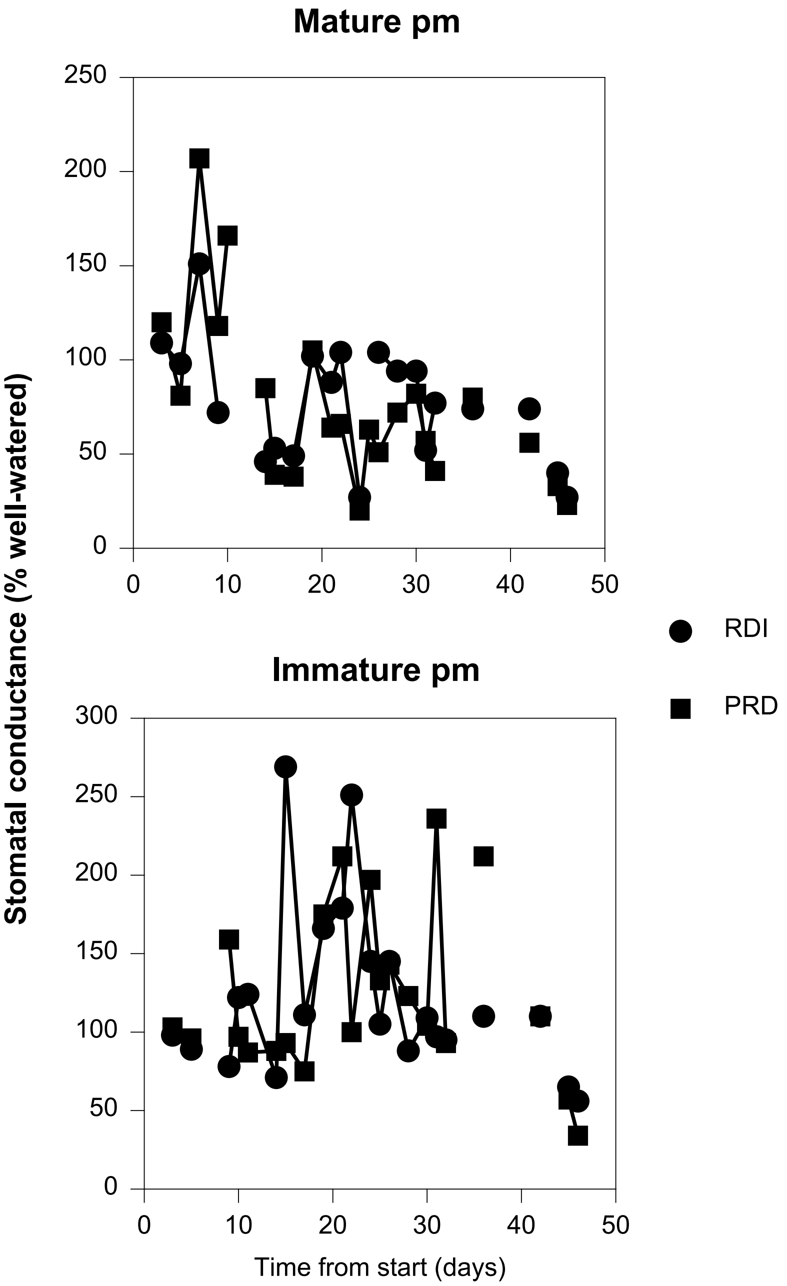


Figure 3.4A. The effect of soil watering regime on the relative water content (RWC) of mature and immature *Hydrangea* leaves. Relative water content is expressed as the experimental fresh leaf weight as a % of the fully turgid leaf weight after dry weight subtraction (n=3).

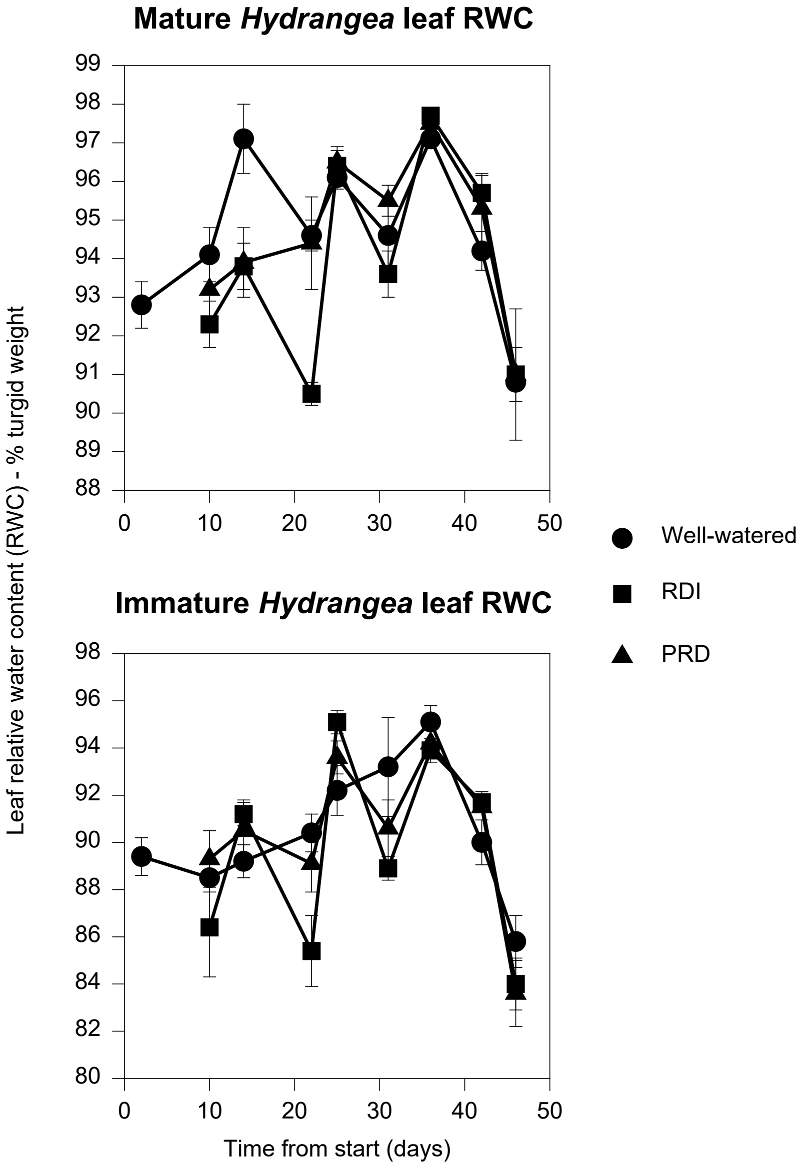


Figure 3.4B. The effect of soil watering regime on the relative water content (RWC) of mature and immature *Cotinus* leaves. Relative water content is expressed as the experimental fresh leaf weight as a % of the fully turgid leaf weight after dry weight subtraction (n=3).

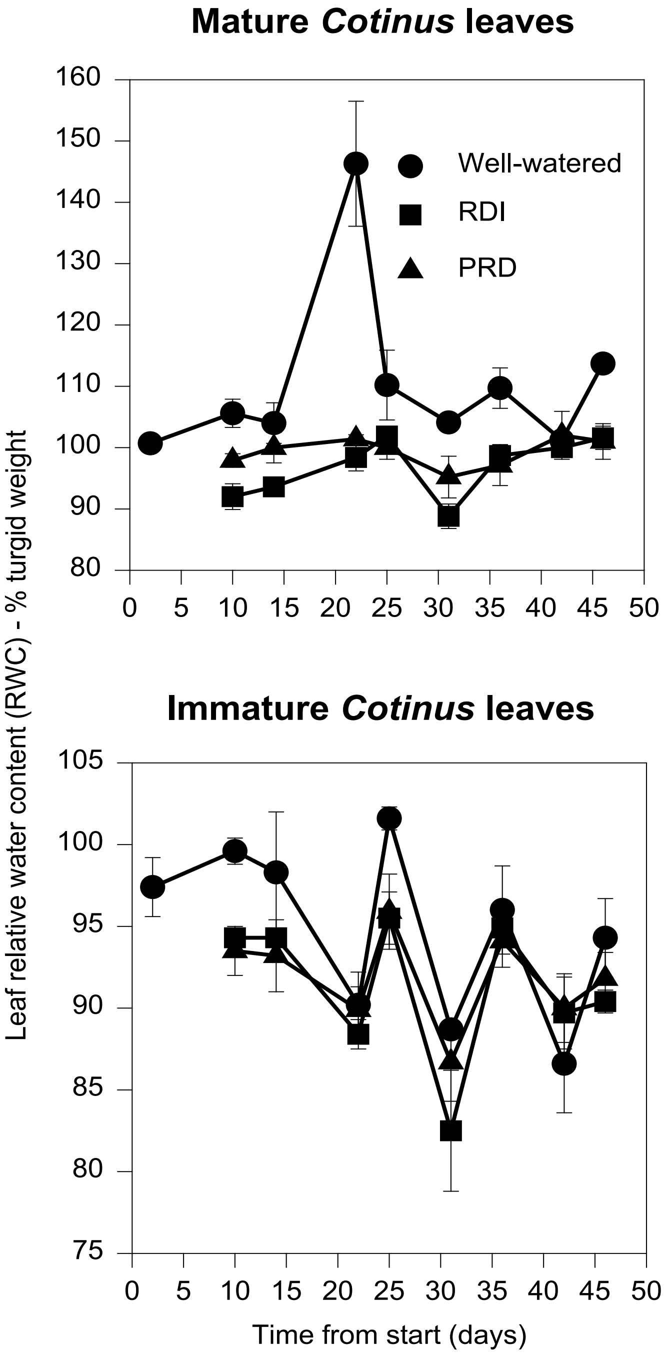


Figure 3.5 shows the effect of soil drying on leaf and internode extension growth in *Hydrangea*. Figure 3.5A shows that only RDI reduced the extension rate of newly initiated leaves (shorter than 8cm), whilst both PRD and RDI inhibited the extension rate of immature leaves between 8 and 12cm in length. However RDI but not PRD reduced the extension rate of almost mature leaves (above 12cm in length) implying that under PRD *Hydrangea* leaves do grow more slowly at the intermediate stage, but that the final size reached by the leaves is unaffected. Figure 3.5B shows that the effect of soil drying on internode extension rate is more straightforward. Both PRD and RDI slowed internode extension rate to the same extent. Thus RDI gives rise to shorter plants with smaller leaves, whereas PRD gives rise to shorter plants with leaves equivalent in size to those of the well-watered plants. Presumably after a long enough time under PRD there would also be fewer of these large leaves on the shorter plant, as a result of the slower growth rate.

Signals sent from drying roots.

ABA

The radioimmunoassay for bulk leaf and xylem sap ABA in *Hydrangea* samples collected in summer 2000 has been carried out, although results are still being collated.

pH

Changes in xylem sap pH over the course of the experiment under the 3 soil water treatment regimes can be seen in Figure 3.6. Well-watered *Hydrangea* xylem sap pH was very variable over the course of the experiment, with initial readings ranging between pH 5.8 and 7.0, and high pressure readings ranging between 6.1 and 7.3 (Figure 3.6A). Well-watered *Cotinus* xylem sap varied over a much narrower pH range, ie. between 5.7 and 6.2 (initial pH) and between 5.9 and 6.4 (high pressure pH). In neither species was there any significant effect of soil drying treatment on xylem sap pH, except for an increase on day 30 in *Cotinus*. This contrasts with the results from 1999 in *Forsythia*. In this species soil drying acidified xylem sap pH under both a sporadic watering regime, and under PRD. Soil drying was of the same order of magnitude in both 1999 and 2000. Therefore xylem sap pH would appear not to act as a signal sent from drying roots to shoots in *Hydrangea* or *Cotinus*.

Effects of the aerial environment on stomatal water loss, and possible chemical signals within leaves.

Stomatal conductance in both mature and immature *Hydrangea* leaves was influenced to a much greater extent by the aerial environment than by soil drying in the morning, but not in the afternoon (Figures 3.7A and 3.7B). Figure 3.7A shows that high PPFD (photosynthetic photon flux density – a measure of light intensity) correlated with stomatal closure, as did the associated aerial conditions of high leaf surface temperature and low humidity (results not shown). These results are similar to the effects of PPFD seen on *Forsythia* leaves in 1999, although in this species the correlation was only strong in the afternoon rather than in the morning, and leaf surface temperature was not strongly correlated with gs at any time of day. High PPFD was also highly correlated with stomatal closure in leaves of *Hydrangea* plants growing under both soil drying regimes (results not shown).

Figure 3.5A. The effect of soil watering regime on the cumulative increase in *Hydrangea* leaf length over time, measuring total extension from day 1. Leaves and internodes in each size category were measured every other day (n=6).

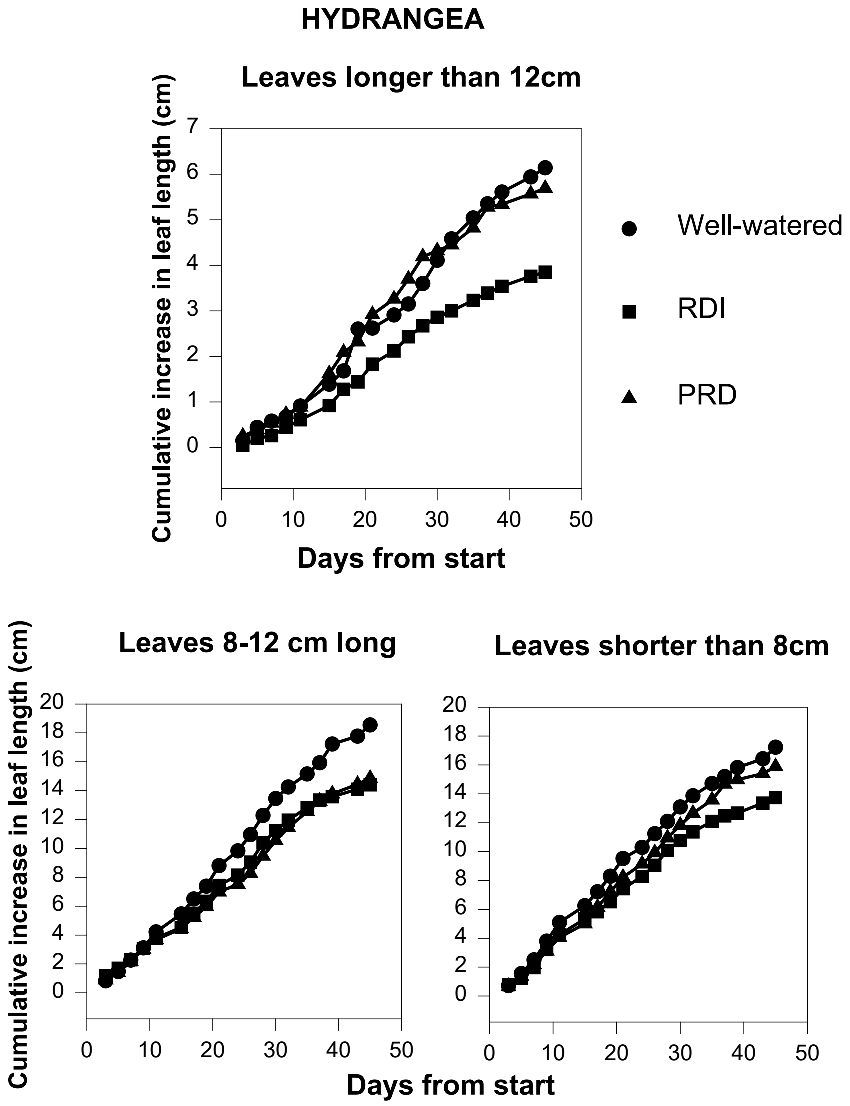


Figure 3.5B. The effect of soil watering regime on the cumulative increase in *Hydrangea* internode length over time, measuring total extension from day 1. Leaves and internodes in each size category were measured every other day (n=6).

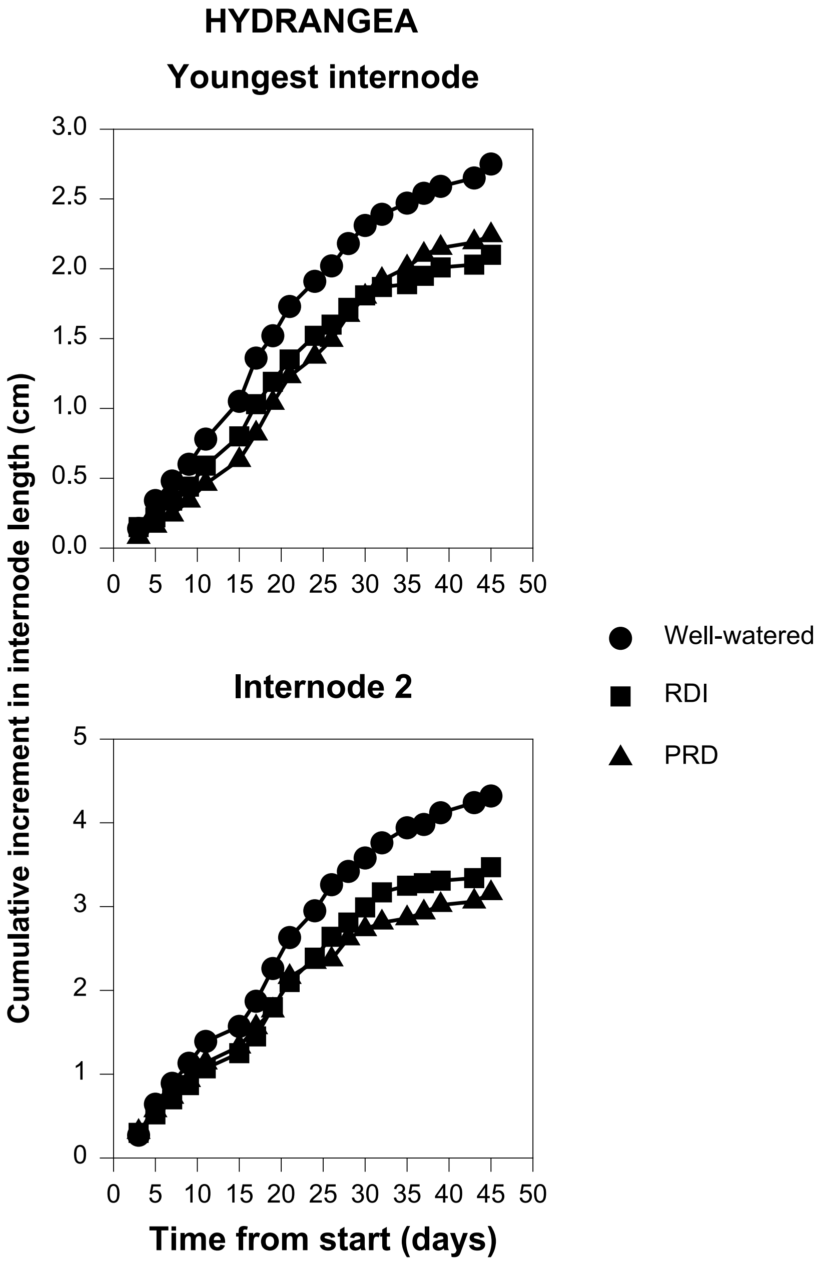


Figure 3.6A. The effect of soil watering regime on the pH of xylem sap expressed from detached *Hydrangea* shoots at 2 bars over balancing pressure (initial pH); 6-8 bars over balancing pressure (high pressure pH) and in both aliquots of sap pooled (mean pH) (n=3).

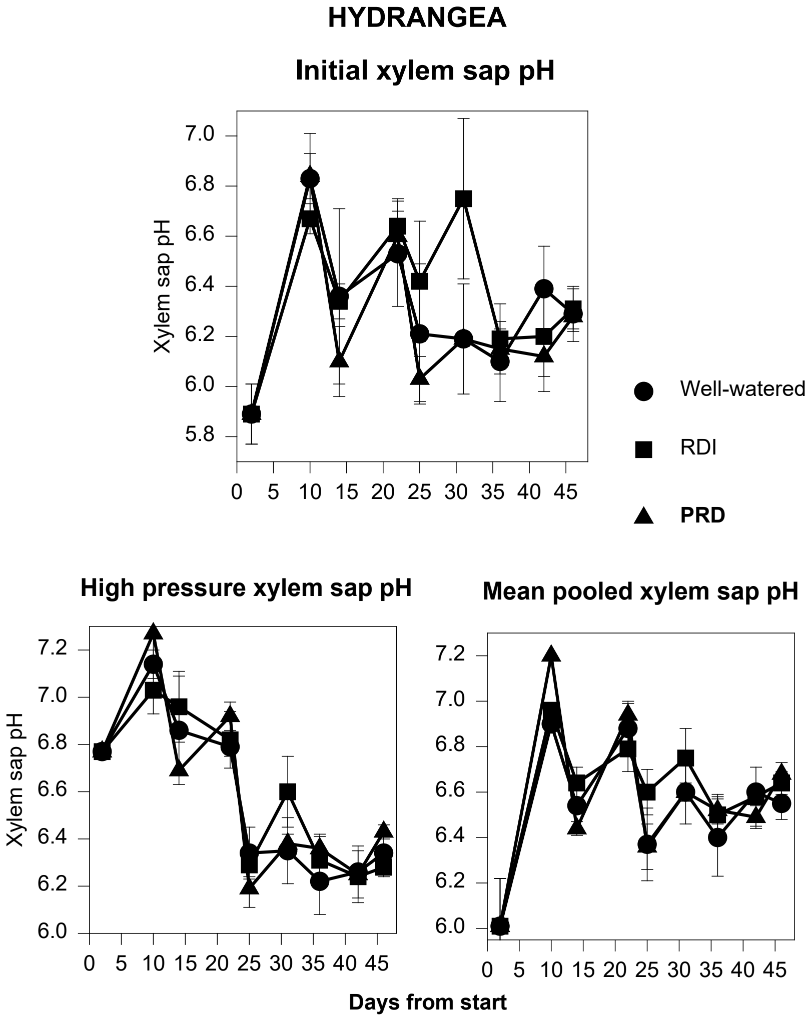


Figure 3.6B. The effect of soil watering regime on the pH of xylem sap expressed from detached *Cotinus* shoots at 2 bars over balancing pressure (initial pH); 6-8 bars over balancing pressure (high pressure pH) and in both aliquots of sap pooled (mean pH) (n=3).

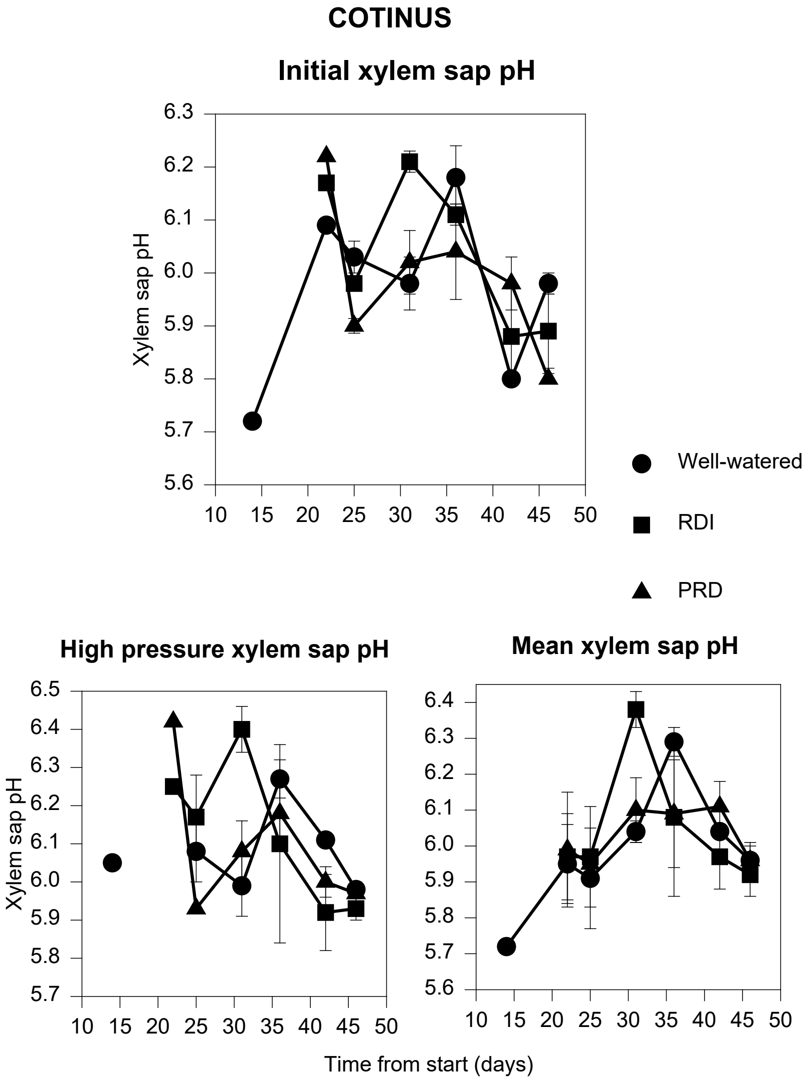


Figure 3.7A. Photosynthetic photon flux density (PPFD) plotted against stomatal conductance (n=6) in mature and immature leaves of well-watered *Hydrangea* plants in the morning.

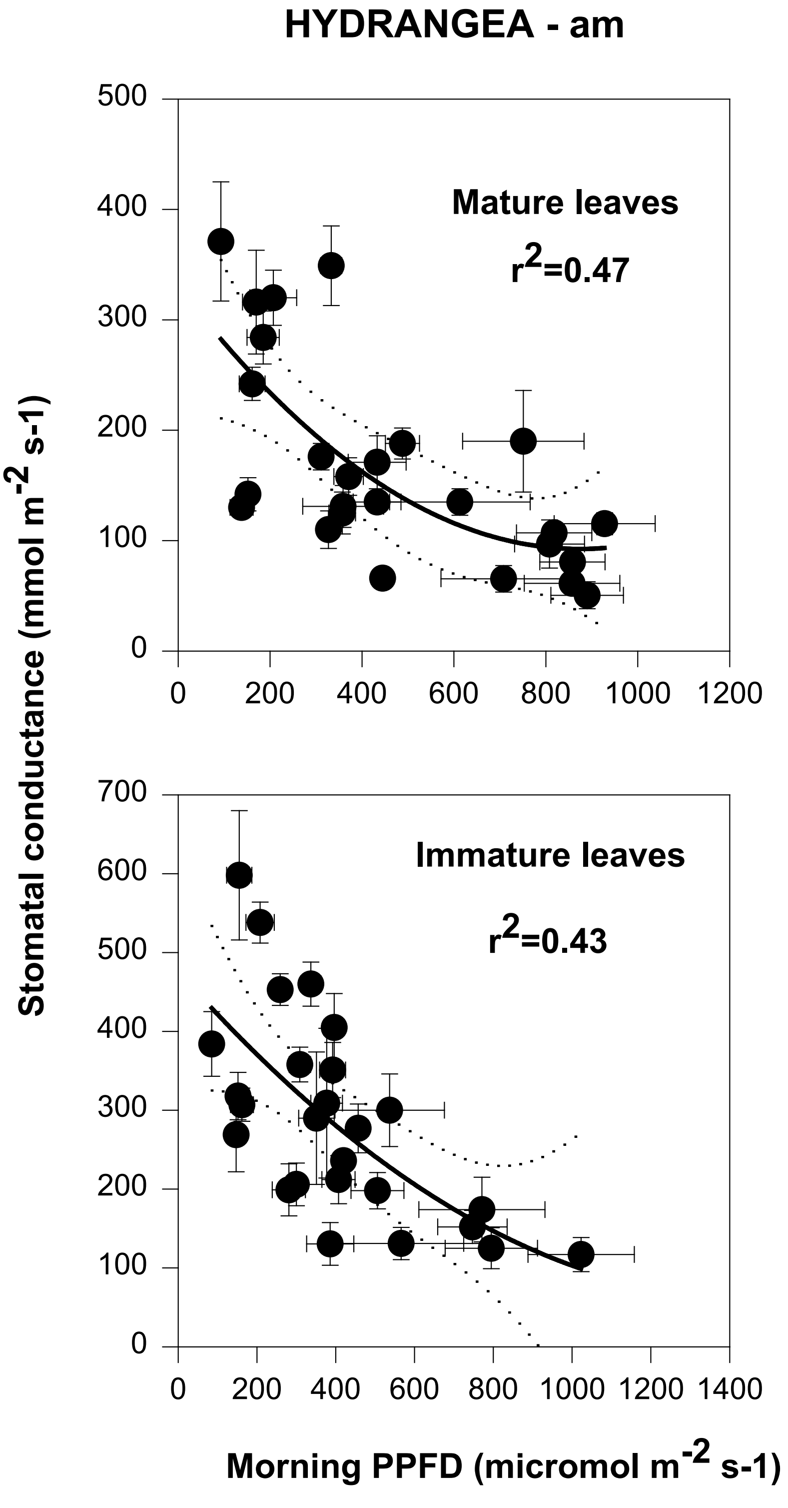
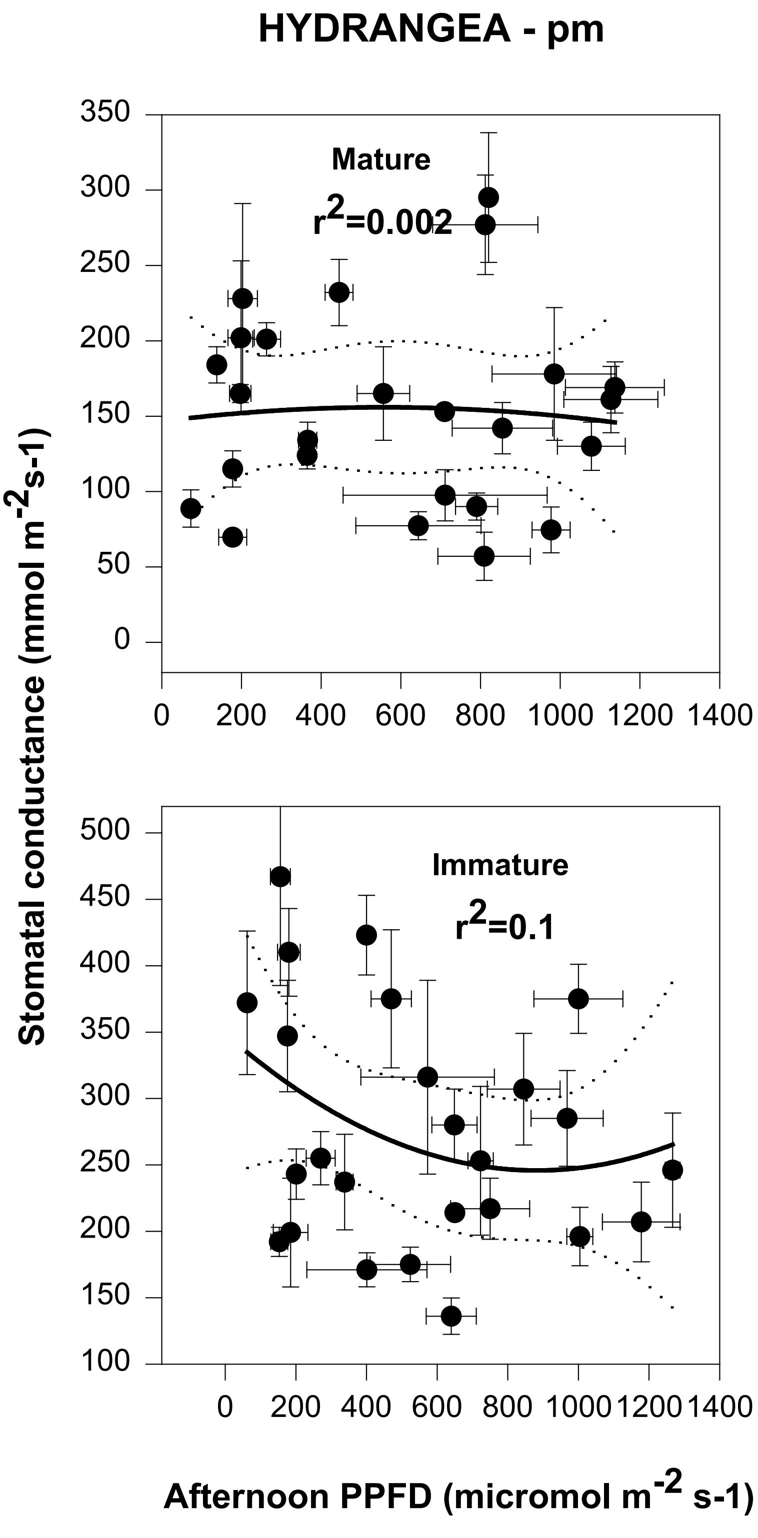


Figure 3.7B. Photosynthetic photon flux density (PPFD) plotted against stomatal conductance (n=6) in mature and immature leaves of well-watered *Hydrangea* plants in the afternoon.



Stomatal conductance in *Cotinus* leaves was influenced by the aerial environment in a very different manner to gs in *Hydrangea*. Figures 3.7C and 3.7D show the effect of relative air humidity (RH) on conductance in mature and immature *Cotinus* leaves in the morning and in the afternoon, in plants under RDI. More as would be expected, high light, high leaf surface temperature and low humidity were associated with open stomata in *Cotinus* leaves. This effect was more marked in the afternoon than in the morning, and more marked in immature than in mature leaves. The correlation between high light/high leaf surface temperature/low humidity and stomatal opening was greater under RDI than under well-watered or PRD conditions.

Data from experiments with *Forsythia* in 1999 indicated that xylem/apoplastic sap pH might be the signal responding to changes in the aerial environment that induces a change in stomatal aperture. Figure 3.8A shows that high xylem/apoplastic sap pH was also highly correlated with high PPFD in *Hydrangea*, but Figure 3.8B shows that there was only a poor relationship between the aerial environment and high pressure pH in *Cotinus*.

CONCLUSIONS

Although the same amount of water was applied to *Hydrangea* plants under the two water deficit regimes – RDI and PRD; PRD plants had greater shoot turgidity than RDI plants. This difference did not lie in differential effects of the soil drying treatments on water loss through stomata, as both RDI and PRD reduced stomatal conductance to the same extent over the course of the experiment. It would also appear that the improved maintenance of turgidity under PRD could not be explained by a greater reduction in leaf surface area. It may be the case that greater ABA production in the drying roots of the PRD plants increased hydraulic conductance and enabled these plants to take up more of the water available to them. An important benefit to growers of the improved turgidity under PRD, is the finding that *Hydrangea* leaves attain the same final leaf size as well-watered plants under PRD, but that these remain smaller under RDI, presumably as a result of hydraulic constrictions as well as a chemical influence. If smaller leaves can be tolerated however, then both PRD and RDI would be useful techniques under which to grow *Hydrangea* on a large scale, with a view to saving water and improving bushiness – both PRD and RDI plants have shorter internodes (although as yet we have no evidence as to any changes in shoot branching). This same conclusion could be applied to *Forsythia* in 1999.

As yet there is no evidence that PRD is more beneficial to the water use or appearance of *Cotinus* plants than RDI. Both water deficit regimes reduced stomatal conductance to the same extent, and shoot water status was identical in both – indeed water deficit appeared to increase shoot turgidity. This may have been a result of the greatly reduced height and leaf size of this species under water deficit (results not shown), thus vastly reducing the area over which water could potentially be lost. Both water deficit regimes would successfully reduce the "bolting" behaviour of this species, and may be of benefit to growers in prolonging the season for *Cotinus* sales in this respect.

It would appear that xylem sap pH is not a signal in either *Hydrangea* or *Cotinus* plants growing in drying soil, that contributes to the reduced stomatal conductance

Figure 3.7C. Air relative humidity (RH) plotted against stomatal conductance (n=6) in mature and immature leaves of RDI *Cotinus* plants in the morning.

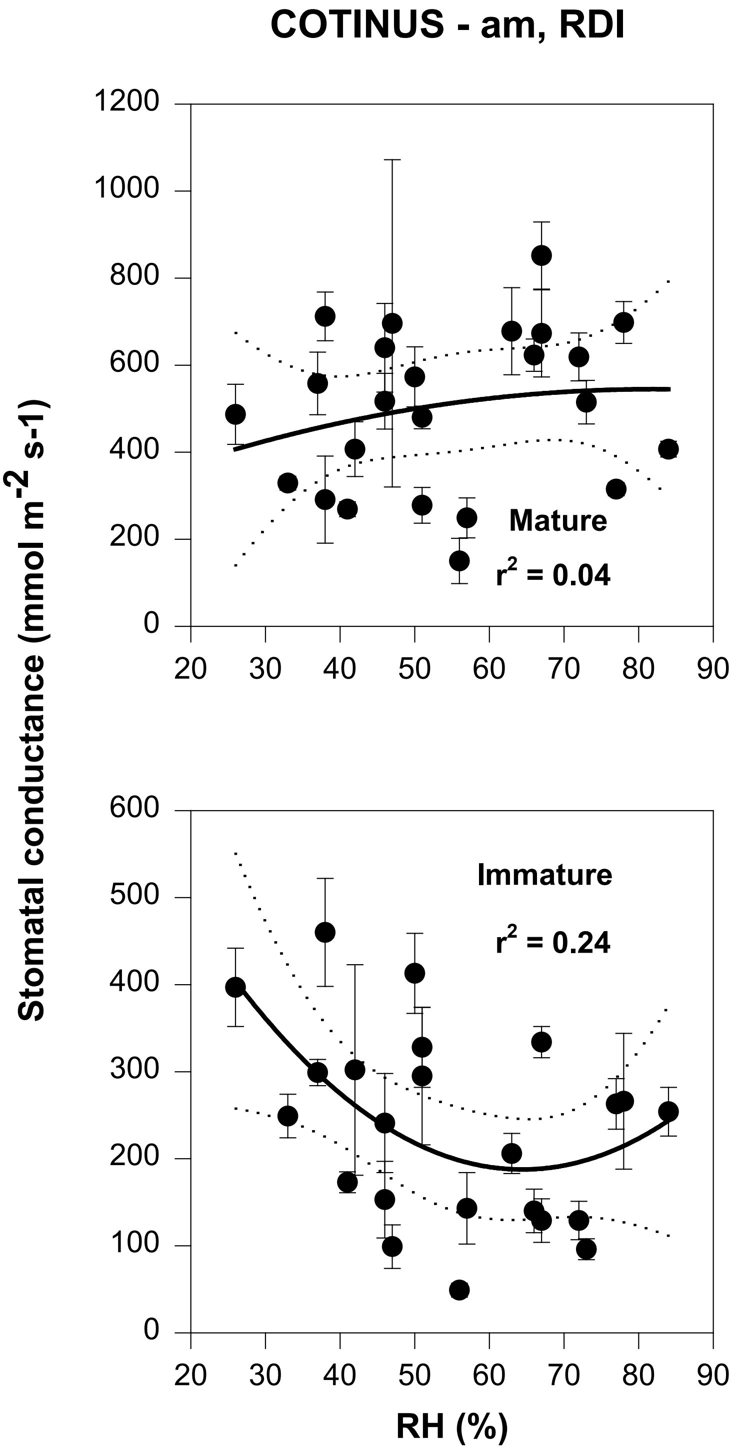


Figure 3.7D. Air relative humidity (RH) plotted against stomatal conductance (n=6) in mature and immature leaves of RDI *Cotinus* plants in the afternoon.

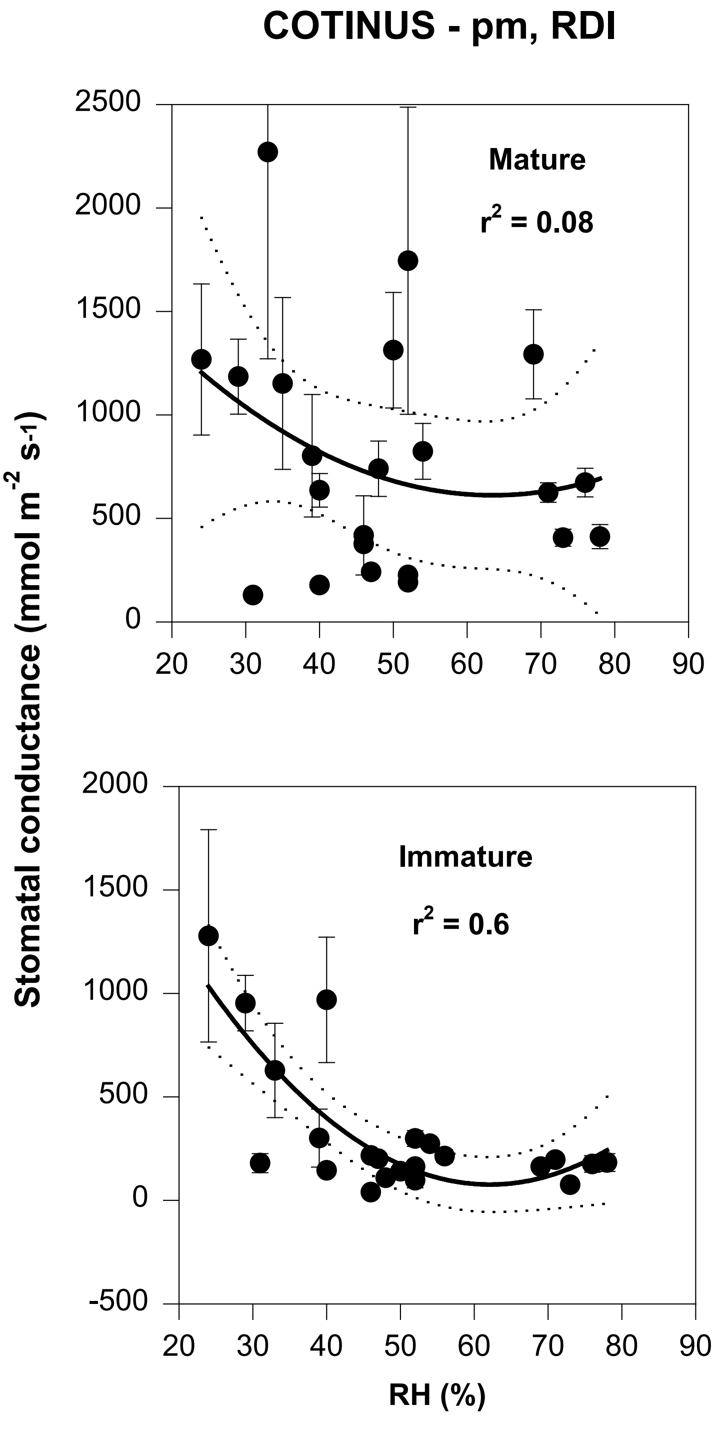


Figure 3.8A. Afternoon PPFD plotted against high pressure xylem sap pH expressed from well-watered and water deficit irrigated (RDI and PRD) shoots of *Hydrangea* (n=3).

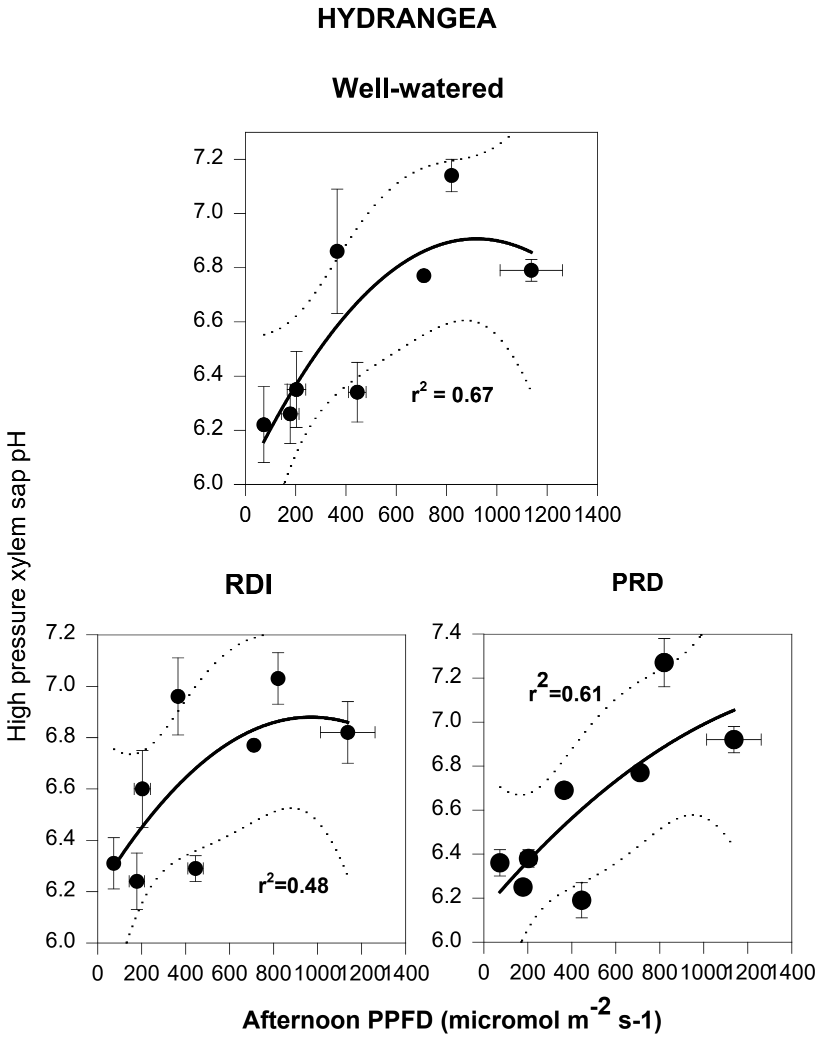
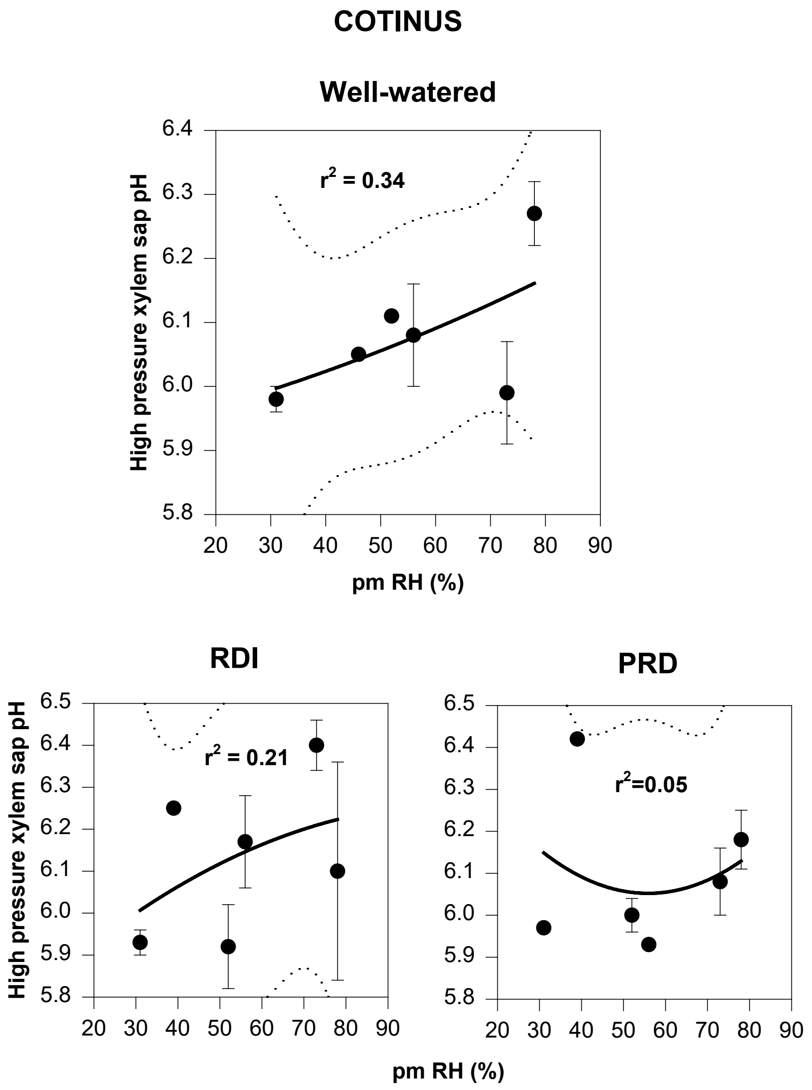


Figure 3.8B. Afternoon air RH plotted against high pressure xylem sap pH expressed from well-watered and water deficit irrigated (RDI and PRD) shoots of *Cotinus* (n=3).



and internode and leaf growth rates seen. ABA analyses are now complete, and the contribution of xylem ABA to root-to-shoot signalling will soon be revealed.

We have also obtained evidence that *Hydrangea*, like *Forsythia* in 1999, is very responsive to the xylem/apoplastic sap pH environment with respect to leaf water loss through stomata, although these changes are in response to aerial conditions. Nevertheless if we can discover more about this signalling system, and begin to devise ways in which to manipulate sap pH, we could potentially have a very powerful tool improve water use efficiency. In the year 2001 we are hoping to investigate ways of changing sap pH, initially by manipulating mineral nutrient availability in the soil.

SELECTION OF SENSORS FOR CONTROLLING THE IRRIGATION OF HARDY NURSERY STOCK

OBJECTIVE 4

CENTRE FOR ECOLOGY AND HYDROLOGY and HRI-EFFORD

INTRODUCTION

Between May and October 2000, various sensors were tested to evaluate how well they might perform as the basis of a system to control irrigation. The evaluation was carried out within the framework of an irrigation trial at HRI Efford, in which three species (*Hydrangea*, *Cotinus* and *Forsythia*) were irrigated under two irrigation regimes. These were, (a) where the plants were given their water requirement (determined by weighing to assess water use) and (b) an "overwatered" regime where the plants were given 1.5 to 2 times the amount provided under (a). The 6 treatments were replicated twice.

Weighing

Weighing is the most accurate method of determining the water use of container grown plants on a daily basis, and provides baseline water use data against which the other methods of estimating water use can be compared. However, it is not practical to use it on a day-to-day basis in a nursery. To apply the method, the growing medium in the containers is thoroughly wetted and then left until drainage has ceased. The container (and plant) is then weighed to determine "container capacity" (CC), beyond which any further losses of water only occur by evaporation. If the container is weighed daily, before irrigation, the difference in weight below CC is the amount of water that needs to be provided by irrigation to bring the container back to CC.

If, for example, the weight was 142 gm below CC, then 142 cm^3 of water must be provided to return the container to CC. In this study, the containers were 19 cm in diameter at the top, giving a x-sectional area of 284 cm^2. 142 cm^3 is equivalent to a depth of 142/284 cm, or 5 mm over the area of the container. This depth of water must be provided over the bed area by the irrigation system. CC must be re-evaluation periodically during the growing season to adjust for the growth of the plants and the change in water retention properties of the growing medium as it settles.

Sensors evaluated

The sensors evaluated fell into two categories:

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

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

2. Those which 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)

The Delta-T ThetaProbe

The ThetaProbe sensor has a cylindrical plastic body, 4 cm in diameter and 14 cm long, with 4 parallel 2mm diameter spikes each 6 cm long projecting from one end. 3 of the spikes are at the corners of an equilateral triangle with the fourth spike in the centre. A cable emerges from the other end of the sensor; this can be connected to a handheld reader unit, or to a data logger. Measurements are made by pushing the sensing spikes into the soil, or growing medium, to their full 6 cm 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, eg 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).

The sensor can only indicate the water content in the upper 6 cm of the growing medium. If there are marked differences in the water content between the top and the bottom of the container, this will not be detected. This is of greater concern in large containers than small ones. However, it could be buried deeper for long term installation.

The volumetric water content is the volume of water per unit volume of soil, and can be expressed as a percentage. If a 3 litre container holds 2.7 litres of growing medium and the water content is 0.5 (50%), then the medium contains 1.35 l (or 1.35 kg) of water. NB not all of this water will be available to the plants. If the water content is measured at CC, any subsequent measurements will show how much the water content is above, or below CC. If the water content is 0.05 (5%) below CC, then the amount of water to be provided by irrigation to bring the container back to CC is 2.7 x 5%, or 0.135 l. This assumes that the ThetaProbe measurement represents the whole container.

4 ThetaProbes were installed in each of the 6 treatments and measured hourly using a Delta-T logger. Each plot consisted of 36 pots in a 6 x 6 array. The outer plants were “guard” rows, with the central 4 x 4 array of pots being used for measurements. The ThetaProbes were installed in pots 4, 7 and 10 of the central group and in one guard row pot (8) on the south side of the plot.

The Skye mini tensiometer

This is a 13 mm diameter transparent rigid plastic tube with a 25 mm long cylindrical unglazed porous ceramic section at the lower end. The ceramic has a hemispherical tip, and the transparent tube and ceramic section are filled with water. A pressure sensor is fitted into the top of the tube. The unit is installed in a hole made in the growing medium, so that the ceramic is in intimate contact with the medium. As there is hydraulic continuity through the ceramic tip between the water in the tensiometer and the water in the growing medium, the pressure inside the instrument responds to pressure changes in the medium. This is measured by the pressure sensor.

When the growing medium is completely saturated (all of the pores within it are water-filled), the pressure is zero, or slightly positive, if the water level is above the ceramic tip. The pressure readings become progressively more negative as the medium dries out. In peat based media most plants will wilt when the pressure reaches about –750 Hpa, which is equivalent to a water content of about 15%. The pressure is generally referred to as a potential. The pressure sensor is connected to a data logger, which converts the sensor output into pressure and records it.

The mini tensiometer is available in a range of lengths. The smallest available were used. These had a total length of about 14.5 cm and could be installed at depths ranging from 5 cm to 12 cm. Installation at shallower depths is not practicable as the instrument is not securely located and will tend to fall over and reduce contact with the growing medium. Good contact ensures that hydraulic continuity with the growing medium is maintained, allowing the instrument to follow reliably the changes in water potential.

4 mini tensiometers were installed in the *Cotinus* “E” treatment and 4 in the *Forsythia* “E” treatment. The tip of each tensiometer was at a depth of about 10cm. In the *Forsythia* plot, the tensiometers were in the same pots as the ThetaProbes. Unfortunately the cable lengths were not sufficient to reach from the logger to the *Cotinus* plot 7 in which the ThetaProbes were installed. The tensiometers were installed in identical positions in the adjacent plot 8 (same treatment). Data were logged hourly.

Automatic Weather Station (AWS)

The station had the following sensors installed:

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

The AWS was installed in the centre of the experimental bed area 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 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 (ie not water-stressed)

Evaposensor

This is a very simple device, which consists of two flat horizontal leaf-like blades, parallel to each other and painted black. Each contains a sensitive temperature sensor. The blades are 4 cm long and 1 cm wide and are mounted 1.3 cm apart above a water reservoir. One blade is covered by a cotton sleeve, which dips into the water reservoir and is kept wet by capillary action. A datalogger is used to measure the temperature of each blade at 10 minute intervals and record the data as hourly averages. Previous studies have shown that the temperature difference between the “wet” and the “dry” blades provides a good indication of evaporative demand. Two Evaposensors were installed, one just above the plant canopy in plot 8, and the other at a height of about 1m, just above the height of the irrigation spray nozzles. In late July, the canopy began to shade the Evaposensor in plot 8 and it was moved to the cross-arm of the AWS at a height of about 2m.

RESULTS

Weight Data

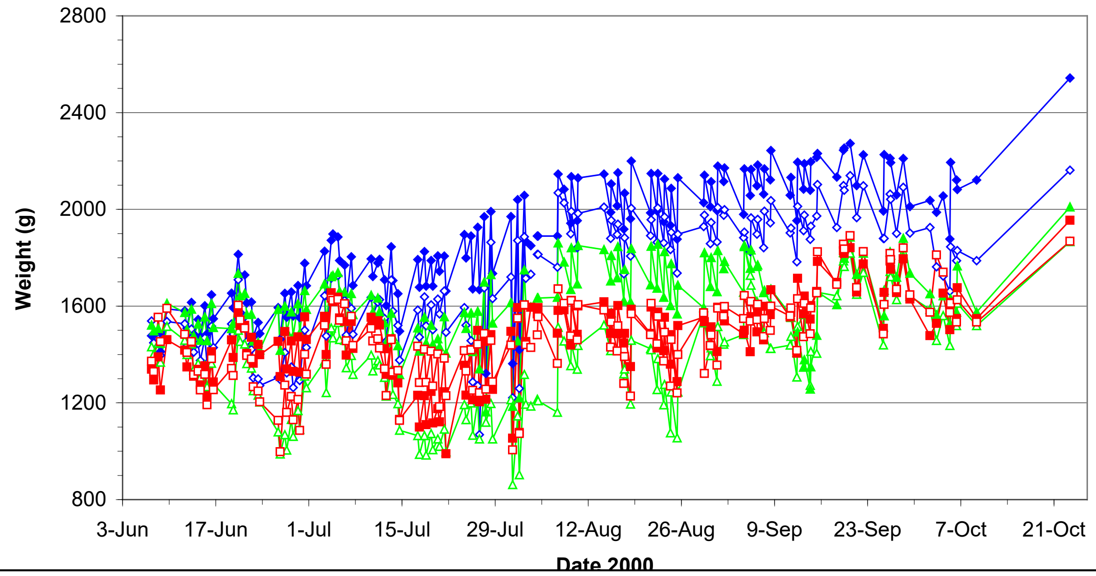


Figure 4.1. Mean weight of the 4 weighed pots in each of the 6 treatments with instrumented pots.

The mean pot weight data for each of the 6 treatments are shown in Figure 4.1. The pots were weighed twice a day (on weekdays) and both weights are shown on the graph. Up to 3 August, the irrigation took place before 0600h and the pots were weighed at about 0800h and 1500h. After August 3, irrigation was done after about 0830h. The pots were weighed just before irrigation, at about 0800h, and soon after irrigation, at about 1030h. The latter regime of irrigation and weighing allowed the weight change as a result of the irrigation to be compared with the amount applied, to look at how much water was actually getting into the pots. The weight change from 10:30h to 0800h the next day provided a better estimate of the daily water use than the previous weighing. The daily fluctuations of water content can be seen clearly.

At the start of the experiment the pot weights were between 1300 and 1500g. In general, there was a steady increase in weight through the season, particularly for the H treatments and notably for *Hydrangea*, which was consistently the heaviest. At the end of the season the *Hydrangea* H treatment weights had reached around 2100g compared to around 1700g for the other treatments. In late October, the wet weights of the above “ground” parts of the plants in the instrumented pots were measured. The *Hydrangea* were the heaviest plants (390g and 243 g for the H & E treatments respectively, compared to 87g – 116g for the other 4 treatments), and this largely explains the greater overall pot weights. It is of note that, even when the plant weights are subtracted from the overall pot weights, the *Hydrangea*s are still the heaviest, indicating that they may also produce the most root biomass. It was not readily possible to separate the roots from the compost to determine the weight increase caused by their growth.

The final weight shown, in late October, was after the pots had been brought up to container capacity as a final check at the end of the experiment. In all cases, the CC weight was higher than during the study period. The overall increase in weight is the result of two main factors, the further wetting of the compost, and the growth of the plant, above and below "ground". Much of the weight gain in the early season was caused by the compost continuing to wet up after planting. This was shown by comparison with the ThetaProbe data (see later). There is also some evidence that the water retention properties of the compost change with time.

During April and May, some *Hydrangea* plants from the previous season's trial at East Malling were monitored with the ThetaProbe and container capacity was determined. These plants were in 2 l pots and CC was around 1650g. Scaling up to a 3 l pot indicated a CC of about 2350g. This is far higher than the water content range in this experiment at the start of the season (1300-1500g). Even when corrections are made for plant growth, there is a strong indication that the compost may not have been fully wetted to the bottom of the pot and only gradually wetted through the season. It may also be that the ability of the compost to retain water changes with time, and with the modification of its structure caused by the growth of roots. The soaking of the peat by immersion before draining to determine CC (as done in April and May) may have led to greater wetting of the peat fibres than high intensity (100mm h^{-1}) irrigation used in the Efford trial. The latter may lead to preferred pathways to drainage through the mass of compost, so that the wetting was less thorough.

ThetaProbes

The "permanently" installed ThetaProbes produced a continuous hourly record from installation on 24 May through to October. The only exception was the loss of 18 days of data from one of the loggers (8 ThetaProbes in 2 treatments) caused by a human error, rather than an equipment malfunction. The experiment itself, with the formal monitoring of weights and the scheduling of irrigation, began on 8 June.

Hourly data from the 4 ThetaProbes in each of the *Cotinus* E and *Hydrangea* H treatments are shown in Figures 4.2 and 4.3 respectively, with the daily irrigation (from the water meters) and the hourly rainfall, from the AWS. The data showed that the ThetaProbe is highly sensitive and able to show in great detail the variations in water content of the compost. The wetting up during irrigation, the slow drying in the evening and early morning and the rapid drying during the middle of the day can be clearly seen. The very low rate of change during the night could also be seen.

It was also possible to observe that when the compost was very wet, and was given a large irrigation, as in the H treatments, the moisture content changes were often small. This was because the water content of the compost was taken above container capacity by the irrigation, and the excess water drained into the lower layers of compost, and/or out of the pot.

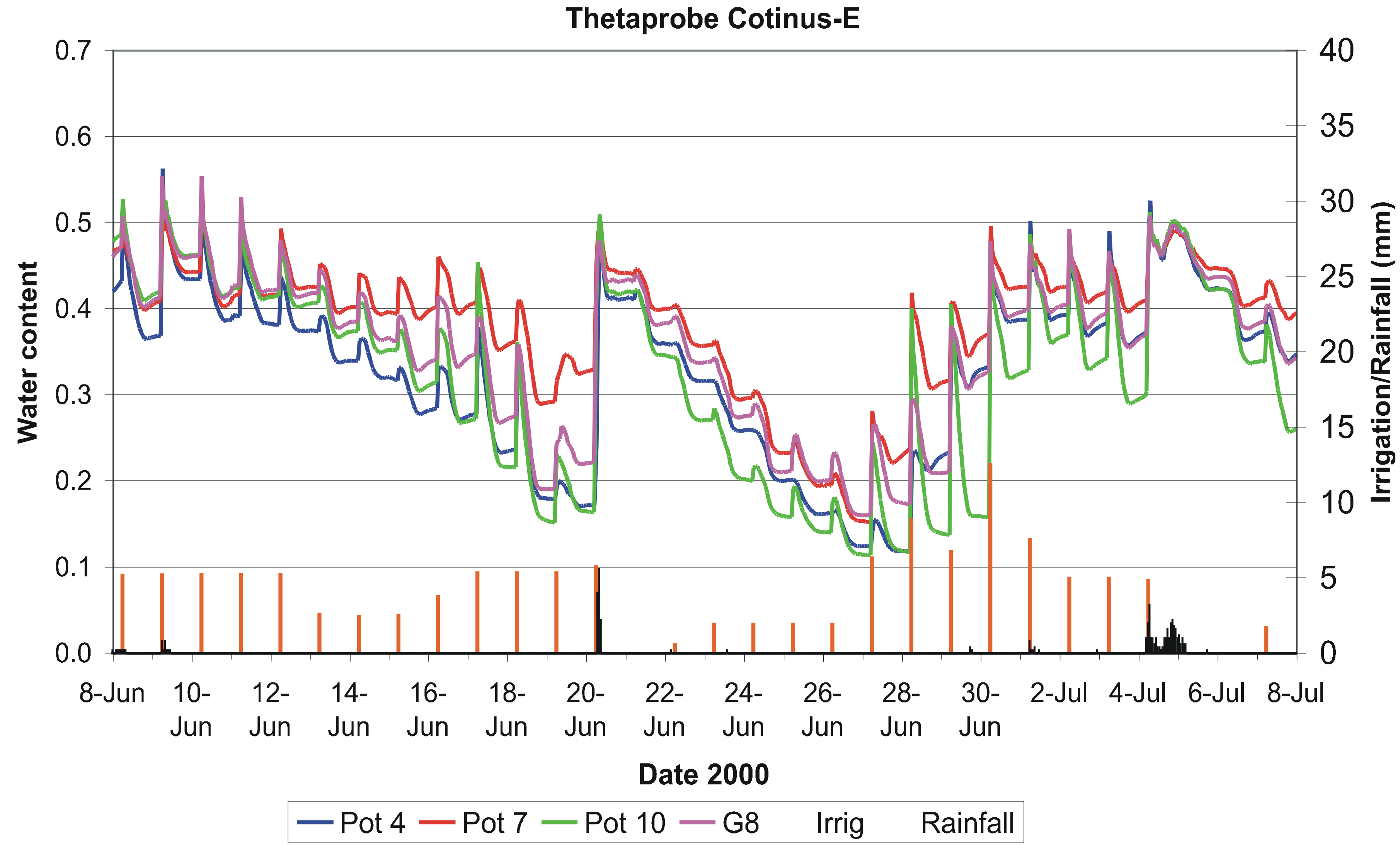


Figure 4.2. **Hourly water content data from the 4 ThetaProbes in the *Cotinus* E treatment, with daily irrigation and hourly rainfall**

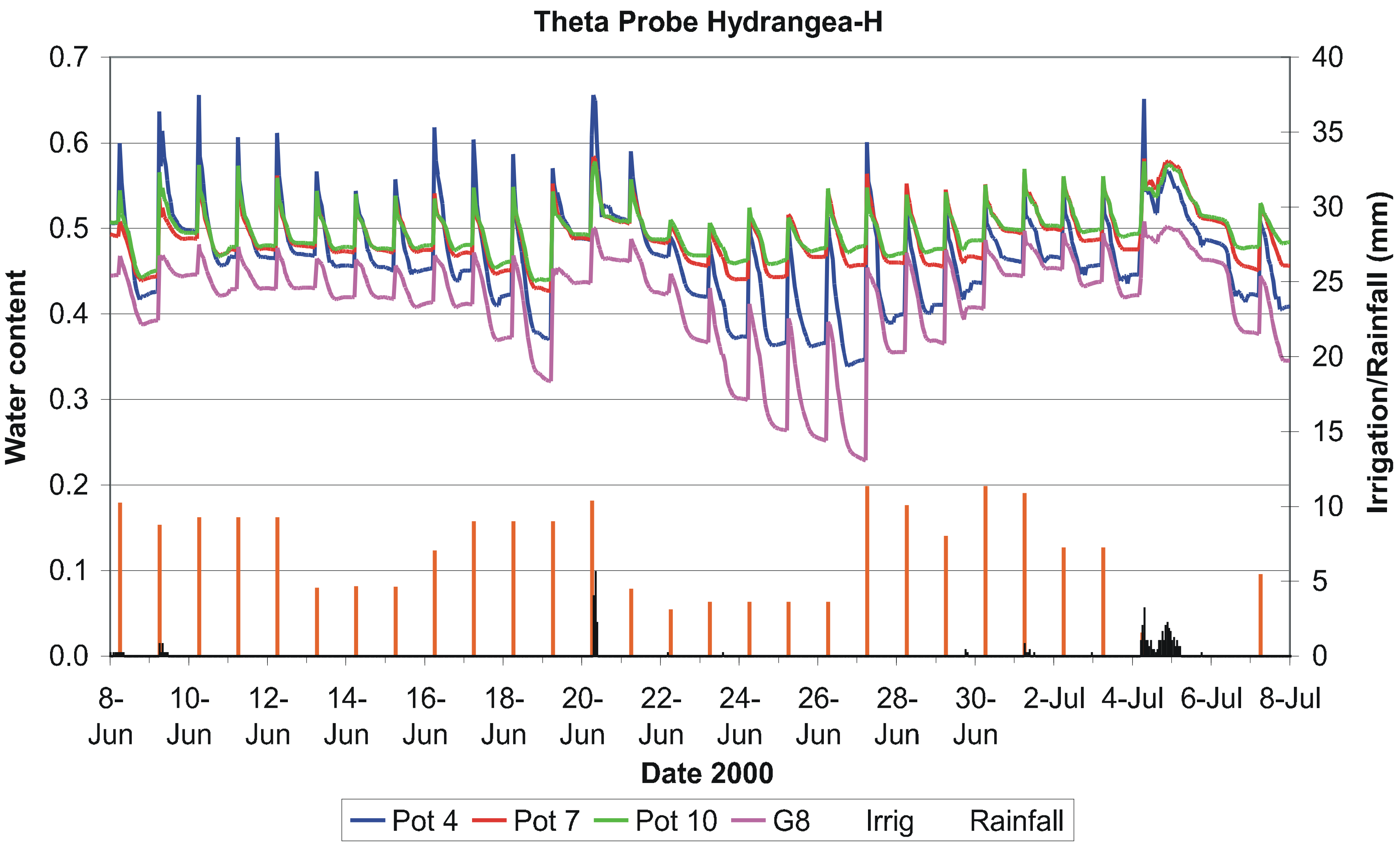


Figure 4.3. Hourly water content data from the 4 ThetaProbes in the *Hydrangea* H treatment, with daily irrigation and hourly

After irrigation, the water content could be seen to fall very rapidly, and then more slowly as the drainage ceased and the container capacity water content was reached. This water content could be identified readily for each pot, particularly in the H treatments. CC (expressed as a water content) was usually between 47% and 50%, compared to about 70% in the previous season's pots. A large rainfall event on 4/5 July (28.4mm) brought all of the water contents measured by the ThetaProbes (NB. of the top 6 cm of the compost) back to CC.

During late June, there was a steady decrease in the water content of the E treatments, indicating that the irrigation amounts were insufficient. The correct amount of irrigation should bring the water contents back to CC. The strong drying caused by hot days can be seen on 18 June, and 27 – 29 June. Overall, the ThetaProbes provided excellent information on the moisture content of the top 6 cm of the compost in the container in which they are installed.

Comparison of ThetaProbe and weight data

Figures 4.4 and 4.5 show the mean pot weights in the *Cotinus* H and E treatments, compared with the mean pot weights estimated from the ThetaProbe data (mean of 3) for the same plot. The changes in plant weights and 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. The ThetaProbe data show 2 readings per day, to correspond with pot weighing times. For completeness, ThetaProbe data are shown for weekends, although there are no corresponding weight data.

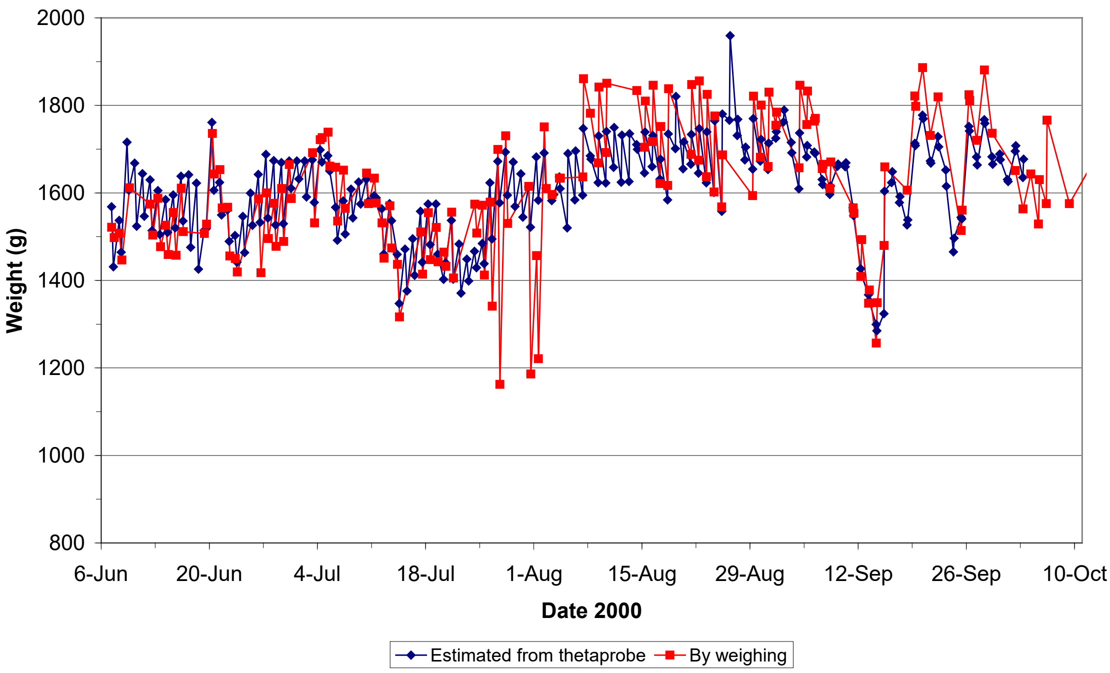


Figure 4.4. *Cotinus* H treatment, comparison of the weight of pots determined by direct weighing, and by estimation from ThetaProbe data

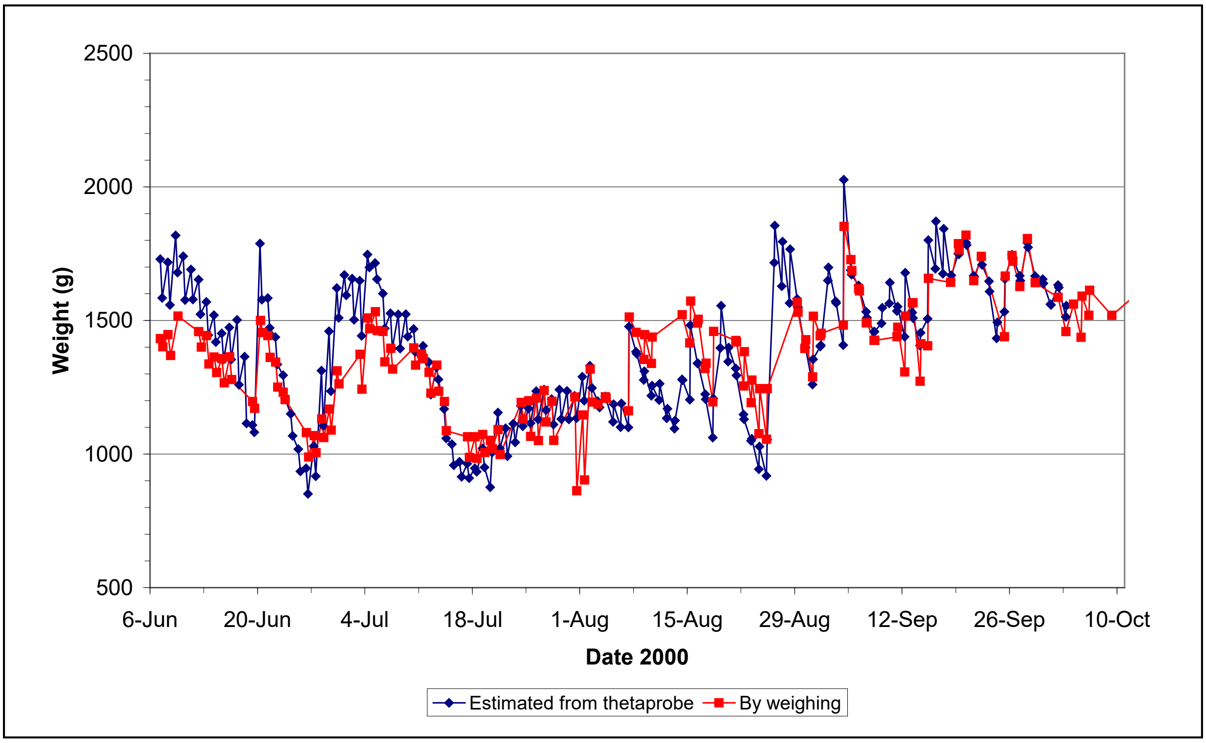


Figure 4.5. *Cotinus* E treatment, comparison of the weight of pots determined by direct weighing, and by estimation from ThetaProbe data

For the over watered *Cotinus* H treatment, in which the compost was maintained wet throughout the season, the mean data from 3 ThetaProbes represented the mean pot weight (mean of 4 pots) extremely well throughout the entire period from June to October with only a few departures. For the *Cotinus*-E treatment, the agreement between the estimated and actual weights was also very good for much of the period, but there are some periods, notably in early June and early July when the ThetaProbe was over estimating the weights. The calculation of pot weight from ThetaProbe data assumes that the reading (in the top 6 cm of the compost) represents the whole container. This assumption holds in well/over-watered treatments as in the *Cotinus* H.

In the E treatments where under watering is more likely to occur, the compost may dry throughout the pot. This was observed (eg in late June and mid-July) and the agreement between the ThetaProbe and pot weights was good during the drying down (because uptake by roots is fairly uniform throughout the pot). However, after such a drying down, and when irrigation has been sufficient to wet only the upper layers of the compost, the ThetaProbe data (as shown) overestimate the weight of the pot because of the assumption that the data represent all of the pot.

In a 3 l container, the 6 cm measuring depth is less than half of the depth of compost, but as the pots are tapered, this in fact represents about 50% of its volume. The representation would be better for 2 l containers and worse for larger volume containers, or taller containers such as those often used for roses.

Under a regime of daily irrigation with sprinklers, the 6 cm measuring depth may not be too serious a limitation in standard containers of 3 l or less. Based on the rates of water loss observed during this summer, the amount of water stored in a fully wetted 3 l container is sufficient for 3 or 4 hot days. The amount stored in the layer monitored by the ThetaProbe should be sufficient for at least a day, so the measuring depth should not be too severe a limitation *if the correct amount of water is being applied*. This is critical, because if the lower part of the compost has dried out, there will be no "buffer" reserve of water to reduce the stress on the plant when the water in the upper layer has been used. Another approach to the sampling depth limitation might be to develop a ThetaProbe with 10cm spikes.

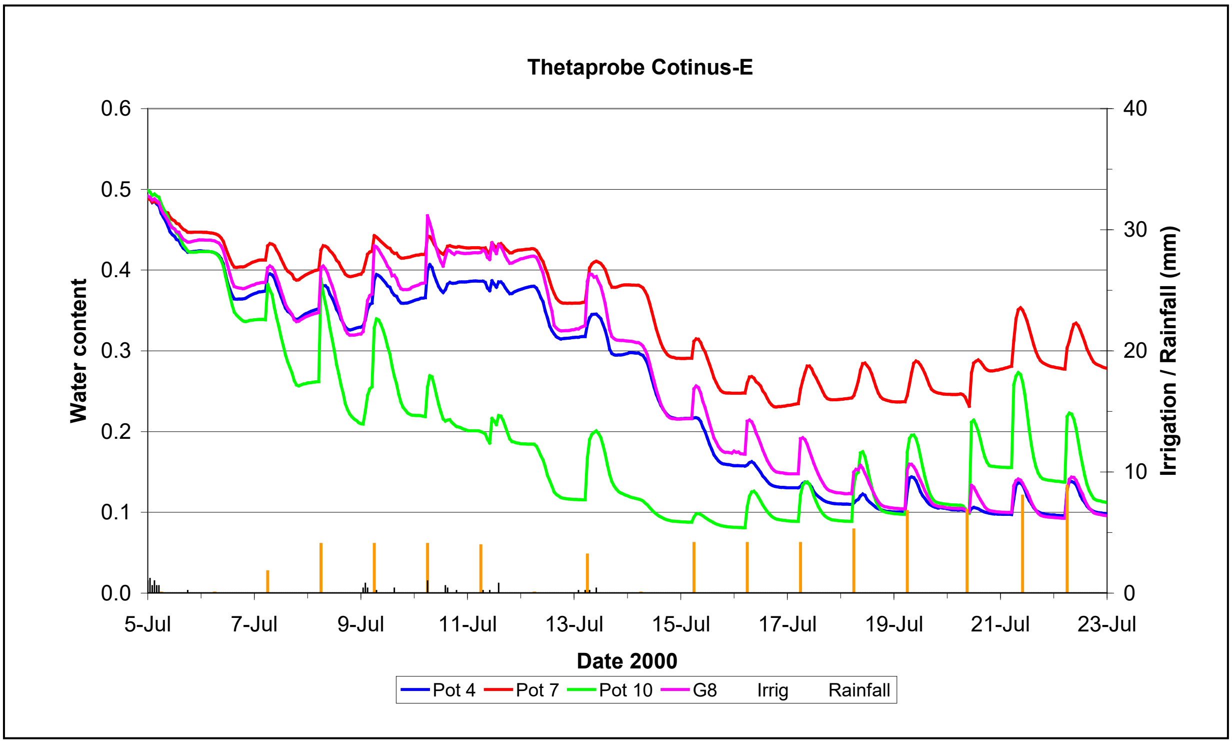


Figure 4.6. Hourly water content data from the 4 ThetaProbes in the *Cotinus* E treatment, with daily irrigation and hourly rainfall

Variability of readings

The data for the *Hydrangea* H treatment (see Figure 4.2) show that when kept well wetted, the variability between sensors is low. This is because CC does not vary much between pots. However, between irrigations, there can still be a large increase in variability caused by differences in uptake. This is very noticeable for the guard row pot G8, and pot 4 between 22
and 27 June when the uptake from these pots was much larger than from the other two.

In general, when the mean water content was high (ie all of the pots were close to a water content of 50%), the variability of the sensor readings within a bed (expressed as the co-efficient of variation, or CV) was typically 10% - 15%, but as the mean water content decreased, the variability increased considerably, sometimes to as much as 80%. Figure 4.6 shows the ThetaProbe, irrigation and rainfall data from the *Cotinus* E treatment, from 5 – 23 July, illustrating a period when the variability was large.

In June (Figure 4.3), the data for this treatment show that all of the sensors respond similarly, with only a small increase in variability as the compost dried. However, a few weeks later (see Figure 4.6), the same treatment shows much greater variability developing. 28 mm of rain on 4/5 July, brought the compost to CC and pot 10 then dried rapidly to an indicated water content of less than 10%. This is exceptionally (and unacceptably) dry. Initially, pot 10 also showed much larger daily losses and responses to individual irrigations than the other pots. The other pots started to dry down on about 13 July, but at different rates. Pot 7 stayed relatively much wetter.

What are the sources of this variability of water content? There are four main categories.

a. Inherent differences between sensors
b. Variation in compost type and packing
c. Differences in water use of the plants
d. Differences in the amount of water entering the container.

Differences between sensors are believed to be small as they are adjusted during manufacture. The variation of compost packing and type within a given bed will probably also be relatively small. Plant water use is affected by the position of the container within the bed (plants along the edges use more water because they are more exposed), the size and vigour of the plant, and the water availability. The latter is partly determined by the amount of water entering the container.

The amount of water entering the container varies with the sprinkler type and layout adopted, and with the position of the container within the spray pattern. The spray patterns are affected by wind drift, and the irrigation inputs to a given container on a bed will vary with wind strength and direction. Containers at the edges can suffer a “double whammy” effect because the demand on them is higher and they often receive less water. As an example, the large demand of the guard row pot G8 in the *Cotinus* E treatment can be seen in Figure 4.2 However, this pattern was not repeated across all of the treatments studied.

At a smaller scale, the distribution of water can vary within a single pot because of shading of part of the pot by the plant itself or by adjacent plants, depending on the position of the container in relation to the sprinkler(s). The amount of water entering the containers will also depend to some extent on the size of the plants, and on their individual canopy structure and leaf area. The plant canopies intercept water, which may be funnelled into the containers in some cases, or shed away in others. The spacing of the containers is also important.

The key questions are – if just one pot/sensor was to be selected, which would best represent the bed in terms of assuring the correct irrigation applications? Would one sensor be adequate?
Given the diverse sources of variability, it can be seen that it is likely that more than one sensor may be required.

Reducing variability

For reliable control of irrigation, the variability of water content across the bed must be minimised. This can be done by various means. Careful design can increase the uniformity of application of sprinkler systems, although clearly drip is a far better option in terms of assured

uniformity of application. The choice of a representative plant (in whose container the sensor is to be installed) is also very important. The position within the bed must also be considered. If an “average” plant is chosen, it is clear that bigger plants will be under watered, and smaller plants over watered. This may not matter in the longer term. The smaller plants may “catch up” because they will have more than adequate water. The larger plants *will* suffer some stress, but this is unlikely to be damaging as studies on RDI have shown that applications of as little as 40% of daily requirements are well tolerated. This is largely because the irrigation is daily. Over a period, the stressed plants may reduce their growth and water requirements to be more in line with the applications. For the very precise control required for RDI irrigation, the variability must be reduced, particular of the irrigation.

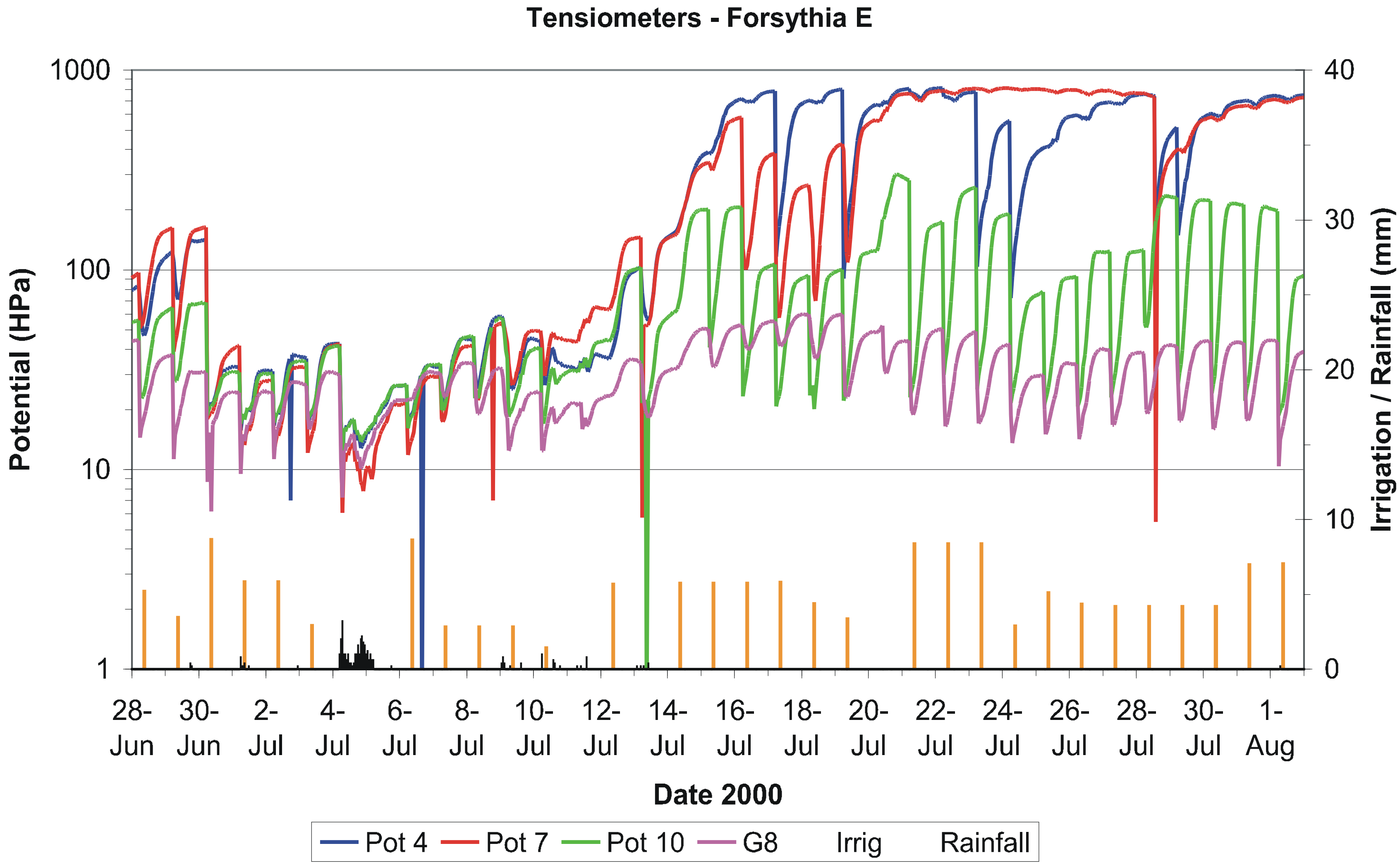


Figure 4.7. tensiometer data for Forsythia E treatment. (NB Data on logarithmic scale. Larger numbers + drier)

Mini Tensiometers

Figure 4.7 shows the data from the 4 tensiometers in the *Forsythia* E treatment for the period from 28 June to 1 August 2000. CC is at about 10 Hpa, and the limit of readily available water is at about 100 Hpa. Wilting point is at about 800 Hpa, and it can be seen that 2 of the tensiometers showed readings as high as this. This corresponds to a water content of about 10% which is extremely low for a peat based compost. These tensiometer data also demonstrate the variability of the readings, as seen with the ThetaProbe.

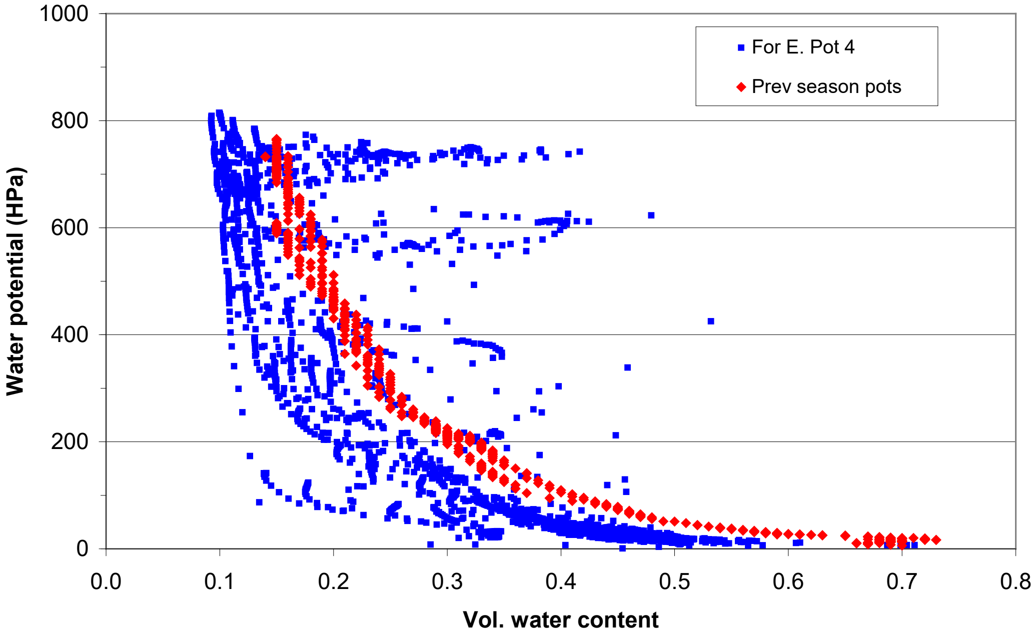


Figure 4.8. Water retention curves for Forsythia E treatment pot 4, and previous season *Hydrangea* pot

The ThetaProbe and tensiometer data are best compared by plotting one set of data against the other. For a given growing medium, or soil, the curve produced is known as the water retention curve, which is unique for that compost mix or soil type. A curve derived in this way is shown in Figure 4.8 for Pot 7 in the *Forsythia* E treatment. Also shown is a curve derived using measurements made in 2 l pots planted with *Hydrangea*. These had been planted in June 1999 and had been used in the trial at E. Malling that year.

There are notable differences between the two curves in Figure 4.8. The previous season pot's data (diamonds) show a very well defined retention curve. The *Forsythia* E data from this year show a lot of scatter as well as some odd horizontal "limbs", which cannot be correct. However, it is possible to identify the main curve, which follows the previous season's data, but is displaced from it. The water content at CC was about 0.75 in the previous season pots, but only about 0.50 in the *Forsythia* pots. This reflects a marked difference in water retention, but it is not possible to say whether this is because the compost was different at planting, or because the compost has aged and changed its water retention properties.

The odd "limbs" in the *Forsythia* data are a result of the different depths of measurement of the tensiometer and the ThetaProbe. The tensiometers were installed so that tip of the 2.5cm long ceramic sensing portion was at 10cm depth. It thus measures in a layer from 7.5 to 10cm. In contrast, the ThetaProbe gives an "average" water content of the layer between between 0 and 6 cm depth. The "limbs" occur when the wetting front from the irrigation wets the upper layers (which the ThetaProbe senses), but does not reach the tensiometer, which is still in much drier compost. This situation, where the compost in the lower part of the pot remained dry, often persisted through many irrigations, and was also identified by comparison of the ThetaProbe and weight data.

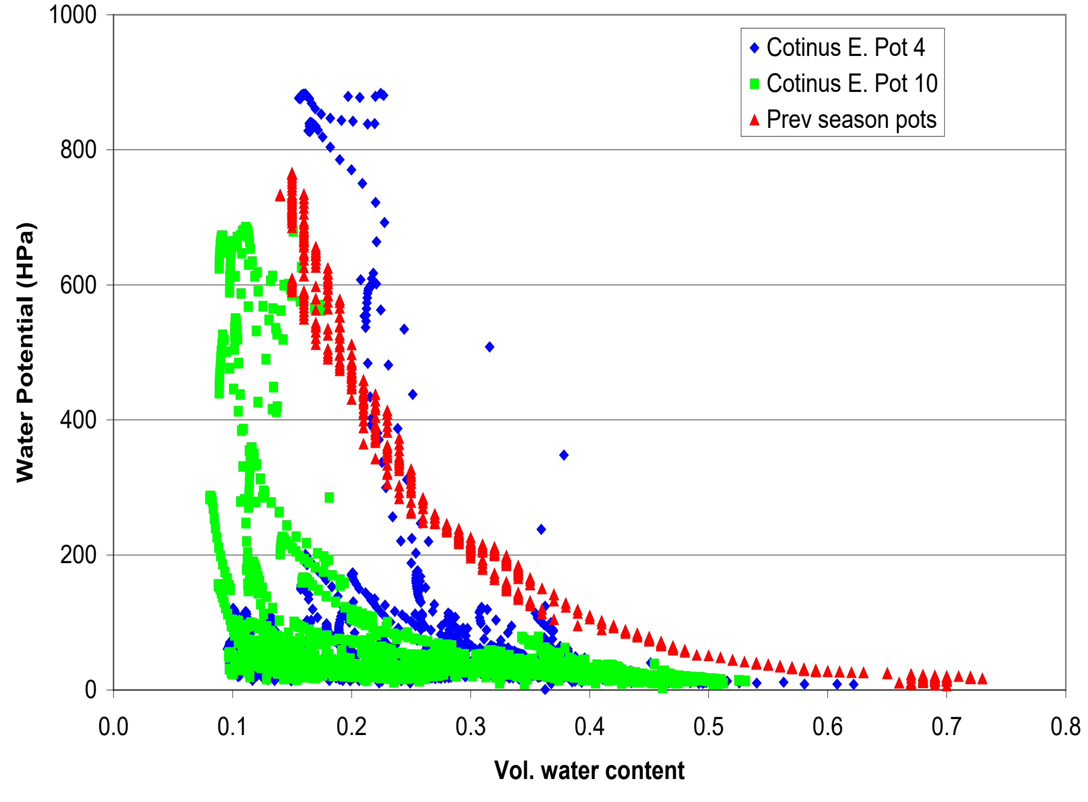


Figure 4.9. Water retention curves for *Cotinus* E treatment pots 4 & 10, and previous season *Hydrangea*

For the purposes of direct comparison, it might have been better if the tensiometer had been installed with its tip at 6cm. However, assuming that water uptake is fairly uniform throughout the pot, a sensor that could be installed at eg 10cm would provide a better control of irrigation, by ensuring that the compost was wetted to that depth before irrigation was switched off. Although the upper 6cm of compost contain an adequate amount of water to sustain uptake on a hot summer day, the lower layers provide a useful buffer of additional water storage to sustain the crop if the irrigation was under estimated.

Water retention data from the *Cotinus* E treatment are shown in Figure 4.9. The water retention curve for the previous season is also shown. Although in the same bed, the tensiometers were not in the same pots as the ThetaProbes (the cables were too short to reach), but were in equivalent positions. Most of the potentials were below 150 Hpa, even though the ThetaProbes showed water contents as low as 0.1. These curves do not match those shown in Figure 4.8. These tensiometers indicated wet conditions almost throughout the season at one end of the *Cotinus* E treatment on bed 5, in contrast to the much drier conditions indicated by the ThetaProbes at the other end of the same bed. Poor contact was suspected as a possible explanation for the lack of drying indicated by the tensiometers, but the data showed a clear diurnal response to the irrigations, implying that contact was not a problem. The data serve to emphasise the amount of variability that can occur within a single bed.

Automatic weather station and Evaposensor

The AWS was set within the beds, rather than over a grass plot, to try to better represent the conditions of wind speed and humidity that the beds experienced. A daily reference crop evaporation (Et_{ref}) was calculated as an indicator of the evaporative demand of the atmosphere on a crop. The Evaposensor output consists of 2 temperatures, for the wet and dry leaves respectively. To obtain the daily Evaposensor reading, the difference between the two temperatures was calculated hourly and the differences were summed over a 24 hour period. Figure 4.10 shows Et_{ref} plotted for the period from May 26 to August 24, together with the data from the two Evaposensors.

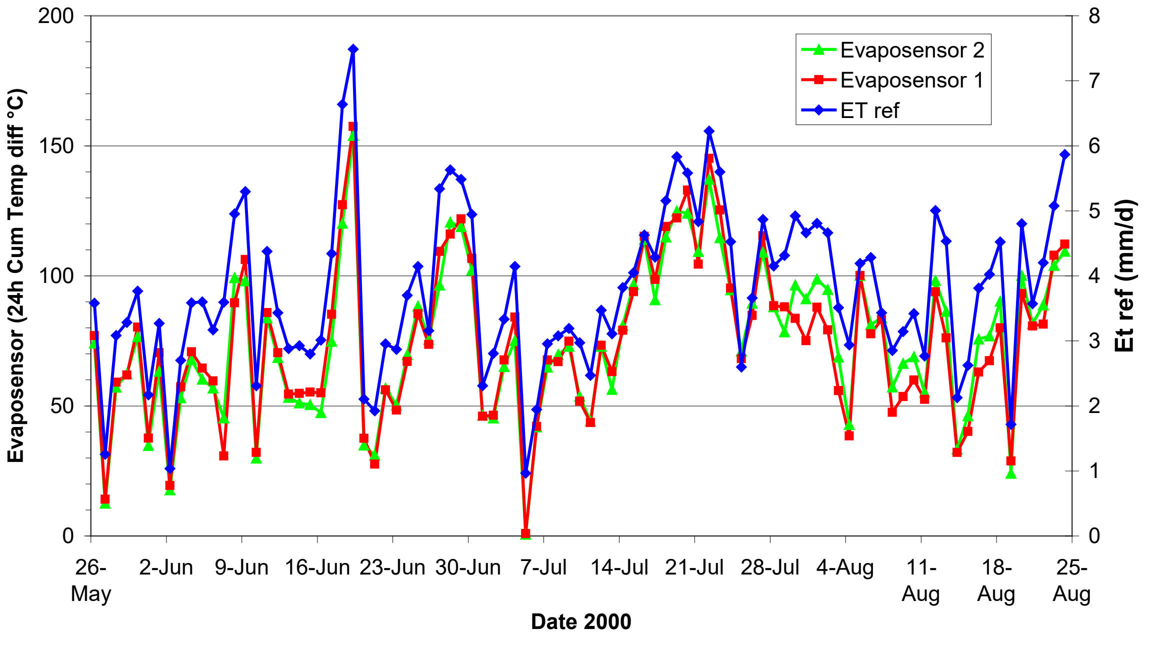


Figure 4.10. Et_{ref} and Evaposensor data for the period from May 26 to August 24

The data show a close relationship between Et_{ref} and the Evaposensor data, and close agreement between the two Evaposensors. Figure 4.11 shows the relationship between the readings of Evaposensor 1 (24h cumulative values, representing a day's evaporation) and Et_{ref}. For ES1, the R^2 of the fitted linear relationship was 0.926. For ES2 (not shown), the R^2 was 0.905. The slopes (22.57 and 21.51 respectively) and intercepts (-9.67 and –9.85) of the fitted linear relationships were virtually identical for both. This is despite the fact that ES1 was exposed to irrigation and ES2 was not. The irrigation would have kept the dry leaf for wetted for a short time, but this did not seem to

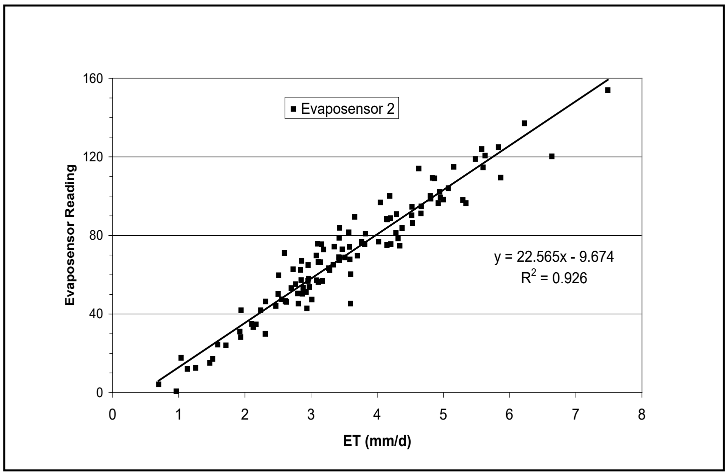


Figure 11. Relationship between ES1 readings

affect the readings significantly. There is some evidence that there was a small difference between the readings after ES1 was moved to the cross-arm of the AWS. This is probably due to the greater exposure to wind at this height. The Evaposensors are probably best mounted at a height of about 1m, or just above crop height.

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 it 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 (estimated at about £300, including a reader unit), 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).

The data in Figure 4.11 show a very good relationship between ES output and ET_{ref}, but it must be borne in mind that the calculation of ET_{ref} provides a prediction of the 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 (eg edge of bed or centre).

Evaposensors could be used to better “sample” different microclimates because of their small size, compared to an AWS.

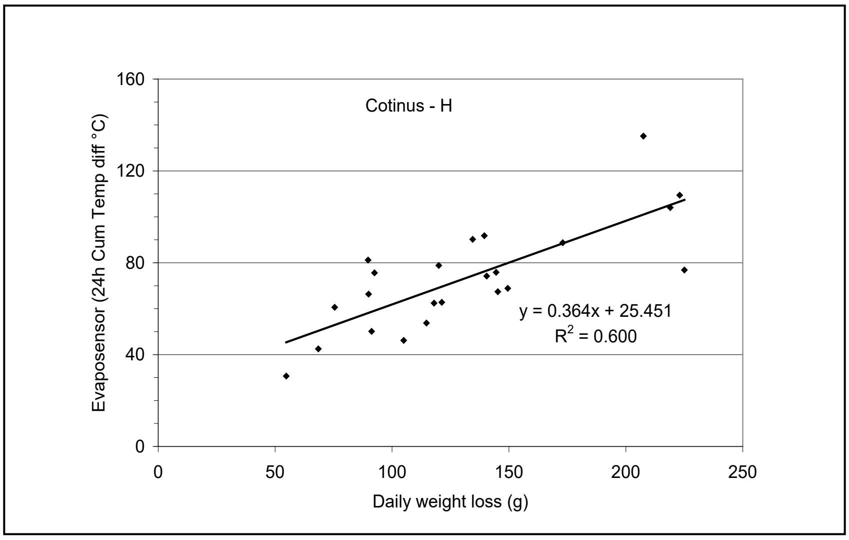


Figure 4.12. Relationship between daily weight loss (water use) and ES reading (ES2)

The relationship between the ES reading and ET_{ref} shown in Figure 4.11 is for the conditions prevailing at Efford between May and October 2000. This site is very close to the coast, and it is likely that the relationships for other parts of the UK may differ slightly.

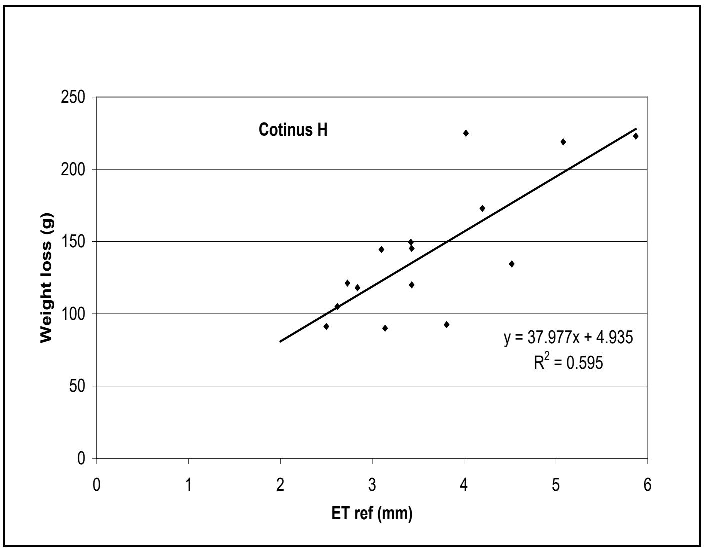


Figure 4.13. Relationship between daily weight loss (water use) and ET_{ref}.

The ES data were compared with daily weight losses to examine the ability of the ES to predict actual plant water use. Figure 4.12 shows the data for the *Cotinus* H treatment. The H treatment data (well watered) were studied to reduce the likelihood that the water use might have been affected by water stress. The data are only for the period after August 3, when the weighing procedure permitted a weight loss to be calculated for an almost 24h period (actually about 22.5h). The ES data are for a full 24 hours and this mismatch may be a source of a small amount of "noise" in the data. There was little plant growth in this period, so the changes in plant water use due to increases in leaf area should be small.

The R^2 for the *Cotinus* H treatment shown was 0.60, but for the *Forsythia* and *Hydrangea* H treatments, the R^2 was 0.502 and 0.405 respectively. There was often a very wide range of water use for a small range of ES readings. The slopes for the *Cotinus* and *Forsythia* were both 0.36, but for the *Hydrangea* the slope was 0.30.

Figure 4.13 shows the *Cotinus* H weight loss data compared to $Et_{ref.}$ The R^2 is 0.595, which is almost the same as for the ES. The R^2 for the *Forsythia* and *Hydrangea* H treatments were 0.403 and 0.144 respectively. These are both rather lower than for the ES.

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.

It is of note that the maximum daily weight loss at Efford in this period was about 220g. Sally Wilkinson of Lancaster University reported that for *Hydrangea* in polytunnels, daily weight losses were much higher. In this study, there were several days with similar, high levels of solar radiation but there was a marked variation in weight loss. These observations, and the relatively poor relationship with ES reading, suggest that there may be a closing of the stomata in these outside grown plants, possibly triggered by high VPD (low air humidity). Humidity may have been rather higher in the polytunnels so that this mechanism was not triggered.

The correlation between ES readings and water use is only moderate. 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 CC. Periods of over-estimation would replenish the storage or lead to drainage losses once CC was reached. The ability of the plants to grow well under RDI treatments that are given only 40 – 60% of ET means that the under watering should not be too much of a problem. However, this assumes a near perfect uniformity of application of water (the same amount applied to all of the pots on a bed). **As the uniformity of application decreases, the number of plants on a bed suffering unacceptable levels of stress will increase.** Uniformity of application is best achieved using a drip system, a well designed capillary system, or possibly a linear move sprinkler system.

To use an ES as a predictor of water requirements, a rain gauge is required to measure the rainfall inputs. The data must be used in a simple water balance program to predict the daily applications allowing for the size and spacing of the plants and the pot sizes (diameters). The relationships between pot spacing and water use of a bed, and between plant size and water use need to be established.

In view of the limitations of methods that estimate water use from atmospheric demand (as opposed to direct measurement of water loss, eg using a ThetaProbe or tensiometer), a “hybrid” approach is proposed. The water requirements would be predicted using an ES, and a roving ThetaProbe would be used on an occasional basis, to check that the irrigation was “on track”. If the pots were found to be dry, a remedial irrigation could be carried out. If the pots were very wet, the irrigation inputs could be reduced.

SUMMARY

The sensors tested fell into two main categories; those that measure in:

- the growing medium, ie *directly* indicating the conditions of water availability to which the plant is subjected
- the atmosphere. These allow the plant water use to be *estimated*. The water status of the growing medium can only be *inferred.*

Direct measurement sensors

ThetaProbe (TP)

- Sensitive, and provided very precise data
- Reliable and maintenance free
- In overwatered treatments, mean of 3 TPs predicted mean bed pot weight very well
- In treatments nominally given the water requirement, prediction less good, and
- Spatial variability also a problem
- 6cm spikes rather short to represent pot water content. Develop 10cm version?
- Minimum one per bed to control irrigation. More if variability is high

- Relatively expensive (£336 +VAT each, quantity discounts available) Need irrigation "control box"/interface

Mini-tensiometer (MT)

- Sensitive, and provided very precise data
- Reliable (but require occasional topping up with water).
- In treatments nominally given their water requirement, spatial variability a problem
- Easy installation at range of depths to 12cm (model tested)
- Min. one per bed to control irrigation, more if variability is high
- Relatively inexpensive (£107 each +VAT).
- Need irrigation "control box"/interface

The mini-tensiometer provides a "spot" measurement at the depth of installation, compared to the ThetaProbe, which averages the water content over the lengths of the measuring spikes. As a result, the way the irrigation is controlled may need to be different for a tensiometer.

For irrigation control, the sensors would need to be connected to a control unit, on which a "trigger" water content or potential could be set, and which could switch 24V solenoid valves to control the irrigation. An alternative would be for the control unit to determine the irrigation requirement and transmit this to an irrigation controller via an interface. The irrigation controller would require an operator to input some key information, in particular the application rate of the irrigation system, the pot spacing and pot diameter.

A more sophisticated development would be an "intelligent" controller, which would automatically determine, after a number of irrigations, the amount of water to apply for a given change in eg water content. This would obviate the need for the operator inputs mentioned above. The sensor control unit could be a single channel device for a bed, or a multi-channel device, to accept inputs from perhaps a dozen sensors controlling irrigation on a dozen beds.

On a bed scale, the measurements made in this study indicate a **considerable variation of conditions in pots**. On a nursery scale, sensing within pots would require at least one sensor for each of the large number of beds. This would be very expensive. There are two main sources of **spatial variability**:

1. **Plant uptake**, which depends on:
   - Plant size/leaf area
   - Exposure/position on bed (eg edge, or centre)
   - Water availability (depends on irrigation)

The effect of this variability on irrigation control can be reduced by:

- having more sensors and taking an average (cost implication)
- choosing a "representative" plant

2. **Irrigation uniformity**, which depends on
   - Design of irrigation system (sprinkler systems often poor)
   - Wind speed/direction (exposure)

Uniformity can be improved by:

- careful design of sprinkler systems (or adoption of linear move, or gantry type)
- adoption of drip, or capillary methods

Indirect "sensors"

Automatic Weather Station (AWS)

- Reliable, produced good data
- Expensive (£2500 or so, with logger)
- Need PC and software to compute evaporative demand (Et_{ref})
- Moderate ability to predict actual water loss from plants in trial (may be better for other species)
- Only need one per nursery

Evaposensor (ES)

- Reliable
- Needs topping up with water & cleaning of wick
- Very good correlation with Et_{ref} from AWS (R^2=0.92)
- Very simple and cheap (probably about £60)
- Could use just one per nursery (but cheap enough to have several)
- Moderate correlation with actual plant water use, but slightly better than AWS Et_{ref} Probably represents conditions better because was closer to the crop environment
- Needs 24h integrator / reader unit (and means to interface with irrigation controller)

The "indirect" methods have the advantage that the atmospheric demand estimated at one location could be used to represent a whole nursery. The use of an AWS or ES to control irrigation requires more operator input than the direct sensors. In addition to the information on pot spacing, pot diameter and irrigation system application rate, corrections for plant size/leaf area and rainfall data are also required.

The results from the Evaposensor were extremely encouraging, the more so when its low cost is taken into account. The fact that it is small and can be located close to crop level means that it is able to give results which are at least as good as an AWS in predicting nursery crop water use. It is anticipated that even with a readout unit (to display 24 hour evaporation totals), its cost will be of the order of £300, which will be affordable to a wide range of nurseries. It could be used merely as an indicator to an irrigation supervisor, who then set manual controls, or it could be interfaced to an automated irrigation controller.

THE WAY FORWARD

The two types of sensors lead to two separate approaches to irrigation control with important implications for cost and precision.

The estimation of evaporative demand with the Evaposensor provides a low cost approach, but with only a moderate to good ability to predict plant water use. There is also a need for various operator inputs to get the irrigation correct for each bed. Rainfall must be measured.

The insitu sensor approach does not require corrections for plant size, and rainfall need not be measured. There is less margin for error, and it lends itself to fully automated control on a bed by bed basis. However, at least one sensor would be required per bed, which make it a much more expensive option. The issue of spatial variability must be addressed. It is recommended that the in situ sensor approach would be best used with an irrigation system that provides more uniform application rates than most sprinkler systems in current use.

To sum up, the two approaches are:

1.“Cheap and cheerful” (but rather better than guessing)

Evaposensor and rain gauge, either with simple 24h Evaposensor readout, or feeding data to an irrigation control system. Both would need operator input for plant size / stage of growth, pot size, spacing etc. One ES and rain gauge could serve a whole nursery, unless conditions varied enormously.

2.“Expensive, but precise, and with the possibility of being completely automatic”

This would be a bed based system with ThetaProbe(s) or mini-tensiometer(s) connected to a control unit. It could be developed to adapt to irrigation system inputs and obviate the need for operator inputs on pot spacing, irrigation rate etc.

A hybrid approach is also a possibility, using an Evaposensor and raingauge, with a roving ThetaProbe as a check that irrigation is “on track”.

ASSESSMENT OF PLANT GROWTH UNDER TWO IRRIGATION REGIMES, AND DEVELOPMENT OF MANAGEMENT PROTOCOL FOR NON-AUTOMATED IRRIGATION CONTROL.

OBJECTIVE 5

HRI EFFORD

INTRODUCTION

Year 1 results indicated that plant quality could be maintained by adjusting the duration of irrigation to an estimation of evapo-transpirative demand, and that savings of water were possible. However a number of practical limitations of the irrigation system used and the application of experimental treatments to a wide range of subjects were highlighted. In 2000, work concentrated on outdoor container crops of just the three core species, using a revised overhead irrigation system.

Experimental objectives

To examine the practical application of an Etp irrigation regime to crops of container nursery stock plants under outdoor conditions, using an overhead irrigation system.

To compare crop growth and water use for the project core species grown under both an Etp based and a 'grower' (i.e. 'generous') irrigation regime.

To investigate the use of a hand-held Theta probe and meter for estimating water status of containers, compared to the gravimetric (weighing) method, and as a basis for developing a management protocol for non-automated irrigation control.

Provide gravimetric reference points and water use data for evaluation of other equipment and methods for estimating water use, in collaboration with the Centre for Ecology & Hydrology (CEH).

- The milestones relevant to these objectives were:

On the basis of preliminary data (from 4.5) select equipments and test as a management aid for regulating overhead irrigation. Compare with conventional control and identify any limitations. (CEH / Eff).

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).

MATERIALS AND METHODS

Treatments

Species

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

Irrigation regimes

E Etp. Irrigation applications based on daily gravimetric records to bring containers back to near pot capacity.

H 'High' regime. Approximately 150% of E treatments - ie. 'generous watering'

Design and layout

Randomised block design with two replicates. Six treatments laid out on 12 beds (1.6 m x 6.0 m) independently controlled for irrigation. Treatment plots were replicated twice on each bed. Plot size 36 plants / plot. Central 16 plants assessed for growth and 4 plants per bed allocated for gravimetric and Thetaprobe assessments of irrigation needs and response. Plants were set out at a spacing of 0.30 m x 0.25 m (approx. 13 plants / m^2).

Method

Pruned 9 cm liners were potted into 3 litre containers in a 100% peat medium containing 5 kg/m^3 Osmocote Plus 12-14 month Spring mix controlled release fertiliser.

Plants were potted in early April, retained under cold glass (frost protection) until mid-May before being moved to the outdoor beds. Some light pruning was carried out in late May on Hydrangea and Forsythia to remove atypically long shoots and to even up plants over the plots, but no further pruning or shaping was carried out over the growing season.

Irrigation applications and records

Irrigation treatments were imposed and records collected from early June - mid October.

180° mini-sprinklers (160 l/h rating @ 200 kPa) on each side of the beds were used to apply irrigation as evenly as practical over the small bed areas. Windbreaks around the site and between plots were used to reduce wind drift.

Four replicate containers per bed, weighed twice daily, were used to estimate differences of container weights from 'pot capacity' (PC) and provided the basis for adjusting the irrigation controller timeclocks on a daily basis. The estimated water requirements and applications were made to each bed independently. Theta probe measurements using a hand held ThetaMeter (Type HH1) were collected from these containers at the same time. ThetaMeter readings were collected using the instrument's built in calibration for moisture content in organic media.

Water use data for each bed (ie total irrigation sprinkler outputs) were recorded with water meters. Water use, expressed as mm, was calculated on a nominal 10.8 m^2 'irrigated area' per bed based on the 9 semi-circle sprinklers as a 1.5 m x 1.6 m spacing.

Plant growth records

Plant height, spread and a count of the numbers of shoots showing new growth were recorded for all plants on four occasions at approx. 6 week intervals from late May to late September.

Final fresh and dry weights were recorded in mid - late October at the end of the growing season.

Other instrumentation on site

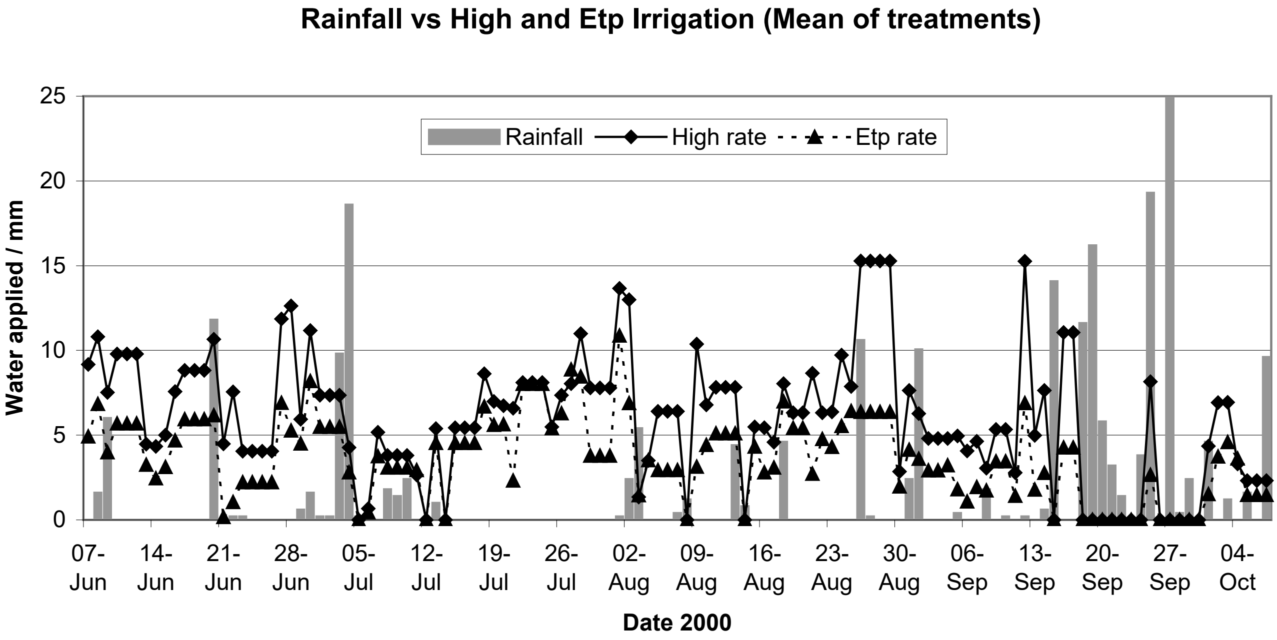
Other instruments (Automatic Weather Station, Thetaprobes, Minitensiometers and Evaposensors) linked to data loggers were set up in the trial by CEH to monitor other important environmental parameters and to examine other methods of estimating water requirements (see CEH report on Sensor Evaluation). This data, together with that from the above experiment, will be used in the development of a practical water management model for testing and demonstrating in Year 3 (milestones 5.8 & 5.9)

RESULTS

Water use under the Etp and High regimes

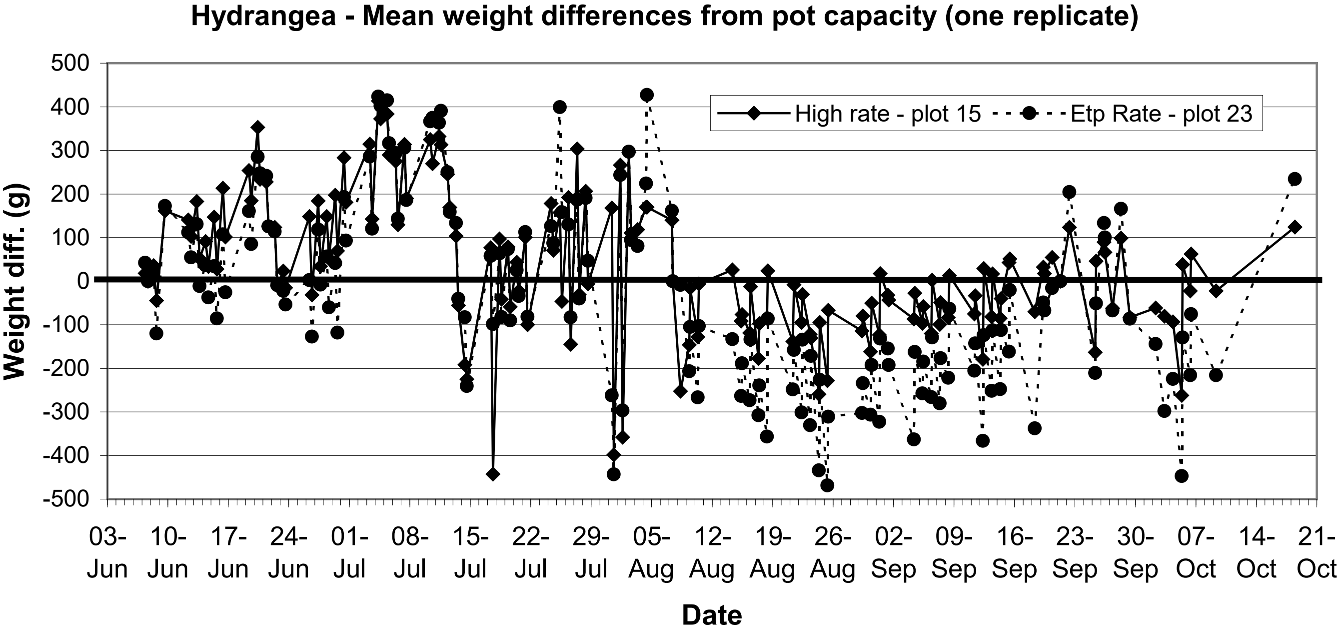
Figure 5.1 shows the mean water application (averaged across species) for the High and Etp regimes, and rainfall, during the season.

Figure 5.1



Mean container weights at PC were established periodically during the season following heavy rainfall or irrigation. The mean weight differences of the sampled containers from PC were used as a basis upon which to apply the irrigation treatments for each plot. Despite redesign of the irrigation system to improve uniformity of application, large within plot variation in container water status still sometimes developed, even between adjacent plants. It was also difficult to control the large daily fluctuations in container water status, both during hot and dry weather (e.g. much of July), or periods of heavy rain (e.g. beginning of July and late September). This is illustrated in Figure 5.2, for a replicate of High and Etp plots on Hydrangea. On two occasions, during hot and windy periods in July, extra irrigation and hand watering, on top of the calculated treatment irrigations, were required to fully wet up and even out the beds, and prevent problems from dry containers blowing over. Nevertheless, very few plants ever reached wilting point throughout the experiment, and guard plants on bed edges rarely needed supplementary hand watering.

Figure 5.2



Irrigation efficiency

The overhead irrigation system used in Year 2 was tested under controlled conditions in a glasshouse. It gave a mean application rate (MAR) of 63 mm/hr with a Coefficient of uniformity (Cu) of 81% and Scheduling coefficient (Sc) of 1.6. Cu is a measure of the deviation of application rate over the irrigated area as a proportion of MAR with 1 being perfectly uniform. Sc is MAR ÷ minimum application rate for the area, and gives a measure of the extra water required over the whole area to provide sufficient irrigation for the driest part. Efficient irrigation systems should have a Cu >85% and Sc <1.5 (ideally <1.2), although frequently these standards are not achieved in commercial practice, particularly under windy conditions for example (Rolfe et al, 2000). A sample of dormant (leafless) containerised plants, from the Year 2 experiments, were subsequently tested with the irrigation system under protection, to establish whether poor retention of applied water in the growing media (run through) might have been a significant factor affecting the efficiency and uniformity of irrigation. It is well known that water absorption can be poor in dry growing media, but irrigation of moist growing media resulted in some 35% - 55%

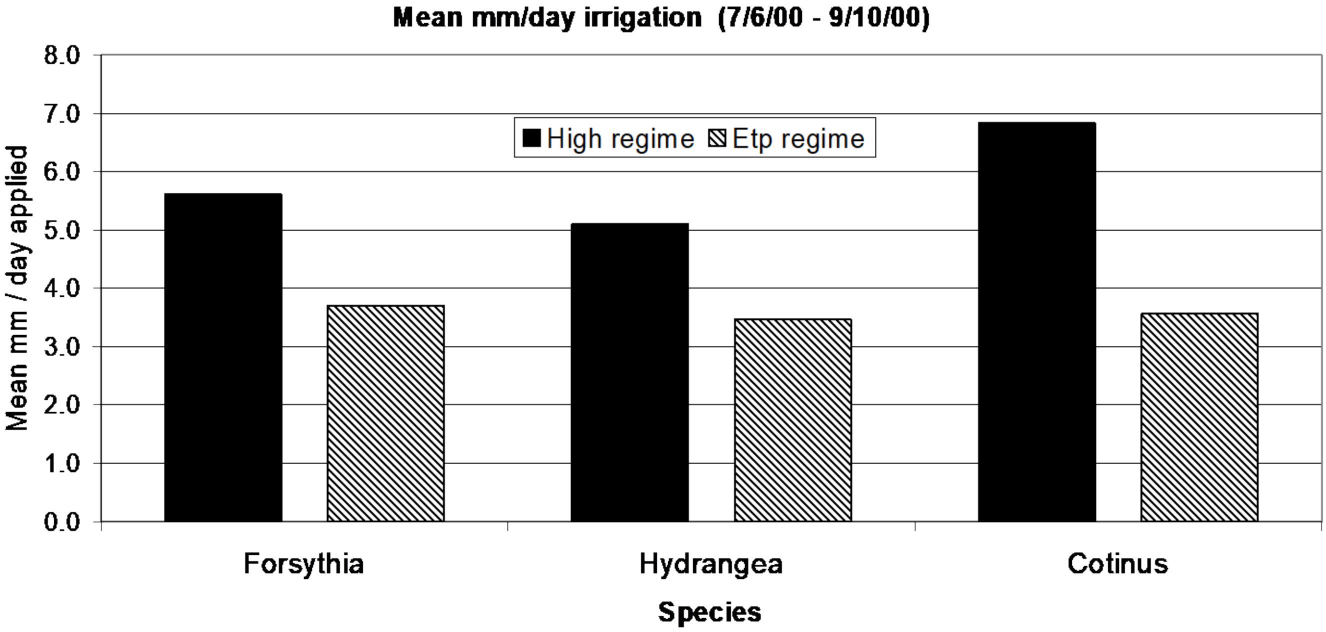
run through when 300 ml/pot was applied through the irrigation system to the 3 litre containers, which had been dried back from pot capacity by an average of 350 g. The foliage canopy would have interfered with capture of water by the media in the growing crop, but it is still possible that the high MAR used in Year 2 may have contributed to poor water retention and uniformity.

Water use between species

Despite the practical difficulties of maintaining a uniform water status within the cropping beds, differences in water applications between treatments were generally well maintained during the experiment. There was no difference in total irrigation applications for the Etp treatment between the three species with a mean value of 3.6 mm/day when averaged over the whole season (Figure 5.3). This finding is consistent with other studies where seasonal water use between crop species can be remarkably similar given comparable size plants under similar environmental conditions. The *Hydrangea* foliage canopy reached 100% ground cover by mid July, and a higher transpiration rate might have been expected than the less leafy *Cotinus* or *Forsythia*. It is possible that this was balanced out by lower evaporation losses from the shaded surface of the growing media with *Hydrangea*, and that foliage intercepted and channelled more irrigation into the pots. However this could not be confirmed with the variable pot weight data available in this experiment and needs examining further under more controlled conditions.

In Year 1 at Efford, *Cotinus* used less water than *Forsythia or Hydrangea*, under the Etp regime, but this was over a short late season experiment. The High treatment averaged 164% that of the Etp in Year 2 with 5.9 mm/day overall. These water use figures are comparable with nursery data obtained by the Water Research Centre (WRc) under Objective 8.

Figure 5.3

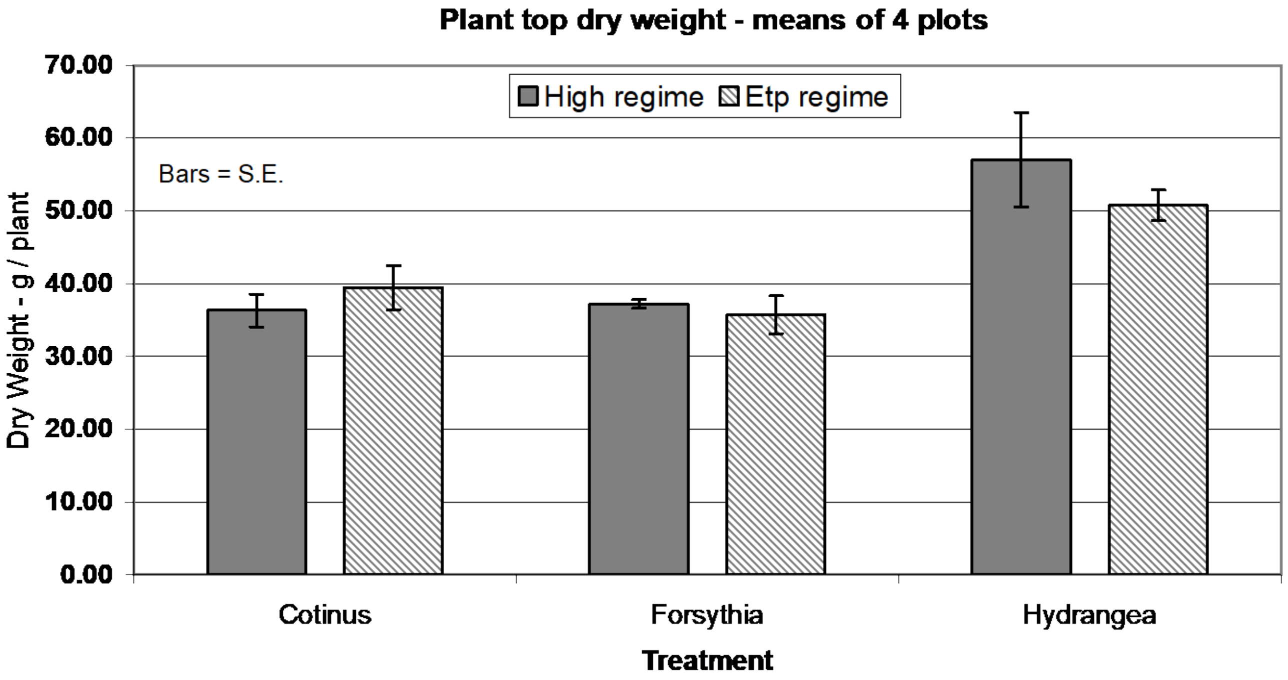


Plant growth and quality

Hydrangea maintained a steady increase in height and spread through the growing season until late September, although older leaves were showing red autumn colouring by then which developed throughout the whole plant by the end of October accompanied by loss of lower leaves. Cotinus also showed a steady increase in height up to the end of September, but without any formative pruning during the season to encourage bushiness, the number of new growth points declined sharply from late June onwards with no further extension growth from late September. Forsythia was slower to bulk up, producing mainly thin 'floppy' shoots until late June, after which the main flush of strong upright shoots developed.

There were no significant differences in top growth biomass between the two irrigation regimes with any of the species (Figure 5.4). Fresh and dry weights followed very similar trends. This supports earlier findings that large savings in water are possible without significant reductions in plant growth, provided irrigation can be controlled more closely with overhead systems. Plant quality (e.g. colour of foliage) was also similar. However, a summer pruning treatment would have been necessary to produce bushier and more compact plants in *Forsythia* and *Cotinus* under both these irrigation regimes.

Figure 5.4



Hand-held Theta probe and meter

The hand-held ThetaMeter readings showed generally poor correlations with the gravimetric estimates of container water status measured in these pots at the same time. This was particularly apparent for wetter containers as the in-built 'organic media' calibration used did not provide readings above an estimated water content of 58%. Better results were achieved with the continuous monitoring fixed position probes where water contents were derived from mV outputs (CEH report).

Publicity

Presentations were given to 55 delegates at an open day at HRI Efford on 24 Oct 2000, where the Year 2 experiment and related HDC funded work on improving irrigation efficiency in nursery stock was exhibited.

CONCLUSIONS AND FUTURE WORK

The practical difficulties of achieving uniform water distribution from an outdoor overhead system were highlighted, but nevertheless it was shown that significant water savings could be made, without reduction plant growth, with daily adjustments of irrigation timeclocks based on plant weight.

For similar sized plants and containers, water requirements over the season were remarkably similar between the species tested where the aim was to apply sufficient, but not excessive, water for maximum growth. Quantities of water applied in this experiment were comparable with those surveyed on container nurseries.

Moisture status measurements using the in-built ‘organic media’ calibration from the hand-held Thetameter HH1 were not reliable enough as a basis for irrigation scheduling. However, more promising results from the static logged Theta probes justifies further examination of these sensors in ‘roving mode’ in Year 3.

Etp estimation from other probes (Evaposensor) looks promising (CEH report) This will be tested further in Year 3 as a basis for irrigation scheduling as a more viable alternative to weighing large numbers of plants, but backed up with gravimetric and/or Theta probe measurements to keep water status ‘on track’.

Amendments, such as the incorporation of a media wetting agent, use of a sprinkler system delivering a lower application rate, and shaping of the plant during the growing season will also be considered for Year 3.

In this experiment, adequate water to maintain good plant growth was supplied to the Etp treatments. Future work will see whether quality can be maintained under a reduced irrigation regime with an overhead system, and whether it can be managed successfully on an outdoor crop.

Reference

Rolfe C, Yiasoumi W, Keskula, E (2000). Managing water in plant nurseries (2^{nd} edn.)
Pub. New South Wales Agriculture, Australia.

DEVELOPMENT OF AN ECONOMIC MODEL

OBJECTIVE 8

WRc

INTRODUCTION

Aim

WRc are required to carry out a cost-benefit analysis of the irrigation control method applied to a number of nurseries and formulate an appropriate economic model (Objective 8).

Data Collection

Procedure

A data collection exercise has been undertaken to provide data for the economic model and also in response to requests made by other research partners to analyse water-use data, so as to give a better understanding of current irrigation practices. To this end, WRc have installed water meters at four nurseries.

The type and size of water meters required was determined through site visits to two nurseries, during which a clamp-on ultrasonic water meter was used to give an estimate of volumetric flow in the pipes. From these estimates, in combination with information provided by the nurseries, it was possible to specify a 40-mm rotary piston meter and a 50-mm helix meter for use at each site. Appropriate meters were subsequently purchased and installed. Data loggers were fitted on the meters at the two nurseries nearest to WRc.

The nurseries were asked to record water use on a daily basis, measure the amount of rainfall, and provide a record of the source of water (mains, bore etc.) used, with associated cost. The nurseries were also asked to keep a record of the following data for each bed being metered:

A record of the total area;
A record of the sprinkler type and distribution radius;
A crop diary for the beds; including:
Species;
Pot size;
Spacing;
Approximate size of plant on placement onto, and removal from the bed;
Media composition (% peat / bark / gravel etc.).

Data Loggers

Data loggers were used to confirm that the paper logging exercise was providing a full picture of the irrigation events and procedures. From the data collected it was determined that the volume of water applied is (approximately) linearly dependent upon the duration of the watering event. Irrigation events generally vary between 10 to 20 minutes, but events lasting 30 to 40 minutes were observed.

The data collected by the loggers showed that some irrigation events were not being recorded, especially when watering occurred more than once a day. However, if meter readings were taken at the end of each day, the unlogged water would simply be added to the next irrigation event logged manually. Such omissions would then only distort the water application data at a temporal resolution less than a day, which is not considered important. Examination of the data did, however, also indicate that meter readings were not always being taken on a daily basis. A more consistent approach to the data collection is thus required.

RESULTS

The water-use data recorded by the water meters has been 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 8.1 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 Figure 8.2 to Figure 8.5. (Note: the weather data for nursery 1 was supplied in an electronic format that could not be read; an alternative format has not been made available.)

Figure 8.1 **Water Application Rate for the Covered Beds**

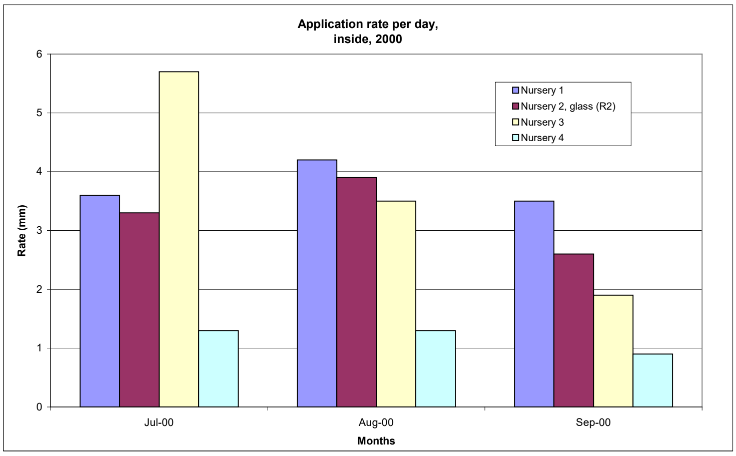


Figure 8.2 Water Application Rate for Outside Beds (Nursery 1)

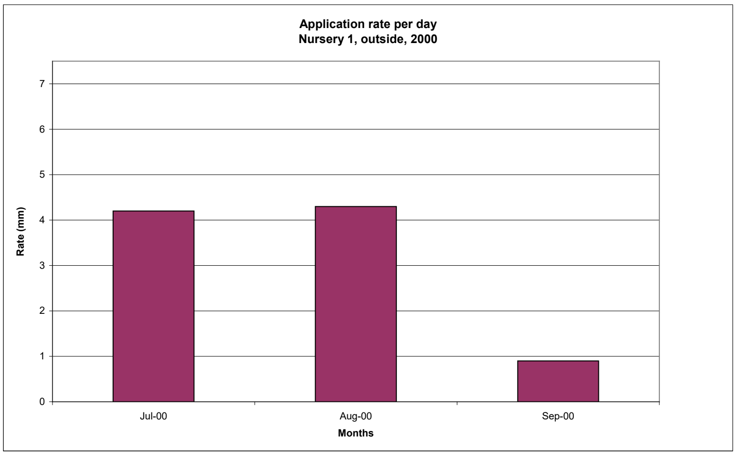


Figure 8.3 Water Application Rate for Outside Beds (Nursery 2)

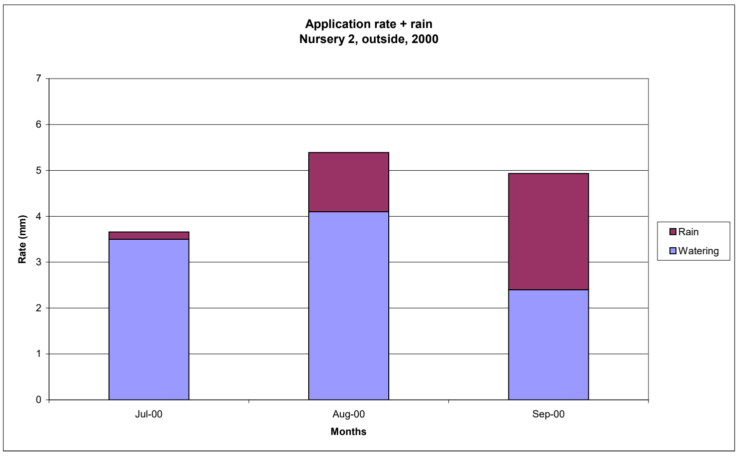


Figure 8.4 Water Application Rate for Outside Beds (Nursery 3)

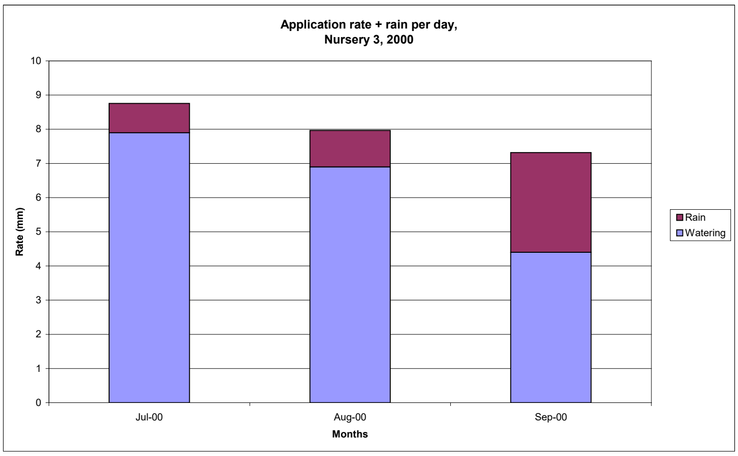
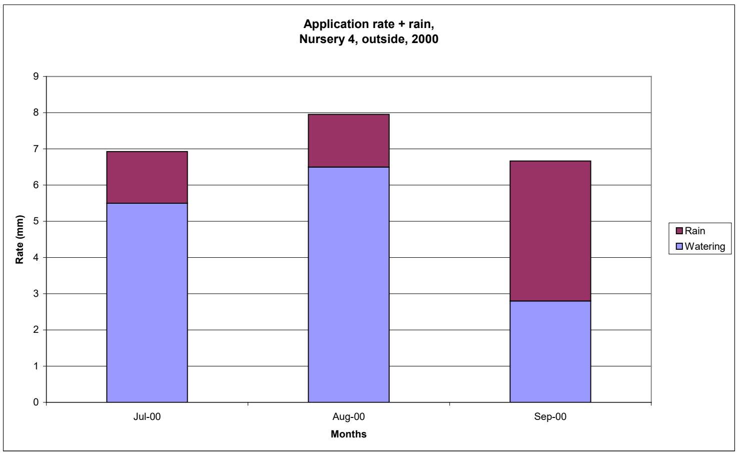
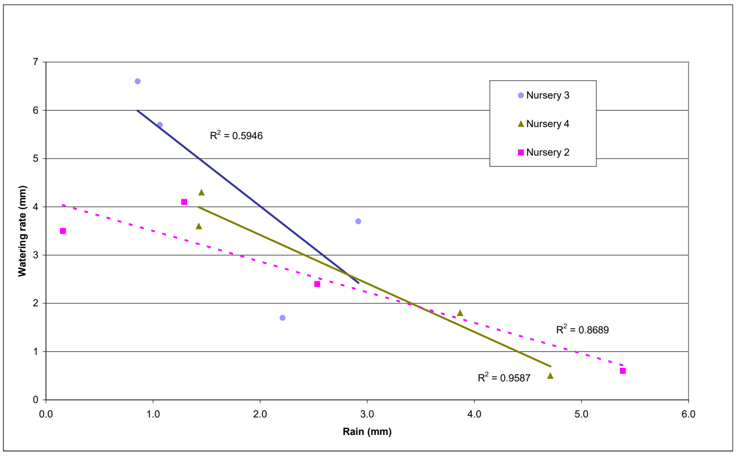


Figure 8.5 Water Application Rate for Outside Beds (Nursery 4)



Analysis was undertaken to determine if there are any strong relationships between the irrigation events and weather. For example, Figure 8.6 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 8.6 Correlation between Rainfall and Irrigation



CONCLUSIONS

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 data collection will continue from April and through the next growing season. The data collected will be used to both check and augment the data collected this year. To this end, the nurseries will be asked to ensure that:

Data is recorded at the end of each day;
A full crop record is kept; and
An unmodified watering strategy 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.

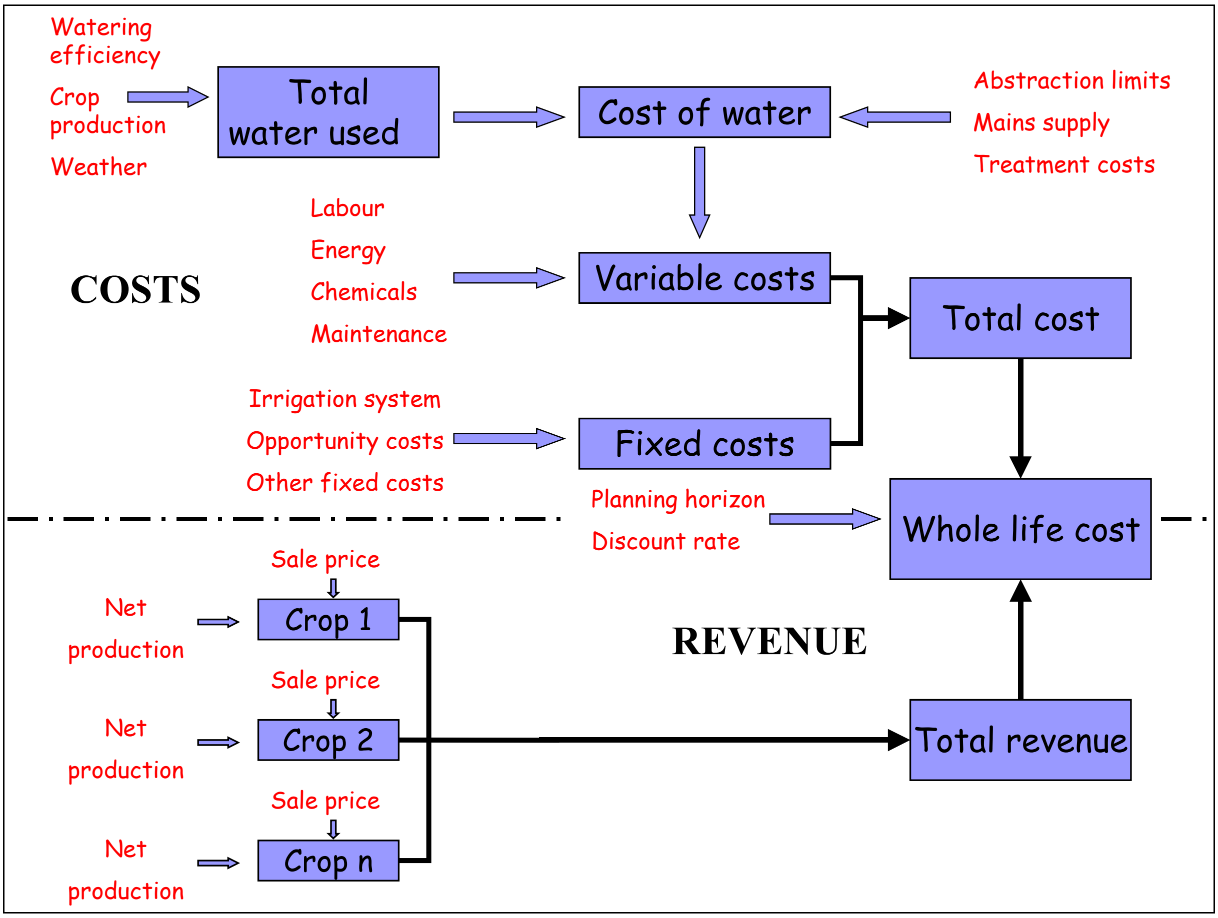
Model Development

The primary reason for collecting water-use data is to facilitate the development of an economic model of the irrigation system. Whilst this modelling work is not scheduled until later in the project, it was deemed prudent to carry out some initial work to clarify approaches and any potential problems.

The proposed model is based on a whole life costing approach where the cumulative net present value of the costs-revenues associated with implementing the irrigation system are calculated. These present values are then compared graphically to the baseline costs-revenues associated with the "do-nothing" option, over the planning horizon. Figure 8. gives a flow diagram of the proposed modelling approach.

It is anticipated that the data used to parameterise the improvements in irrigation will come primarily from experimental work carried out by other research partners. The coarse scale data collected at the nursery level will provide the baseline water-use data.

Figure 8.7 Flow Diagram of the Proposed Economic Model



Objective 4: Instrumentation

Instrumentation Specification

As previously agreed the specification for the instrument will not be progressed until requirements are known.

Patent Reviews

The review of patents and other information sources pertaining to innovations in irrigation scheduling and techniques is on-going, although there are no significant developments to report.