Project title:	**Hardy nursery stock:** **Optimising rooting media for leafy cuttings**
Project number	**HNS 98**
Project leader	**Dr R.S. Harrison-Murray**
Annual report	**September, 2001**
Previous reports	**February, 2001**
Key workers:	**Mrs J.M. Taylor** **Mrs W.B. Oakley**
Location of project:	**HRI-East Malling**
Project co-ordinator	**John Hedger, New Place Nurseries Ltd.,** **London Road, Pulborough, W. Sussex, RH20 1AT** **John Woodhead, Hilliers Nursery Ltd.,** **Ampfield House, Romsey, Hants, SO51 9PA**
Date project commenced:	**1 September, 1999**
Date completion due:	**31 August, 2002**
Key words:	**hardy nursery stock, rooting, propagation, media, aeration, drainage, rotting, environment, water balance, peat, perlite, tension, mist, fog, cuttings**

CONTENTS

PRACTICAL SECTION FOR GROWERS

This project is investigating the way that cuttings respond to conditions in the rooting medium. The objective is to provide guidelines to growers for the selection and management of rooting media and arrangements for their drainage.

Commercial benefits of the project

Progress in this project is expected to have the following commercial benefits:

- Reduced wastage: about 200 million HNS cuttings are taken every year and while failure rates vary from nursery to nursery and from crop to crop, it has been estimated to be at least 25% overall. Optimising the rooting environment could contribute to reducing this wastage.
- Cost savings: See cost benefit analysis below.
- Reduced management costs: by identifying media that are easier to manage, and that avoid the need for hard-to-manage drainage materials (e.g. sand base).
- Reduced need to import liners, that are often of uncertain quality, from abroad.
- Increased ability to respond to any future pressure to avoid the use of peat.

Background and objectives

The purpose of this project is to understand how the rooting medium contributes to successful rooting of cuttings so as to be able to recommend how growers should select and manage the medium for different types of cutting and different types of propagation environment.

Little is known about what constitutes a satisfactory rooting medium from the cuttings viewpoint, with most of the literature simply reporting comparisons of alternative media in a specific context.

It is not known how wet the medium can be before it starts to suppress rooting. Indeed, it is not known whether this depends on the volume of pores that remain filled with air, or the water content, or the tension with which the water is held. There is evidence that the response to the wetness of the medium varies depending on the transpiration demand of the cuttings.

Nurserymens' experience shows that the rooting medium, and the management of its water content, can have a profound influence on rooting failure rates. They modify their media in an attempt to reduce losses but useful basic principles and practical guidelines are lacking. This project addresses this need.

The move away from sand under propagating trays, towards cleaner and more hygienic surfaces such as concrete makes additional demands on the properties of the medium because such surfaces do not provide ‘positive’ (i.e., capillary) drainage.

Summary of results and conclusions

The main conclusions at the end of the second year of this project are as follows:

- Continuous wetting by mist or fog causes a small rise in water content of a rooting medium (and a corresponding decrease in air content) compared with the value expected from the water release curve
- The difference is small enough that water release curves can safely be used in a propagation context, to compare rooting media and make decisions about suitable drainage arrangements.
- Capillary drainage can have a major effect on the air content of rooting media, particularly those with a high proportion of peat.
- Capillary matting is much less effective than sand as a drainage medium
- Contact between the medium and the capillary substrate may be a bottleneck for drainage. This may account for the relatively weak drainage effect observed with capillary matting even when a 'tail' is used to increase tension. This requires further study.
- About 10 cm of fine sand increased rooting and decreased rotting of most subjects and in all media, particularly when combined with generous wetting.
- 3 cm of sand was sufficient to raise the air content of pure peat to above 10%, which is generally sufficient to keep a medium well aerated.

- Water tension and air content appear to have *independent* effects on the response of cuttings.
- The proportion of peat in the medium can influence rooting and rotting in a way that is unrelated to its effect on air/water relations, perhaps a chemical or biological effect. E.g., a high proportion of peat stimulated stem rotting of *Fremontodendron* cuttings
- The results suggest that the most reliable approach to managing the rooting medium is to ensure that wetting is enough to avoid water stress and then use an open-textured medium combined with a layer of sand to ensure sufficient tension and drainage.
- There was no consistent difference in rooting between Elle Pots, Plug-Its, and a conventional 50:50 peat:bark mixture. Oasis and rockwool gave significantly poorer rooting than the peat-based media but only with *Fremontodendron*.
- Severe rotting was often associated with environments in which cuttings suffered water stress. It is important that nurserymen do not assume that rotting always indicates that the medium is too wet.

Action points for growers

- **Capillary drainage** dramatically **increases the air content** of rooting media, especially in shallow trays.
- Where rooting results are disappointing, particularly if there is extensive rotting at the base of the stem, try testing whether capillary drainage improves matters.
- A large tray filled with sand, placed underneath the propagation tray, provides a simple means of doing a small-scale test.
- **Do not assume that rotting is necessarily a sign that the medium is too wet**. It can also be a sign that the evaporative demand of the aerial environment is too high. Try increasing **misting frequency** and consider whether **shading** could be increased.
- If adding a coarse material to peat to increase aeration, always add at least an equal volume of the coarse material (e.g. Perlite). **Below 50%, the coarse particles have very little effect.**

Anticipated practical and financial benefits

Cost benefit analysis

Estimate of number of cuttings which fail to make saleable liners

= 25% of 200M cuttings p.a.

= 50M cuttings p.a.

At an average price of £0.20, the value of this lost production

= 50M x 0.2 = £10M

Making the conservative estimate that improving rooting media could increase overall rooting percentage by 0.5%, that would be equivalent to reducing losses by 2% and the value of lost production saved

= 2% of £10M= £200K *per annum*

Total cost of the project is approximately £108K, therefore the ratio of ***annual*** **benefit** to total cost

= 200 / 108 = 1.9

SCIENCE SECTION

Introduction

Purpose

The purpose of this project is to understand how the rooting medium contributes to successful rooting of cuttings so as to be able to recommend how growers should select and manage the medium for different types of cutting and different types of propagation environment.

The research plan relates closely to a number of current industry trends that are likely to render the drainage characteristics of the medium more critical :

- Many growers want to achieve more supportive aerial environments, which usually involves generous wetting of the foliage and hence increased danger of overwet media.
- There is a move away from sand under propagating trays, towards cleaner and more hygienic surfaces such as concrete which do not provide ‘positive’ (i.e. capillary) drainage.
- With increased use of shallow modular rooting trays, the depth of rooting medium below the base of the cuttings has decreased. This decreases the water tension and increases compaction of the medium at the base of the cutting, both of which tend to decrease aeration.

A few basics

The basic requirements of the rooting medium are:

- to hold the cutting upright
- to supply water
- to supply O_2 (oxygen) and remove CO_2 (carbon dioxide)

Therefore, mechanical strength, **water content**, and **air content** are likely to be the important properties. This helps us focus on the properties that determine air and water contents:

- The total volume of pores accessible to air and water (i.e. excluding closed air pockets that exist in materials such as pumice and perlite), known as the total porosity.
- The proportion of pores that are filled with water.
- This in turn depends on the size of the pores: the larger the pore the smaller the force required to pull the water out of it (as in a glass capillary tube).
- The forces tending to draw water out of the medium. In a rooting medium, gravity is the main source of such force, and its size depends on the height of water-filled pores which are acting like a hanging water column or syphon.
- If the propagation tray is on a non-capillary substrate, such as a solid floor or coarse grit, then the water columns ends at the base of the tray
- If the tray is in intimate contact with a capillary substrate such as fine sand then the hanging water columns can be much extended and drainage thereby improved.
- Therefore, the ratio air and water in the pores depends partly on the nature of the medium and partly on the drainage regime.

A few complications

This simple model of the air/water relations of rooting media ignores a number of complicating factors. These are summarised diagrammatically in Figure 1.

Firstly, water uptake by the cutting. This represents an additional force removing water from the system and, since it alters conditions in the immediate vicinity of the cut base of the cutting, it is potentially of great importance. The extent to which local depletion of water content occurs depends partly on the rate of transpiration and thus on the aerial environment to which the cutting is exposed. However, it will also depend on the rate at which water moves in from the surrounding medium to replace what has been taken up which depends on the hydraulic conductance of the medium. The hydraulic conductance increases rapidly with increasing water content so that significant localised drying around the base of the cutting will not occur if the medium is very wet to start with. Work with an artificial cutting suggested that local drying in a pure peat medium does not start to become significant until the water content drops below about 70% (Thomas and Harrison-Murray, 1995). Therefore, it is unlikely to help maintain aeration of a medium that is too wet. Instead, it may add to the water stress sufferred by cuttings exposed to high evaporative demand (i.e. suboptimal aerial environment)

The second major complicating factor is the intermittent addition of water to the system in the form of mist or fog. This raises the water content above that predicted from laboratory deteminations of drainage characteristics (i.e.the water release curve) by an amount that is hard to predict. This is considered in more detail below (under Work in Year 2).

The most important area of uncertainty is how wet the medium can be before it starts to suppress rooting. Indeed, it is not known whether this depends on the volume of pores that remain filled with air, or the water content, or the tension with which the water is held. For a given medium, these three parameters are uniquely related and it is necessary to compare markedly different media to attempt to study their separate effects. One of the aims of the project is to attempt to achieve this separation but success cannot be guaranteed.

Despite such complexities, nurserymen have no doubt that the rooting medium, and the management of its water content, can have a profound influence on rooting failure rates. As a result they modify their media in an attempt to reduce losses. However, most recognise that there is little rationale behind these adjustments because useful basic principles and practical guidelines are lacking. This project addresses these needs.

To be in a position to offer robust guidance to practical nurserymen it is essential that we obtain a clearer understanding of the many complicating factors that are summarised in Figure 1. This requires an emphasis on the interactions between different parts of the system, which is central to this project.

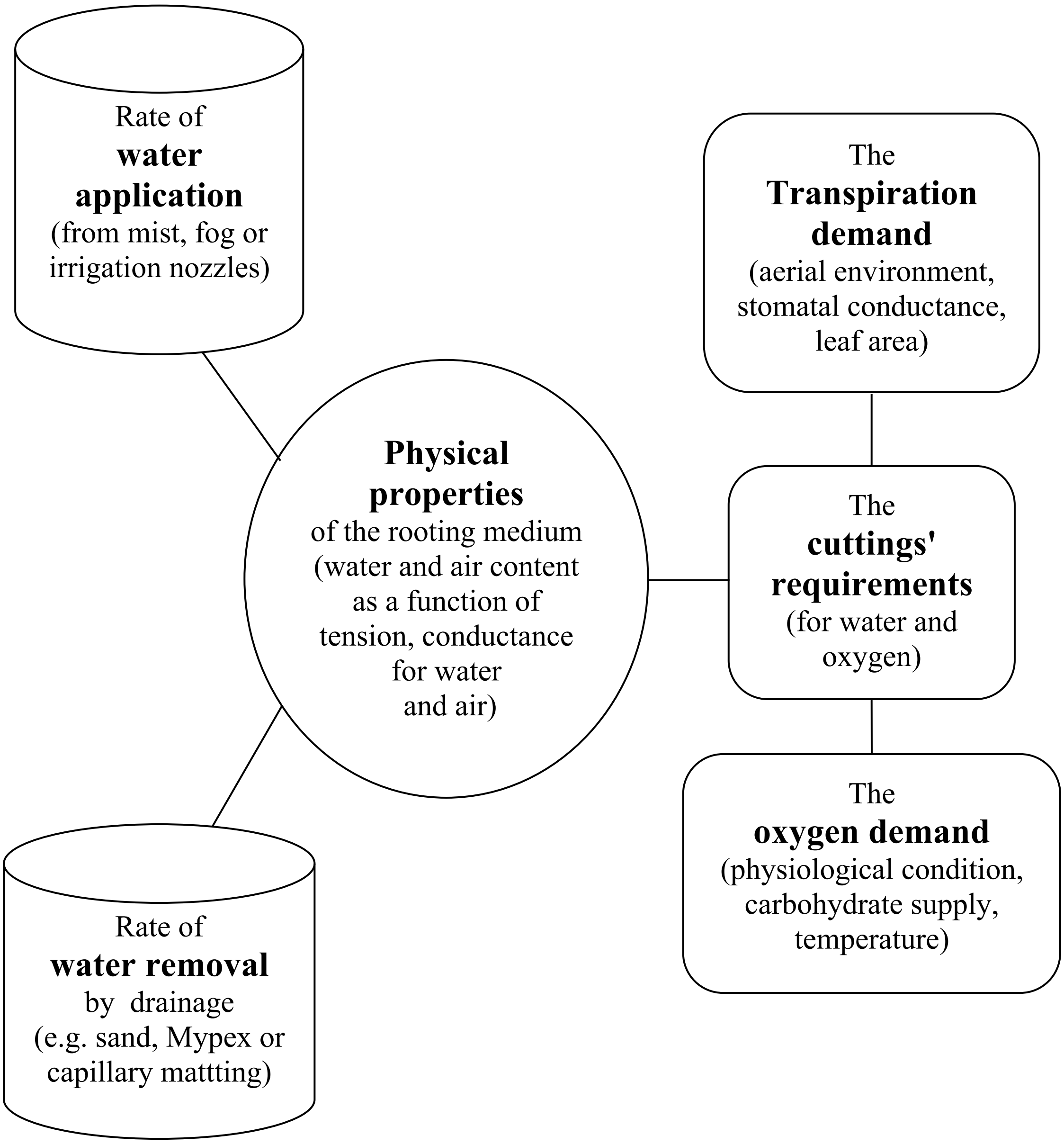


Figure 1. Model of the ways in which the influence of the physical properties of the rooting medium are likely to be affected by other aspects of the propagation environment and by physiological differences between cuttings (between cultivars, stockplants, time of year, etc.)

Work in Year 2

Dynamics of wetting and drainage

Water release curves, such as those reported in the first annual report for this project, provide an objective comparison of the drainage characteristics of different media. They provide a means to predict the water content of a particular rooting medium from the suction provided by the substrate on which it is standing. The assumption is made that sufficient water is being applied in the form of mist, fog, etc. to exceed that lost by evaporation and transpiration (i.e. uptake by the cuttings). This is likely to be the case in most propagation systems.

However, in the determination of water release curves, time is allowed for water to drain out until an equilibrium is achieved between the applied suction (e.g. from a hanging water column) and the capillary forces holding water in the medium. At this point, no further drainage occurs and the system is said to be at 'static equilibrium'. This provides a convenient practical end point for the determination.

However, static equilibrium will rarely, if ever, be reached in a propagation system because additional water is being applied frequently as mist, fog, or from a lance. The medium is therefore likely to be wetter than predicted by the water release curve, but how much wetter? The answer depends on how much the water content needs to rise to result in a rate of drainage equal to the rate of water application. The system is then at 'dynamic equilibrium'. The problem is analogous to that of water running into a bath with the plug out: the level of water will rise until the rate of outflow through the drain exactly balances the rate of inflow through the taps. As in the bath analogy, the system is likely to be sensitive to the characteristics of the drainage system as well as the nature of the rooting medium itself.

Experiment 1 explored the effect of differing rates of water application and different drainage arrangements on the water and air contents of two contrasting rooting media.

Influence of evaporative demand on the optimal air and water contents of the rooting medium

An important purpose of the water release curve studies initiated in year 1 was to identify contrasting media suitable to attempt to measure the separate effects of air content, water content and tension. It had been hoped that different grades of sand and gravel would provide the required range of water release characteristics whilst being chemically identical. However, over the very narrow range of tensions that are of practical relevance in propagation, suitable sands could not be identified. Instead, we opted to work with mixtures of peat and vermiculite These have the required drainage properties but are less physically stable and are not chemically identical. It was decided that this disadvantage was more than outweighed by their much greater commercial relevance as media for practical propagation.

Vermiculite was chosen in preference to the more widely used perlite for technical reasons. It was found that water penentration into the granules of perlite continues over many weeks, whereas with vermiculite, water penetration is complete within a few days. The effect of the slow penetration of water is that total porosity is not fixed but increases gradually. This has no effect on the behaviour of perlite as a rooting medium because it involves seepage of water into virtually closed cells within the structure of the perlite granule which do not contribute to transport of air or water. However, it makes precise quantification of the air filled porosity much more time-consuming. The water release curves of peat:perlite mixtures are very similar to those of peat:vermiculite (Harrison-Murray et al., 2001), so that conclusions from experiments with peat:vermiculite mixes are likely to be applicable to peat:perlite mixtures.

By varying the suction applied to the different peat:vermiculite mixes, it is possible to reduce the correlation between tension and air/water content to determine whether cuttings respond primarily to tension or to air content.

Superimposed on this set of media conditions, evaporative demand of the aerial environment was varied to explore the interaction between the two parts of the cutting's environment. The first experiment in this series used a specialised controlled environment facility know as the ‘Gradient Controlled Propagation Environment’ (G-

CPE) to impose the variation in evaporative demand. Space in the G-CPE proved to be a severe constraint for this type of work and current experiments are using the wetting gradient in large fog house to achieve the same thing.

Rooting media trials

In addition to the carefully structured experiments referred to above, this report includes the results of further experiments comparing rooting in a variety of rooting media and preformed plugs.

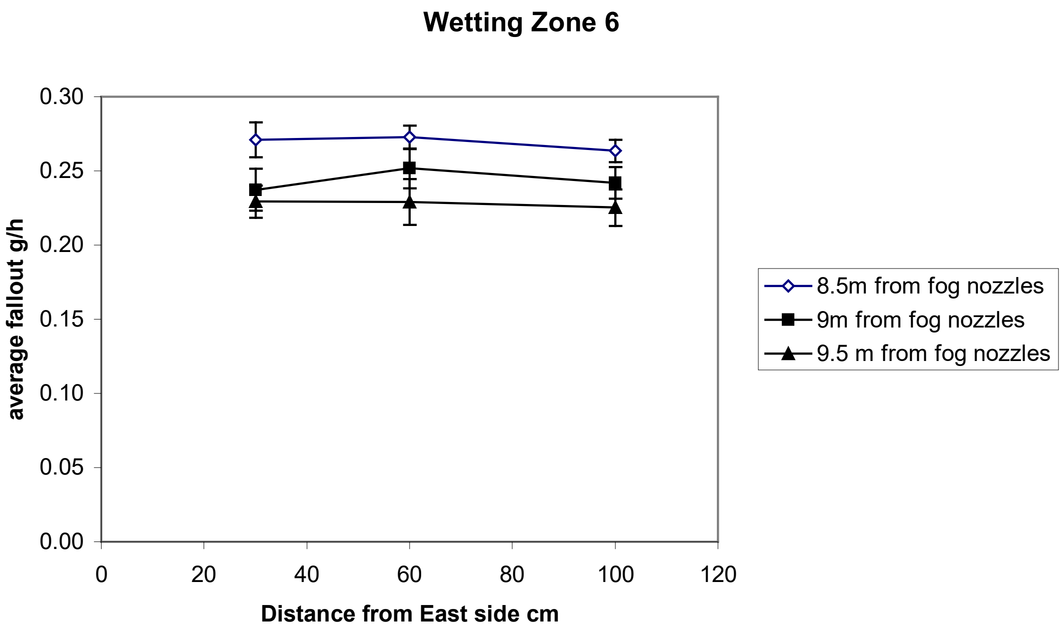
Materials and Methods

Experiment 1. Effects of continuous water deposition on air/water relations of rooting media and its interaction with capillary drainage

Water application rates

Contrasting rates of water application were obtained using the G-CPE facility which has been described in detail elsewhere (Harrison-Murray et al., 1998). In normal use it creates two environmental gradients, a light gradient and a wetting gradient, perpendicular to each other. For the present purpose, only the wetting gradient was relevant and, to achieve sufficiently large areas of uniform wetting intensity, it was necessary to decrease the steepness of the wetting gradient. This was achieved by turning off the high pressure sodium illumination. In the absence of the lights, the proportion of the fog droplets which evaporated before they settled out on the ground was reduced, so that the decline in wetting with distance from the nozzles was also reduced. The artificial lighting is an essential component of the system for 'environmental fingerprinting' of cuttings but was not needed in this case because no cuttings were involved. A further benefit was that the absence of the warming effect of the lights also minimised evaporative loss of water from the media samples so that their water content depended only on the balance between water deposition onto the upper surface and drainage from below.

Further variation in the rate of water application was achieved by varying the proportion of each 100 s for which the fog nozzles were operating (e.g. 40s on / 60s off to achieve 40% of maximum output). The data in Figure 2 show that this made it possible to compare water application rates of 43 μm/hour and 267 μm/hour (=1 mm/day and 6 mm/day, which is equivalent to light versus heavy misting)


Wetting Zone 6

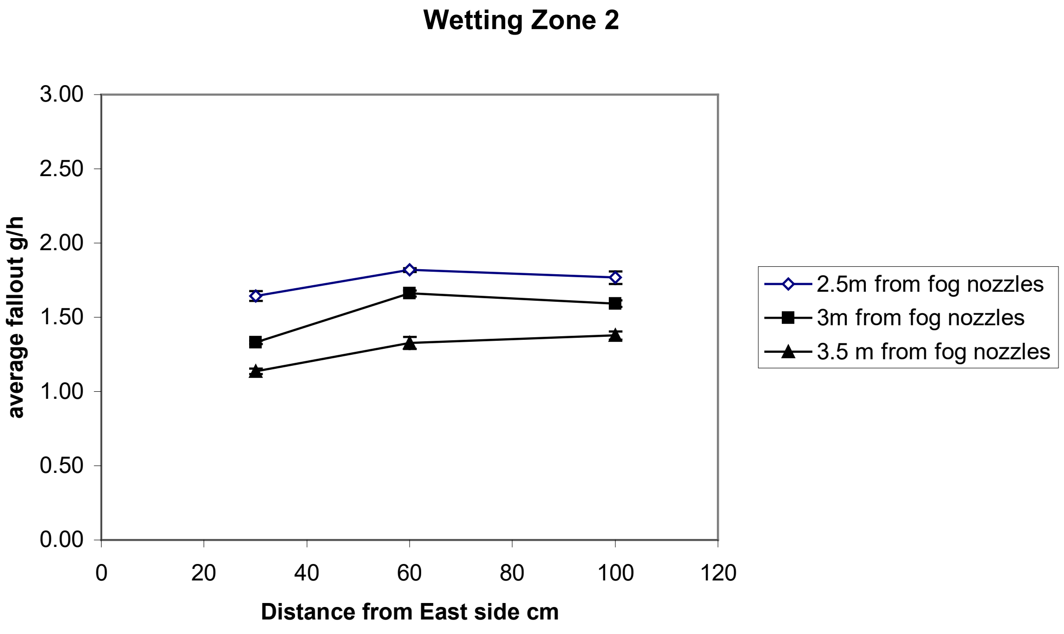

Wetting Zone 2

Figure 2. Variation in water deposition within the two zones used for Experiment 1. Notice the 10-fold difference in scale on the Y-axis of the two graphs. The mean rates of water deposition (into a 9cm petri dish) were 1.52 g/h in zone 2 and 0.25 g/h in zone 6, equivalent to 267 µm/h and 43 µm/h respectively. This difference was in part due to reducing the fogging nozzle duty to 40% of maximum when zone 6 was in use.

Media

1. Peat (Shamrock sphagnum peat, medium grade) (abbreviated **P**)
2. 50:50 Peat:Vermiculite (Shamrock medium grade: Pro Gro medium grade) (abbreviated **PV**)

Preparation of media samples

Sample holders were made from 70 mm square plastic pots (Thovadec 0.3 L square pots) which have four drainage holes, 5 mm in diameter cut down to a height of 5 cm. Samples were packed into these holders to a depth of about 20 mm, the actual depth achieved being determined with callipers at the end of the water release curve process. The quantity of material in a sample was set by filling a 50ml glass Pyrex beaker to the lip and settled by tapping the base on a solid surface. The sample was then tipped into a sample holder, levelled by tapping the sides, and firmed gently using the base of another pot. At this stage the material was slightly moist, as sold.

Twenty samples of each medium were prepared as described. They were then wetted up thoroughly in a way that avoided the disruption of structure that occurred if they were flooded (floating, slumping and separation of the components of the peat:vermiculite mix). This was achieved by placing them in the G-CPE, very close (50-100 cm) to the fog nozzles, for seven days. We believe that this simulates the wetting up that would occur in a generously misted commercial propagation unit. During this period the samples were placed in a rigid plastic tray, with drainage holes (i.e. without capillary drainage). This proceedure was very similar to that used to prepare samples for water release curve determination (1st Annual Report). It allows time for water to penetrate the majority of accessible micropores within the peat fibres and vermiculite granules so that particle density and total porosity stabilise.

Drainage regimes

1. Fine sand, 12 cm layer, over a concrete floor
2. Fine sand, 3 cm layer, in a seed tray on a double layer of coarse nylon mesh (Netlon)

3. Capillary matting, over the base of an inverted seed tray with a 3 cm hanging tail hanging over the edge of the tray to apply a tension of 3 cm of water
4. Capillary matting, as above but without the tail so that any tension applied depends on the thickness of the material
5. Solid surface – the base of a rigid plastic tray with drainage holes

Procedure

- For each wetting zone, three replicate samples were allocated randomly to each of the five drainage regimes
- Samples were carried singly from the G-CPE to a precision balance for weighing. A petri dish was held below the sample holder to collect any water draining out during the transfer. This occurred mainly when samples were first moved from the holding zone at the start of the experiment (~0.4 g of drainage water collected).
- The weight of the sample and any collected drainage was recorded.
- The sample was placed on the designated drainage regime, pressing sample holders down firmly to try to establish contact between the medium and the capillary substrates.
- To monitor progress towards a new dynamic equilibrium water content, samples were removed weighed and replaced after approximately 1, 6, and 24 h.
- After 24 h the fog was switched off
- Samples were removed for a final weighing after a further 24 h without wetting, this provided an estimate of the water content at static equilibrium.
- Samples were returned to the holding area
- The whole process was repeated a number of times
- The depth of each sample was measured carefully with a micrometer and, from the mean of 3 measurements, the volume of the sample was calculated.
- Samples were oven dried at 80 °C for at least 48h and then weighed.

Water deposition measurements

Water deposition was measured on 3 occassions and the average calculated. Water was collected in transparent plastic petri dishes, 9cm diameter, placed on special stands and weighed on a precision balance (to 0.001 g).

Estimating air content

Air content was estimated from the difference between total porosity and the measured water content (=water-filled porosity). Total porosity was estimated from the measured bulk density and the particle density of the same media determined previously, using the following formula

$$TP = 100\,(1 - BD/PD)$$

where TP = total porosity, %

PD = particle density, kg m^{-3}

BD = dry bulk density, kg m^{-3}

Experiment 2. Influence of evaporative demand on the response of *Fremontodendron* cuttings to the air/water status of the medium.

Media

These were mixtures of peat (Shamrock sphagnum peat, medium grade) and vermiculite (Pro Gro medium grade) as follows:

1. 30:70 Peat:Vermiculite
2. 50:50 Peat:Vermiculite
3. 70:30 Peat:Vermiculite

Drainage

+	12 cm deep bed of fine sand over a concrete floor
-	A double layer of coarse nylon mesh (Netlon) beneath the trays to create a capillary break from the sand bed beneath

Evaporative demand

Trays were placed in the G-CPE in either the high (identified as L1) or moderate light (L4) zones to create substantially different evaporative demand. Average light levels were ca. 200 and 80 μmol m^{-2} s^{-1} PAR in L1 and L4 respectively)

Additionally, the experiment was repeated in two different wetting zones (W1, where water deposition is ca. 400 μm h^{-1}, and W5 where wetting is barely detectable)

Plant material

Fremontodendron 'California Glory' single node cuttings, treated with 1.25 g L^{-1} of IBA in a 50:50 (v/v) mixture of acetone and purified water. Cuttings from two groups of stockplants were mixed within each plot.

Experimental design

The media were packed into the cells of a 60 cell propagation tray (of the type supplied with Elle pots) in plots consisting of a single row of 10 cells. Within a block of three such plots, the position of the media was allocated at random. Drainage treatments were applied at the whole tray level, their positions within wetting and light zones being randomised.

In summary, it was a multifactorial design as follows:

3 media x 2 drainage regimes x 2 light levels x 2 wetting levels
x 2 blocks x 10 cuttings

Non-destructive measurements

To monitor differences in the water balance of cuttings between treatment combinations, two cuttings per plot were tagged and weighed at intervals over the first 10 days of the experiment (i.e. before roots emergence). These measurements were confined to media 1 and 3 and light zone L1.

Rooting media trials

The rooting media

In all the trials reported here, the media were as follows:

- Bulrush Plug-Its
- Elle Pots
- Grodan Rockwool cubes (SBS 36/77)
- Agrimedia Oasis rootcube cylinders (35mm diameter x 35mm deep)
- fine peat:fine bark mix (50:50 mix of fine grade Shamrock Irish sphagnum peat and fine grade Cambark). This is our standard propagation medium as used in previous HDC projects such as HNS 55.

Each was tested with and without contact with a bed of fine sand to provide capillary drainage.

There were 24 replicate cuttings per treatment combination in four plots of six cuttings. Plots were arranged in four completely randomised blocks.

A plot consisted of a row of six cuttings across a 6 x 10 cell tray. The trays used were of the type supplied with Elle Pots and Bulrush Plug-Its, so that the Rockwool cubes and Oasis cylinders did not fit as snugly as in the trays supplied for them.

Trial 1 - *Convolvulus cneorum*

Material was collected on 28 June, 2000, from well established field grown plants

Apical cuttings, 10-12 cm long, were dipped for 5 s, to a depth of about 8 mm, in a solution of 1.25 g L^{-1} of IBA in a 50:50 (v/v) mixture of acetone and water.

Cuttings were placed in open mist or in a relatively dry part of the 'Agritech' ventilated fog house. Both systems were evaporimeter controlled.

Rooting was recorded 10 August (i.e. after 6 weeks).

Trial 2 – *Fremontodendron* 'Pacific Sunset'

Material was collected on 6 July, 2000 from stockplants in an unheated glasshouse. Cuttings were a mixture of single node and apical cuttings (in the ratio of 3:1) and all were treated with 1.0 g L^{-1} IBA in a 50:50 (v/v) mixture of acetone and water.

Cuttings were placed in two contrasting zones of the G-CPE, wetting zones W1 and W5. Replicate blocks were arranged along the light gradient (light zone L1 to L6).

Rooting was recorded on 3 August (i.e. after 4 weeks)

Trial 3 – *Garrya elliptica* 'James Roof'

Soft material was collected on 1 August, 2000 from well established hedges in the field. This was a hot day and cuttings were already wilting on the hedge before collection.
Apical cuttings were prepared and treated with 1.7 g L^{-1} IBA in a 50:50 (v/v) mixture of acetone and water.

Cuttings were placed in two contrasting zones of the G-CPE, wetting zones W1 and W3 (this being the driest zone where any rooting of Garrya would be expected). Replicate blocks were arranged along the light gradient (light zone L1 to L6).

Rooting was recorded on 7 September (i.e. after 5 weeks)

Trial 4 – *Fremontodendron* 'Pacific Sunset'

Following the disappointingly low rooting percentages achieved in Trial 2, compared with our experience in previous years (see for example Harrison-Murray et al., 1998) another trial was conducted incorporating two additional factors to try to identify the cause of the poor rooting. On 16 August, stockplants growing in a unheated twin-span polythene house were flowering profusely. Flowers were removed from half of them and cuttings were collected three weeks later, on 6 September, 2000.

Cuttings were a mixture of equal numbers of single node and apical cuttings and all were treated with 1.0 g L^{-1} IBA in a 50:50 (v/v) mixture of acetone and water.

Cuttings were then divided between a relatively dry zone in the 'Agritech' ventilated fog house and wetting zone W3 of the G-CPE, to test whether the poor rooting in Trial 2 might indicate an adverse effect of the artificial lighting in the G-CPE on this cultivar.

Rooting was recorded on 16 October (i.e. after 7 weeks)

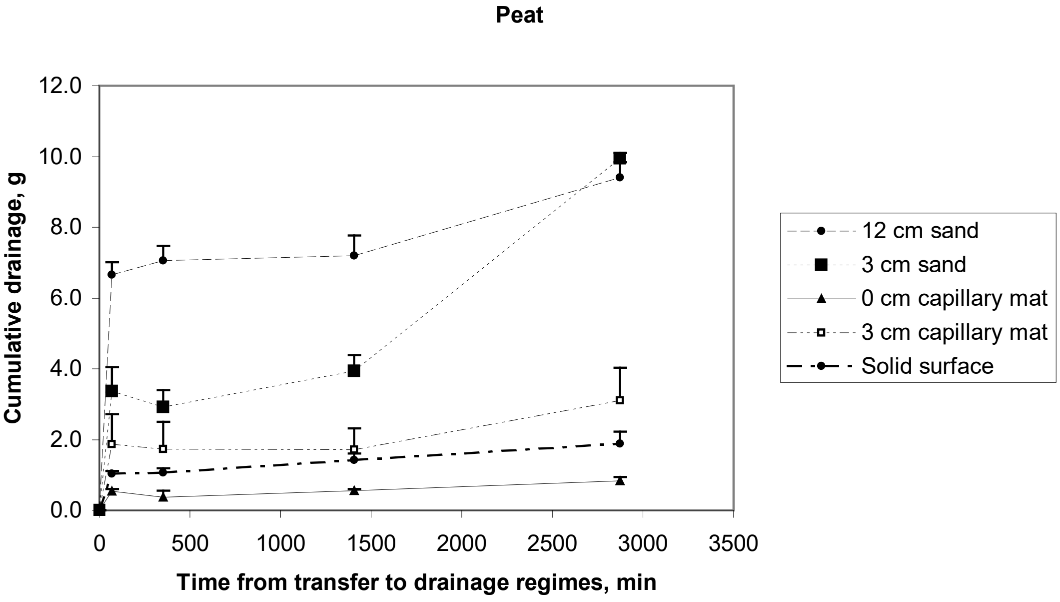
Results and Discussion

Experiment 1. Effects of continuous water deposition on air/water relations of rooting media and its interaction with capillary drainage

The graphs in Figure 3 and 4 show the change in weight of the media samples following transfer from trays in the heavily wetted 'holding zone' to the five different drainage regimes. It is clear that the effect of drainage provided by a sand bed is very rapid, most of the change being complete within the first 60 minutes. With a shallow layer of sand (3 cm) equilibration was slightly less rapid, especially in the less heavily wetted zone (Figure 4). In comparison with sand, capillary matting was much less effective at draining the medium. Even with a 3 cm tail of material hanging below the surface to generate additional tension, the drainage was barely detectable compared to the non-capillary control treatment (i.e. the 'solid surface'), and much less than the same depth of sand.

The irregularities in the curves in Figures 3 and 4 (e.g. the *increase* in weight of peat:vermiculite samples over the third interval under heavy wetting) suggest that the action of removing the samples to weigh them disturbed the drainage process, despite care being taken to push the samples firmly onto the drainage bed after weighing. This in turn suggests that contact between the medium and the substrate may be a critical bottleneck. Relatively poor contact with the capillary matting compared with sand may explain why sand was clearly a more effective drainage medium.

Despite a 6-fold difference in water application rates between the two wetting zones, the difference in the change of weight observed in the two zones was much smaller than the differences between the drainage regimes. The size of the changes in weight of individual samples would be sensitive to any differences in water content at the start of the experiment due to variation in conditions within the holding area. This potential error is eliminated in Figure 5 which shows the absolute air content of the samples once dynamic equilibrium had been achieved (i.e. after ca. 1400 minutes). This figure similarly indicates very little difference in air content at dynamic equilibrium associated with the large difference in rate of wetting. In contrast, the substantial benefit of increased air content achieved by as little as 3 cm of sand is very clear, irrespective of the rate of water deposition.



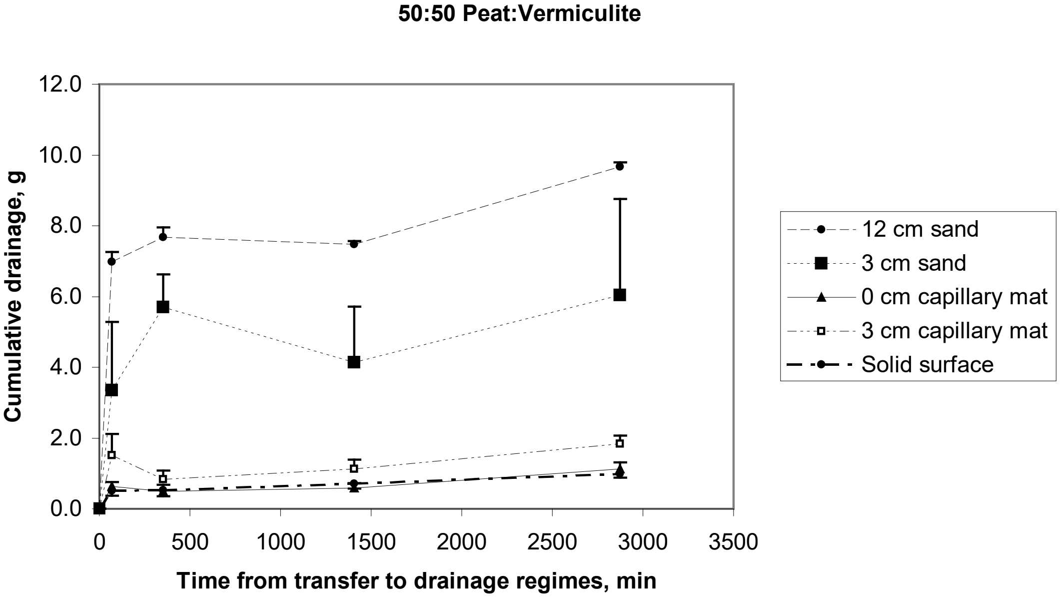
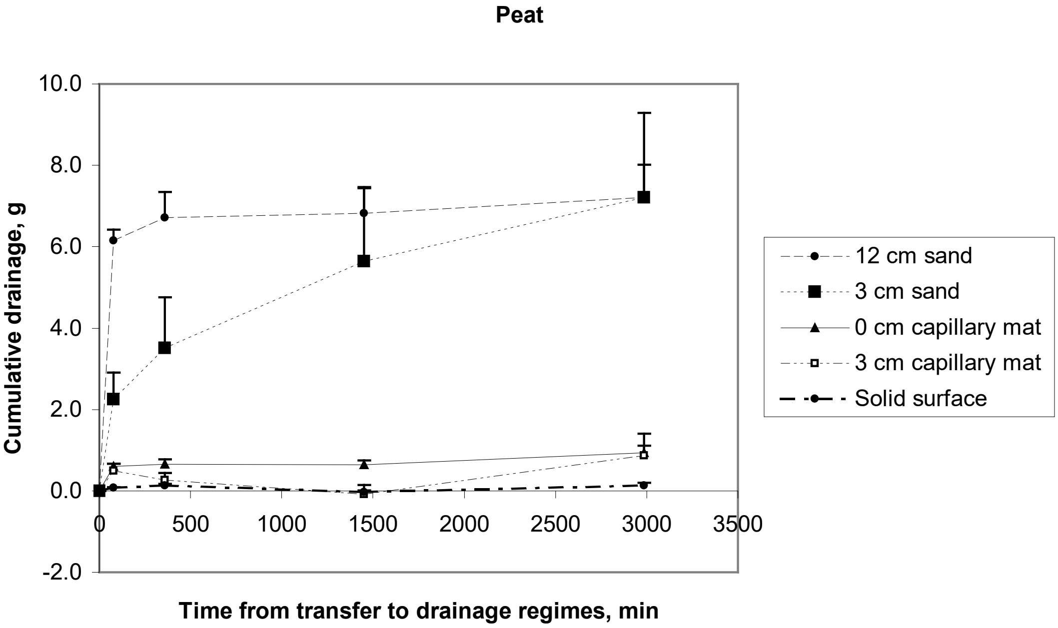


Figure 3. Time course of drainage (i.e. reduction in weight) of media placed on various different surfaces under **heavy** water deposition (267 µm h^{-1}). Prior to the start, the samples were held under even heavier wetting (>400 µm h^{-1}) on a solid surface (i.e. without capillary drainage). The 'solid surface' line shows the net drainage attributable to the decrease in water deposition without any change in drainage regime. After 1400 minutes, the fog was switched off and water deposition rapidly dropped to zero. Vertical bars represent one SE.



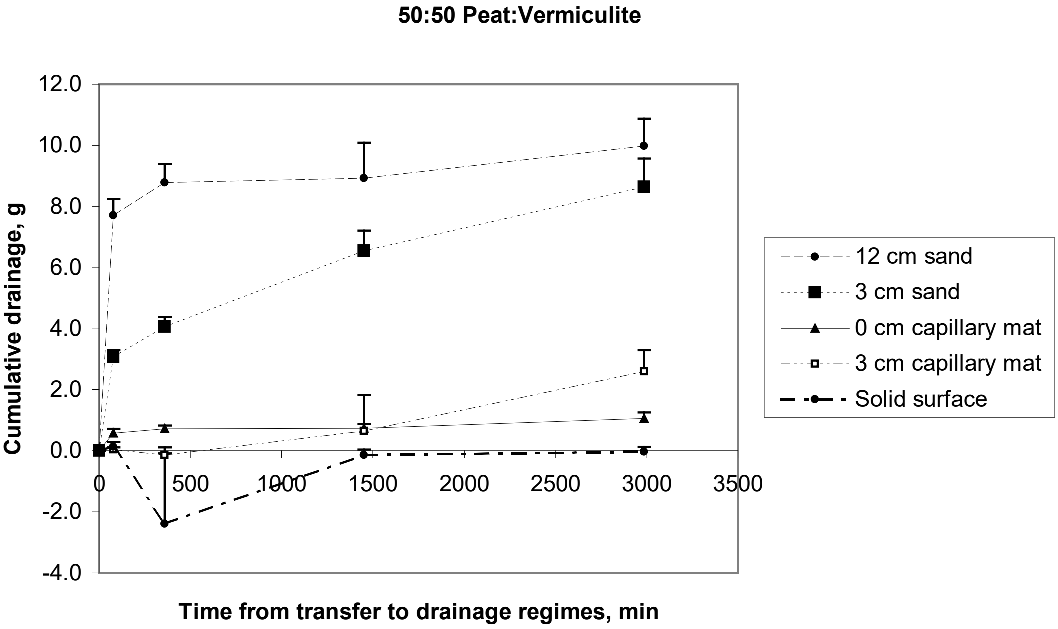
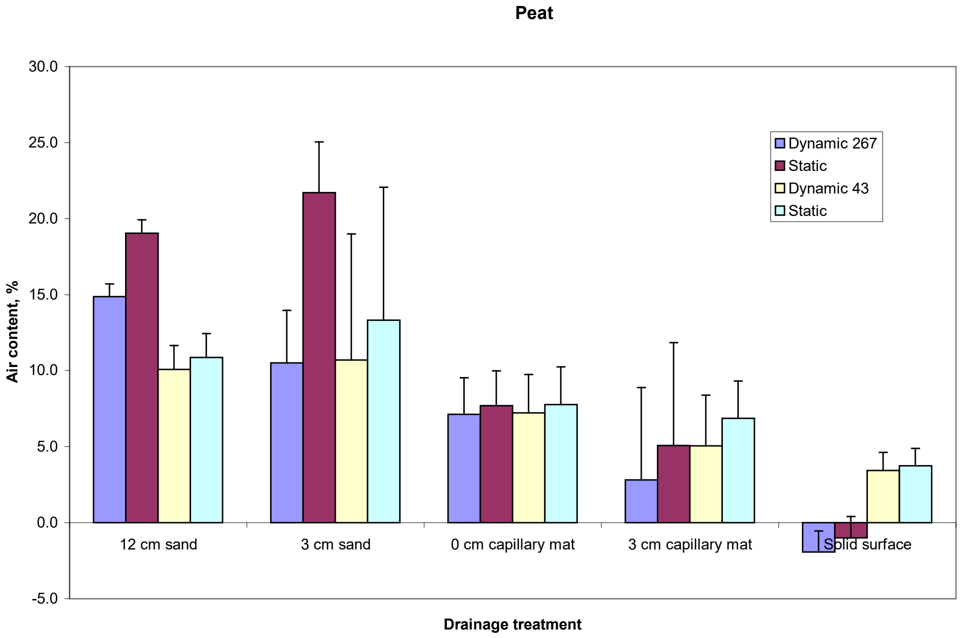


Figure 4. Time course of drainage (i.e. reduction in weight) of media placed on various different surfaces under **light** water deposition (mean of 43 µm h^{-1}). Prior to the start, the samples were held under even heavier wetting (>400 µm h^{-1}) on a solid surface (i.e. without capillary drainage). The 'solid surface' line shows the net drainage attributable to the decrease in water deposition without any change in drainage regime. After 1450 minutes, the fog was switched off and water deposition rapidly dropped to zero. Vertical bars represent one SE.



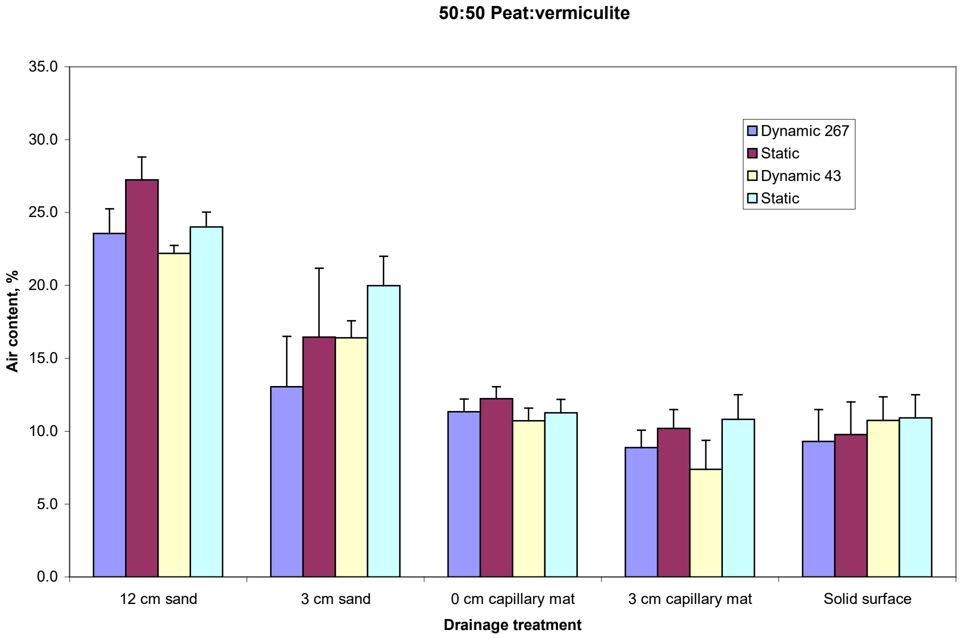


Figure 5. Air content of samples whose water content had reached dynamic equilibrium with a water deposition of 267 or 43 µm h-1 (‘dynamic 267’ and ‘dynamic 43’ respectively) under various drainage regimes. Also shown are the values of air content observed 24 h after water application ceased, when the water content was expected to have reached static equilibrium (‘static’).

Experiment 2. Influence of evaporative demand on the response of *Fremontodendron* cuttings to the air/water status of the medium.

The data in Table 1 summarise the air/water relations created by the combination of media and drainage regimes used in Experiment 2. The coarse textured mixture with 70% vermiculite drains at lower suctions so that its air content without capillary drainage is similar to that achieved in the more fine textured 70:30 peat:vermiculite mixture with capillary drainage (10 cm of sand) (9.3 and 11.3 % respectively). Overall, the combination of media and drainage regimes creates a very wide range of air contents (1.7 to 21.9%) as well as providing the basis to determine whether cuttings can respond directly to the applied tension.

Table 1. Water and air contents of the peat:vermiculite mixes used in Experiment 2, based on water release curve data.

	Water, % v/v		Air % v/v	
	- drainage	+ drainage	-drainage	+ drainage
30:70 Peat:Vermiculite	83.0	70.4	9.3	21.9
50:50 Peat:Vermiculite	82.6	71.9	8.8	19.6
70:30 Peat:Vermiculite	89.0	79.4	1.7	11.3

Rooting

Figures 6 and 7 summarise the results for rooting of the *Fremontodendron* cuttings. Overall, rooting was poor and was suppressed more by the dry conditions in W5 than by the heavy wetting of W1. This is the opposite of what we had expected from previous experience (Harrison-Murray et al. 1998). Other attempts to root cuttings from the same source suggests that a change in the stock plants is responsible. Interestingly, much higher rooting percentage (85%) with much less rotting (2%) was recorded in a set of 40 cuttings placed in the Agritech ventilated fog house (in 50:50 peat:vermiculite). This suggests an adverse reaction to the unnatural conditions of the G-CPE which did not occur in earlier experiments with the same subject.

There is litte doubt that the reduced rooting in W5 was due to water stress since cuttings wilted, particularly in the high light zone. That rooting was lowest in the high peat mix, even under conditions of high evaporative demand, suggests that its relatively high water content did not substantially improve water supply. In fact, in the dry conditions of W5, rooting was greatest in the high vermiculite mix (Figure 7), perhaps because it minimised the spread of basal rotting initiated by the water stress.

Capillary drainage had no effect in W5 but favoured rooting under the heavy water deposition of W1. Best rooting was achieved by the combination of 30:70 peat:vermiculite with capillary drainage, this being the combination with the highest predicted air content (Table 1). The high rooting in the 50:50 mix without drainage (Figure 7) runs counter to any explanation of the results in terms of either air content or tension. However, it was not statistically significant and, in an experiment with so many treatment combinations, isolated anomalous results are common.

Basal stem rotting

A high proportion of cuttings suffered some basal rotting in all environments (Figures 8 and 9). This is not unexpected since the propensity of *Fremontodendron* to basal rotting was the main reason for chosing it as an experimental subject. The frequency of rotting was greater in drier conditions of W5 than the heavily wetted W1, indicating that water stress predisposed cuttings to rot. In W1, the frequency of rotting clearly increased with increasing peat content in the medium but there was no effect of capillary drainage (Figure 9) suggesting that this is a direct effect of presence of peat in the medium (e.g. a chemical or biological influence) rather than its influence on air content.

Evidence for separate effects of water tension and air content

Considering the length of stem affected by basal rotting (Figures 10 and 11), a slightly different picture emerges. In W1, drainage had a clear benefit which was largely independent of the nature of the medium (Figure 11). This result is consistent with a direct response to water tension with little or no effect of air content. For example, the average rotted length in the high peat mix with drainage was 5.6 mm compared with 11.9 mm in the low peat mix without drainage, despite very similar air contents.

In the drier W5 location, the extent of rotting increased with increasing peat content in the medium, with little effect from drainage (Figure 11). This again suggests a direct effect of the presence of peat in favour of the development of rots in cuttings which are predisposed to it by some stress factor, in this case water stress.

Water balance of cuttings

Changes in the fresh weight of cuttings showed that cuttings in W1 increased in weight while those in W5 decreased in weight progressively over the rooting period (Figure 12). In W1, the increase was initially greater in the absence of capillary drainage. This may well reflect excessive uptake of water that could have predisposed to the greater basal rotting later observed in the same cuttings.

After cuttings had been removed and rooting recorded, subsamples of media were removed from the propagation trays, weighed and then oven dried to determine their water content and bulk density. Despite some loss of water during the assessment of cuttings, the results (Figure 13) were broadly consistent with predictions from the water release curves. For example, the substantial effect of capillary drainage is clearly evident.

Conclusions

Overall, the results emphasise the complexity of the interactions involved in responses to rooting media. They also suggest that cuttings may be sensitive to more than one compenent of water status (i.e. to water tension and air content) as well as responding to the presence of peat independent of its effect on water release characteristics. Effects on the activity of fungi and bacteria, as well as chemical and pH effects, could provide a mechanism to explain such effects.

In practical terms, the results suggest that generous wetting of cuttings to avoid water stress, combined with capillary drainage and an open textured medium, is the approach to follow to achieve reliably high success rates with *Fremontodendron.* Since water stress adversely affects rooting in such a wide range of subjects, this is an approach that is likely to apply widely.

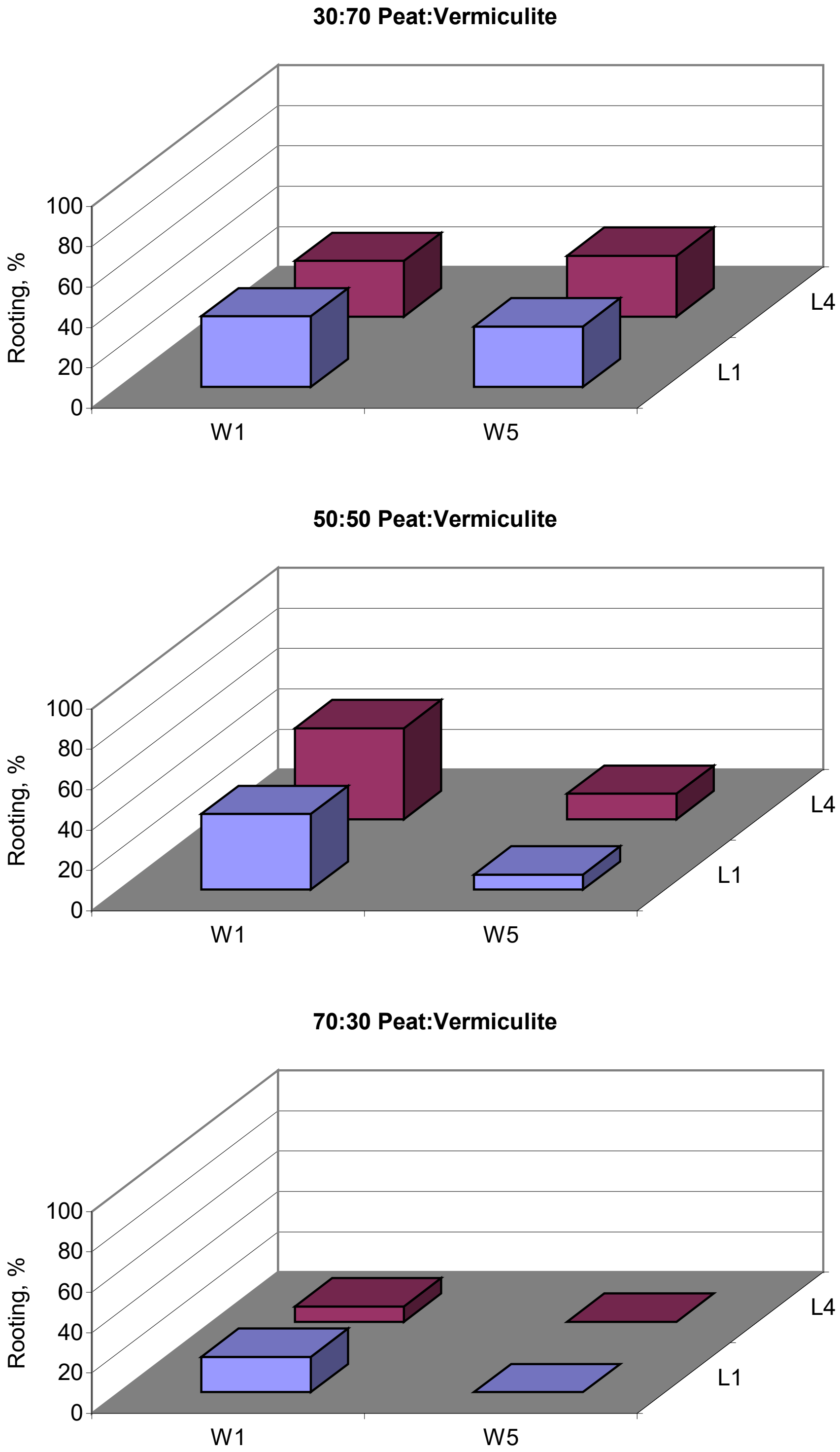


Figure 6. Rooting percentage of *Fremontodendron* 'California Glory' cuttings. Interacting effects of medium, wetting and light. [L1 = high light, L4 = low light; W1 = heavy wetting, W5 = light wetting. The effects of medium and wetting were significant (P<0.001). Neither the effect of light nor any interactions were significant.]

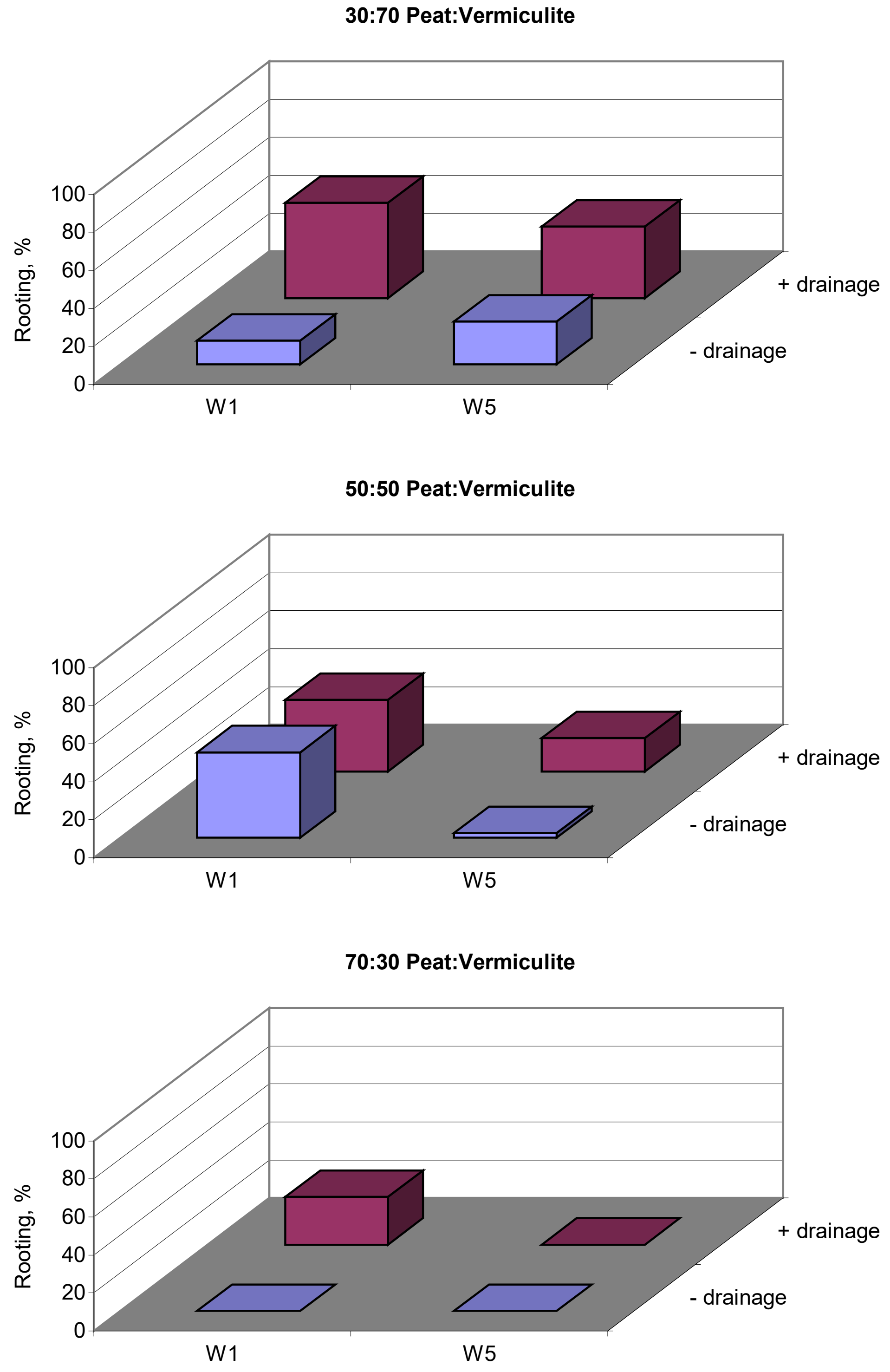


Figure 7. Rooting percentage of *Fremontodendron* 'California Glory' cuttings. Interacting effects of medium, wetting and drainage. [W1 = heavy wetting, W5 = light wetting. Soil water tension at the base of the cutting would have been appoximately 2 cm of water in the '-'and 12 cm in the '+' drainage treatments. The effects of medium, wetting and drainage were significant (P<0.001) but their interaction was not.]

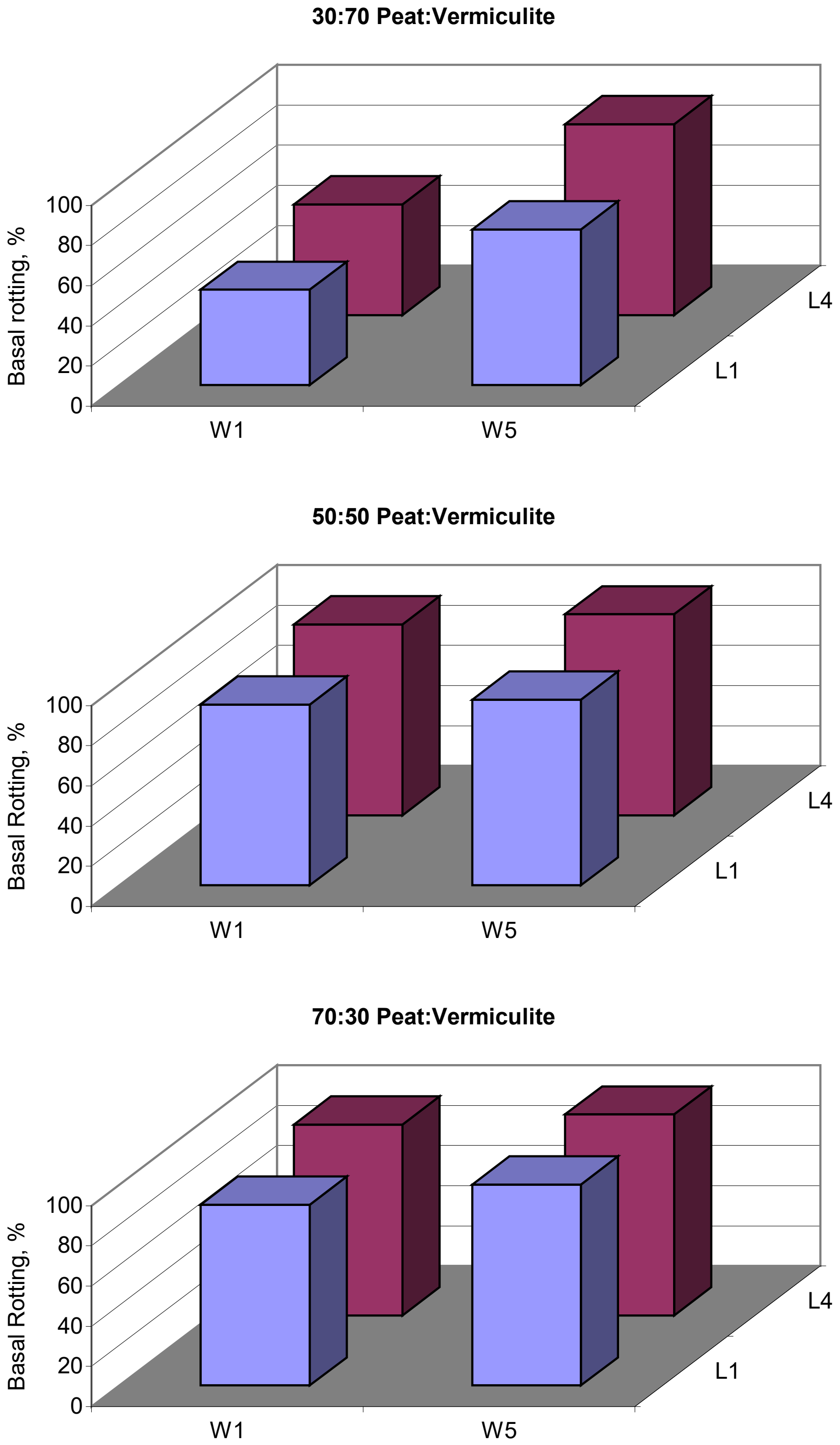
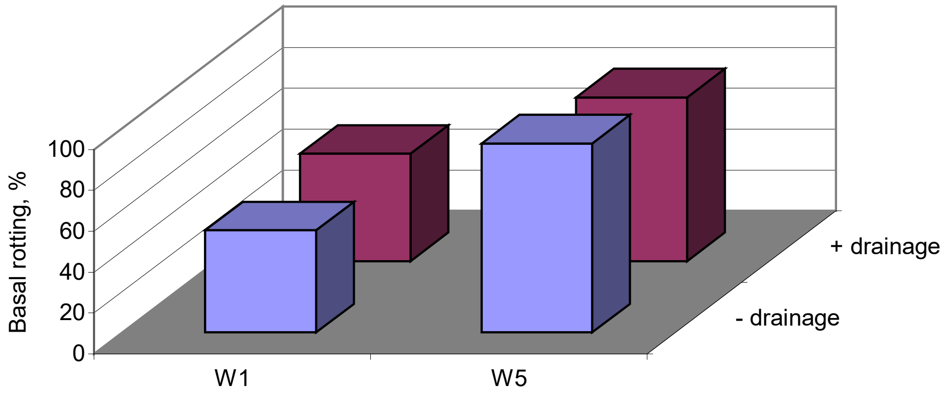
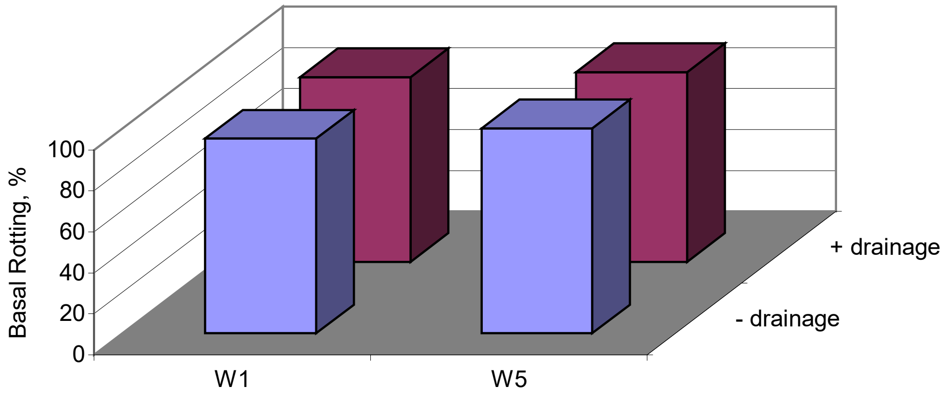


Figure 8. Percentage rotting of *Fremontodendron* 'California Glory' cuttings. Interacting effects of medium, wetting and light. [L1 = high light, L4 = low light; W1 = heavy wetting, W5 = light wetting. The effects of medium, wetting and light were significant (P<0.01) as was the light x wetting interaction (P<0.05).]

30:70 Peat:Vermiculite



50:50 Peat:Vermiculite



70:30 Peat:Vermiculite

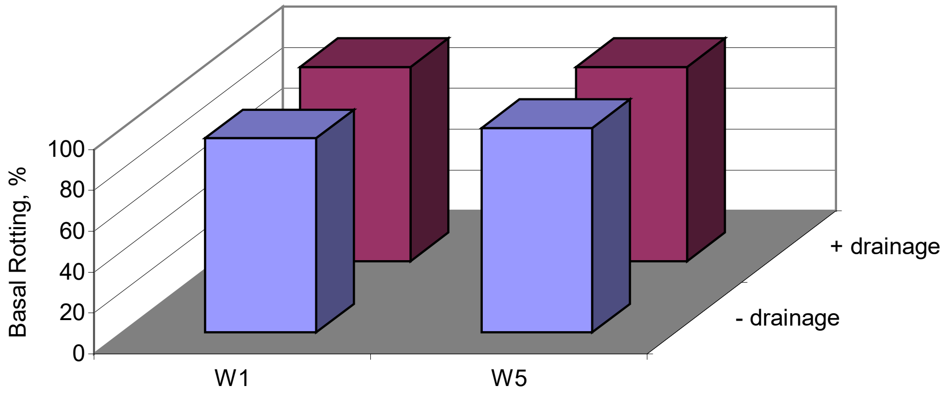
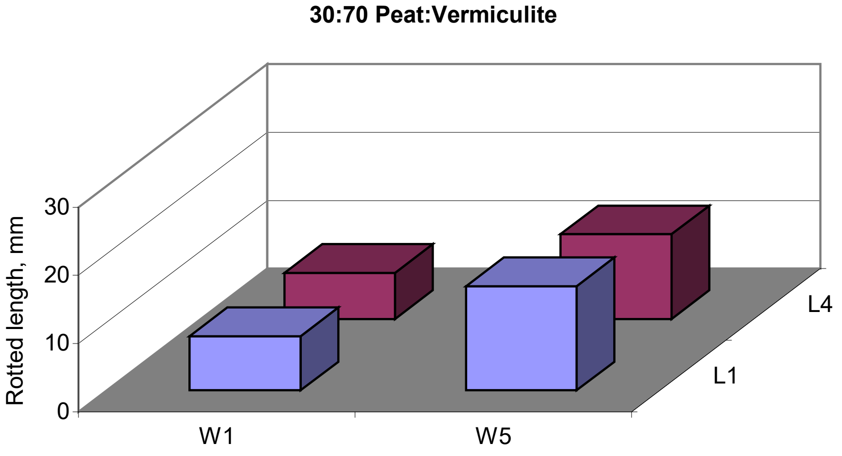
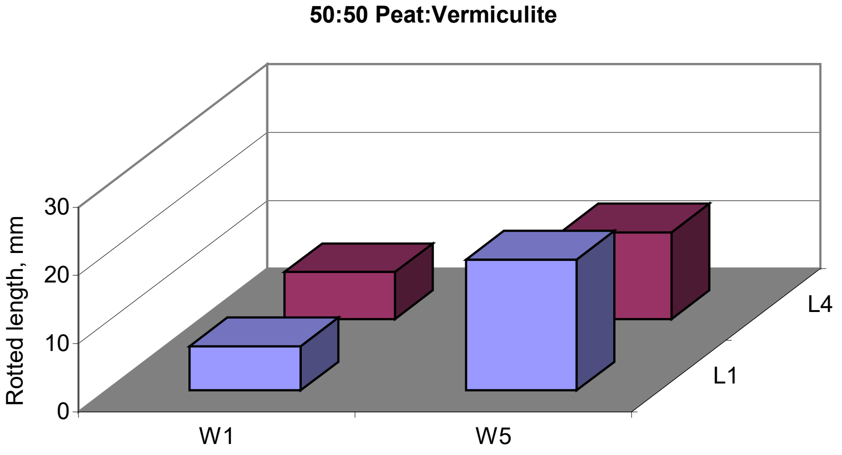


Figure 9. Percentage rotting in cuttings of *Fremontodendron* 'California Glory'. Interacting effects of medium, wetting and drainage. [W1 = heavy wetting, W5 = light wetting. Soil water tension at the base of the cutting would have been appoximately 2 cm of water in the '-'and 12 cm in the '+' drainage treatments. The effects of media and wetting but not drainage were significant (P<0.001).]





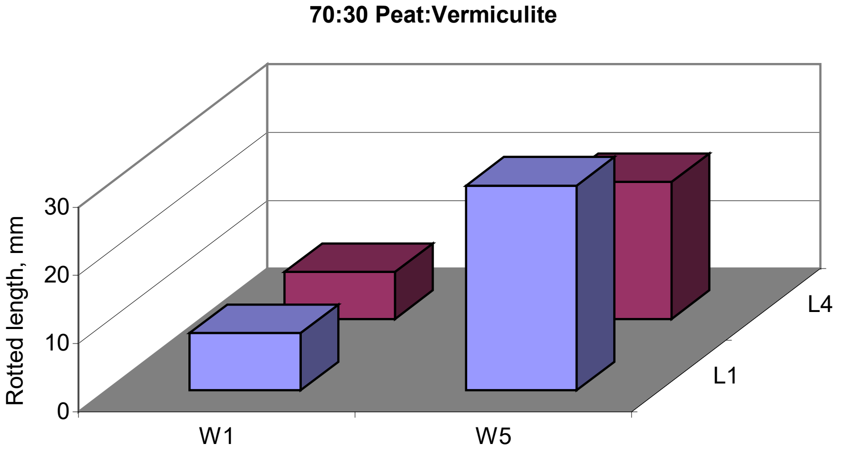
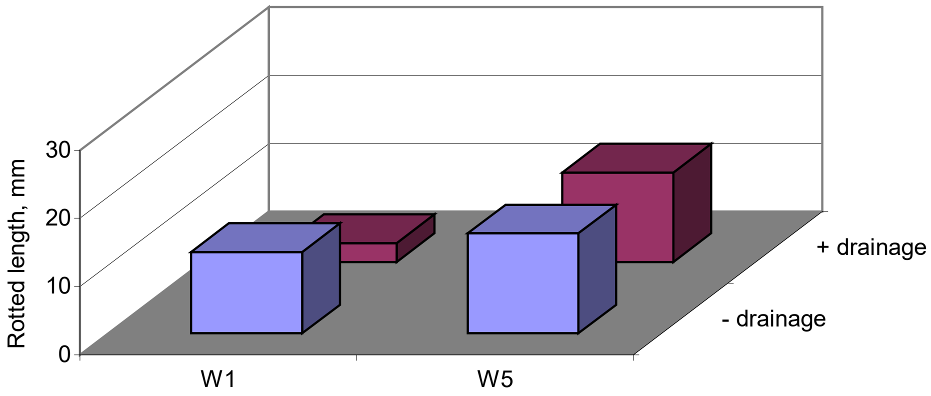
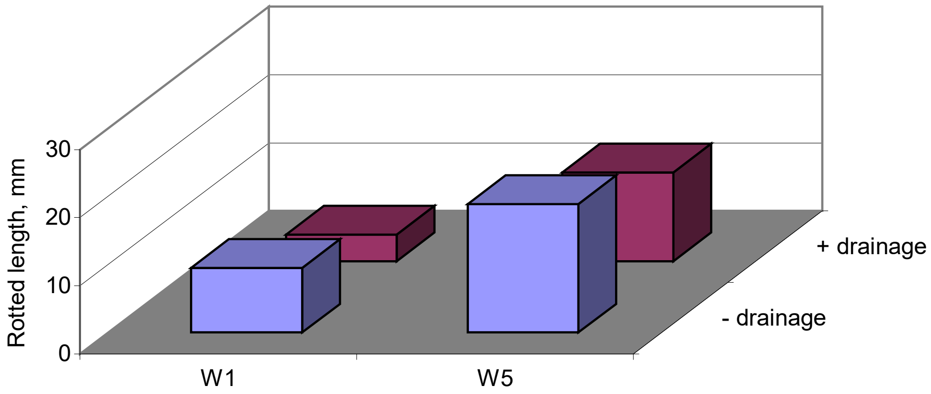


Figure 10. Extent of basal rotting of *Fremontodendron* 'California Glory' cuttings. Interacting effects of medium, wetting and light. [L1 = high light, L4 = low light; W1 = heavy wetting, W5 = light wetting. The effects of medium, wetting and light were significant (P<0.01) as were the interactions of wetting x light and wetting x media (P<0.05).]

30:70 Peat:Vermiculite



50:50 Peat:Vermiculite



70:30 Peat:Vermiculite

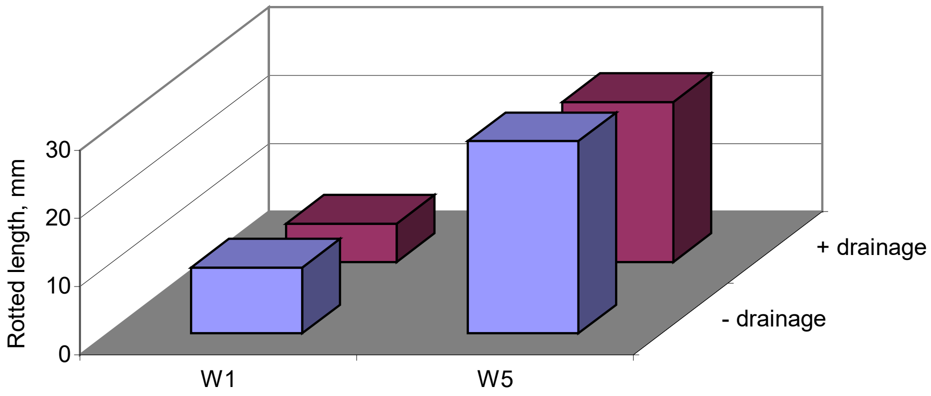


Figure 11. Extent of basal rotting of *Fremontodendron* ‘California Glory’ cuttings. Interacting effects of medium, wetting and drainage. [W1 = heavy wetting, W5 = light wetting. Soil water tension at the base of the cutting would have been appoximately 2 cm of water in the ‘-’and 12 cm in the ‘+’ drainage treatments. The effects of medium, wetting and drainage were significant (P<0.001), as was the medium x wetting interaction (P<0.01).]

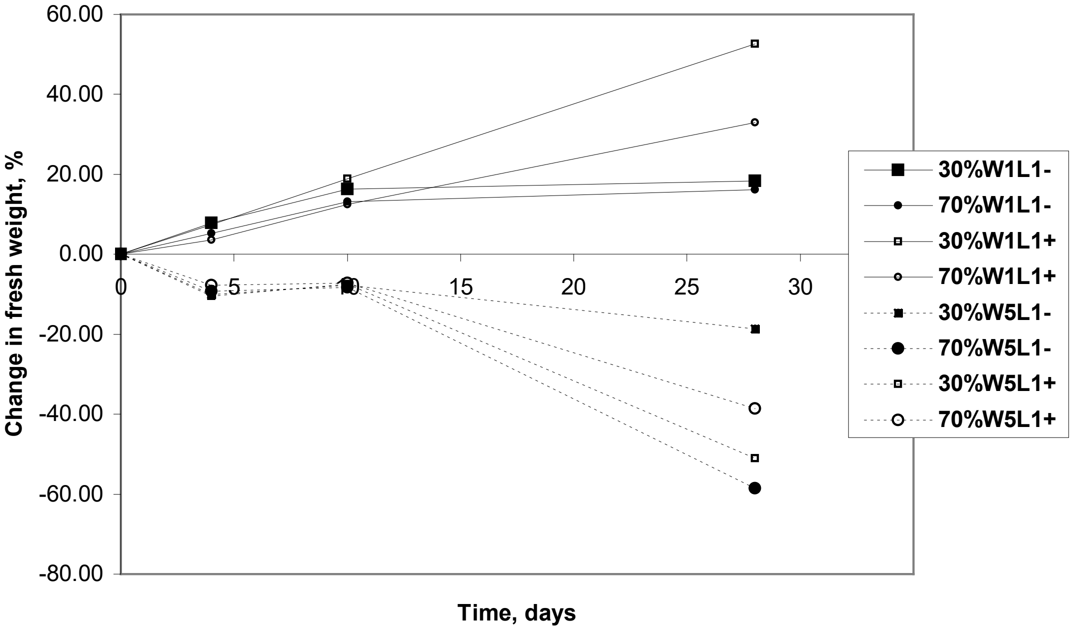


Figure 12. Changes in fresh weight of a subsample (n=4) of cuttings within the high light treatment combinations.

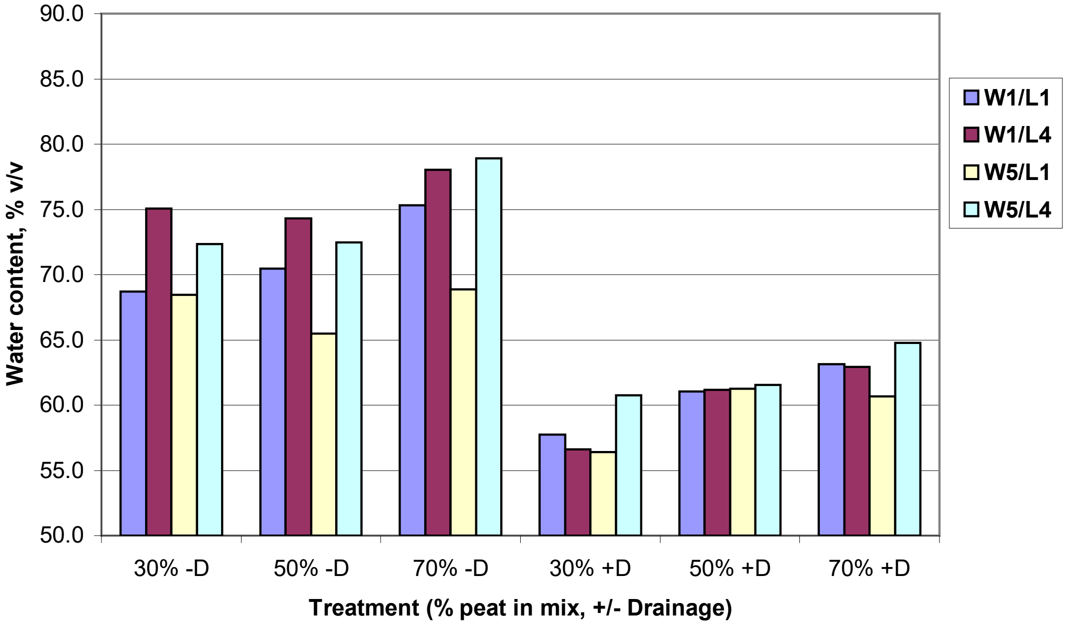


Figure 13. Water content of media at the end of Experiment 2, determined on a subsample of cells (n=3) after cuttings had been removed and rooting recorded.

Rooting media trials

Based on their water release characteristics the air/water relations expected in the various media included in the trials are shown in Table 2.

Table 2. Air and water contents of the media used in the rooting experiment, estimated from the water release curve data.

	Non-capillary drainage		Capillary drainage	
Medium	Water, %	Air, %	Water, %	Air, %
Peat:Bark	85.1	1.0	71.6	14.5
Plug-its	85.7	4.8	75.6	14.9
Elle Pots	81.5	8.4	70.3	19.6
Oasis	87.1	6.3	78.2	15.2
Rockwool	91.0	6.8	86.1	11.7

Trial 1 – Convolvulus cneorum

Rooting percentage varied from below 20 to almost 100% (Figure 14), the most consistent response being the beneficial effect of capillary drainage. Amongst the media, only oasis was consistently substantially poorer than the others. Overall, the best medium was the peat:bark mix in which rooting averaged 69%. There is no obvious relationship between the predicted air contents and the ability to support rooting without capillary drainage.

It is interesting that there was little difference between open mist, in which cuttings were heavily wetted, and a relatively dry location in the Agritech fog house in which water deposition was light and leaves often dried out. It is widely held that this subject, like many grey-leaved Mediterranean subjects, is intolerant of leaf wetting. Earlier results from the G-CPE (Harrison-Murray, 1998) showed that rooting could be completely inhibited by the combination of leaf wetting and high humidity but left open the question of whether this was due to leaf wetting itself or to excessive suppression of transpiration. The results of the present experiment support the former interpretation. Since mist and fog were both under evapo-sensor control they would have imposed similar evaporative demand by different combinations of humidity and leaf wetting. The results also suggest that the absence of capillary drainage may predispose to poor results in wet systems and give a false impression that leaf wetting is itself harmful.

A substantial proportion of non-rooted cuttings were still healthy and/or had callused, especially amongst those with capillary drainage in mist (Figures 15 to 17). This suggests that many non-rooted cuttings might have rooted given extra time.

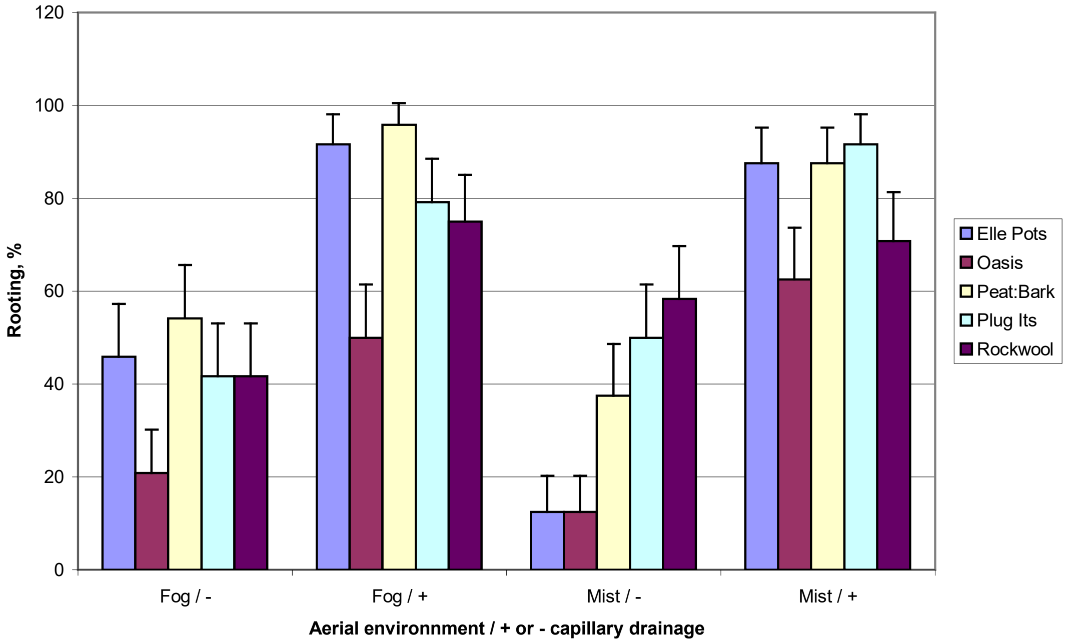


Figure 14. Percentage rooting of *Convolvulus cneorum* cuttings in Trial 1

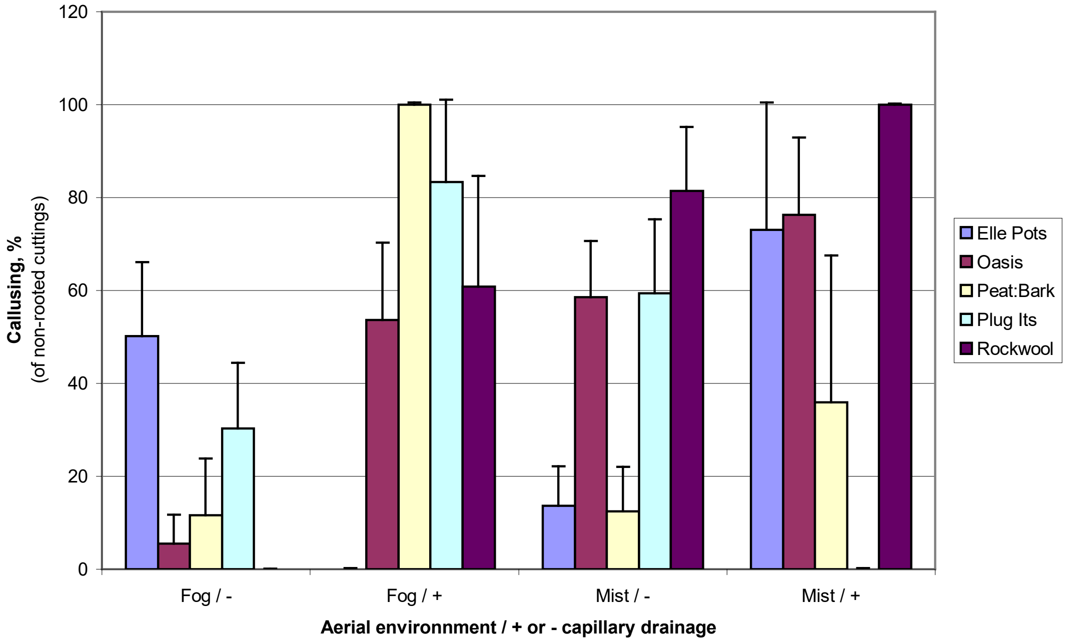


Figure 15. Percentage callusing amongst non-rooted cuttings of *Convolvulus cneorum* cuttings in Trial 1

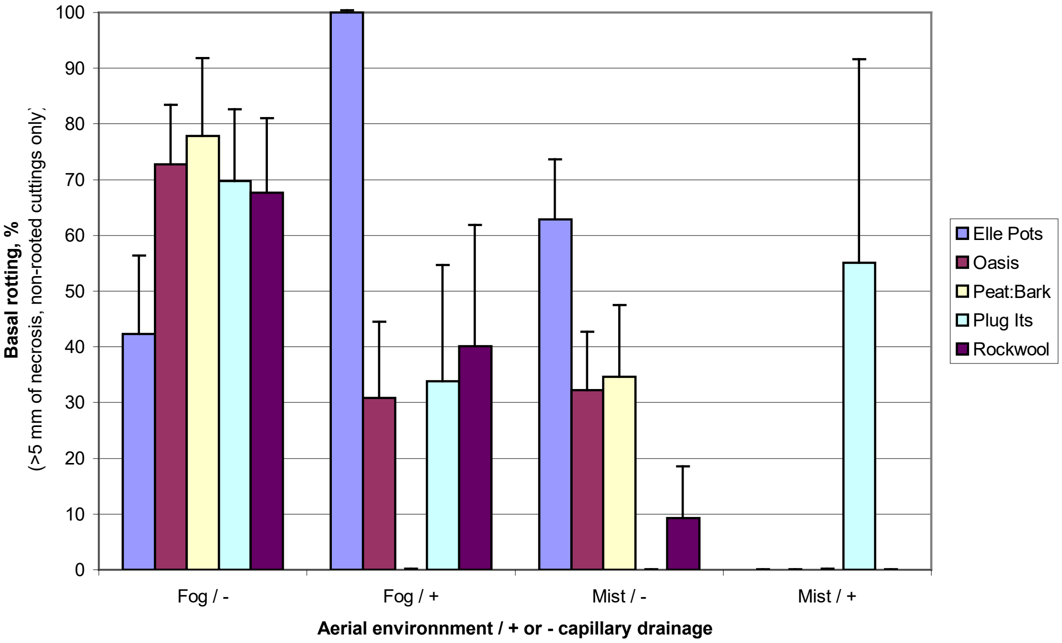


Figure 16. Percentage basal rotting in *Convolvulus cneorum* cuttings in Trial 1

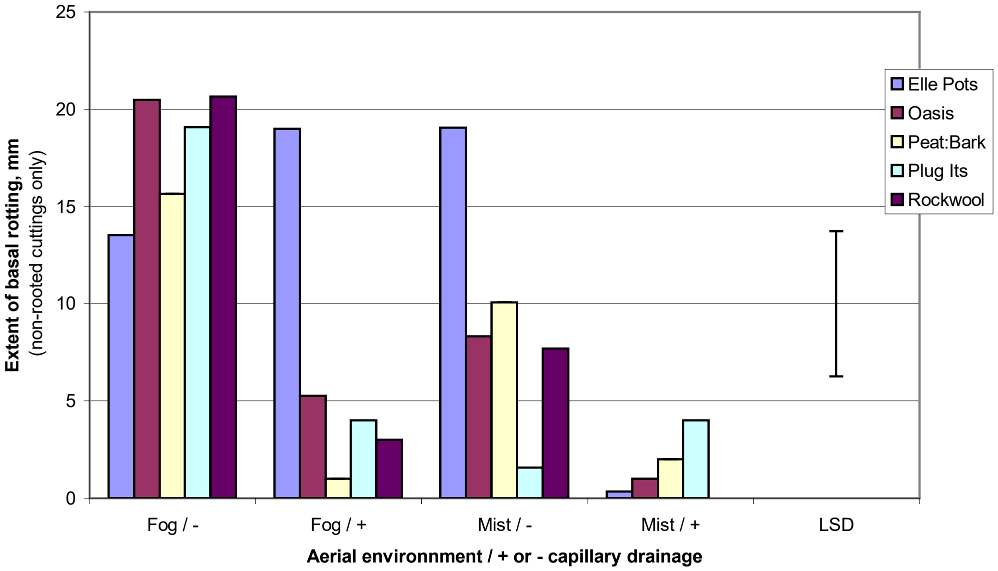


Figure 17. The extent of stem rotting at the base of non-rooted *Convolvulus cneorum* cuttings in Trial 1.

Trial 2 – Fremontodendron 'Pacific Sunset'

Rooting was much lower in this experiment than had been observed in earlier work with this subject in HNS 55 (Harrison-Murray, 1998). Nonetheless the results show a number of significant differences (Figure 18). Whether in the dry or wet zone, capillary drainage was the most important determinant of rooting success but rooting was substantially less in oasis and, to a lesser extent, rockwool than in the other media. It may be significant that all the other media are peat-based. Amongst other factors, this would have led to substantially higher pH in Oasis and Rockwool, because these materials have little buffering capacity and the water supply has a pH of about 7.5.

There were no consistent trends in production of basal callus (Figure 19) and no evident association with rooting percentage (Figure 18).

Basal stem rotting affected a high proportion of cuttings in all treatments was slightly worse in the absence of capillary drainage (Figures 20 and 21).

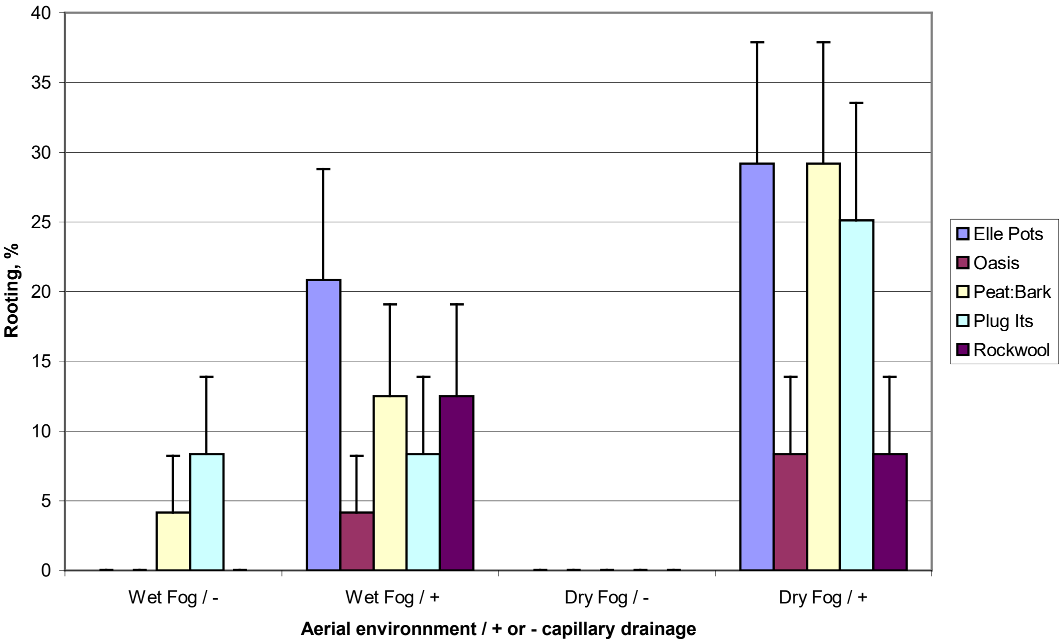


Figure 18. The rooting percentage of *Fremontodendron* 'Pacific Sunset' cuttings in Trial 2. 'Wet Fog' and 'Dry Fog' refer to W1 and W5 zones in the G-CPE, as used in experiment 2.

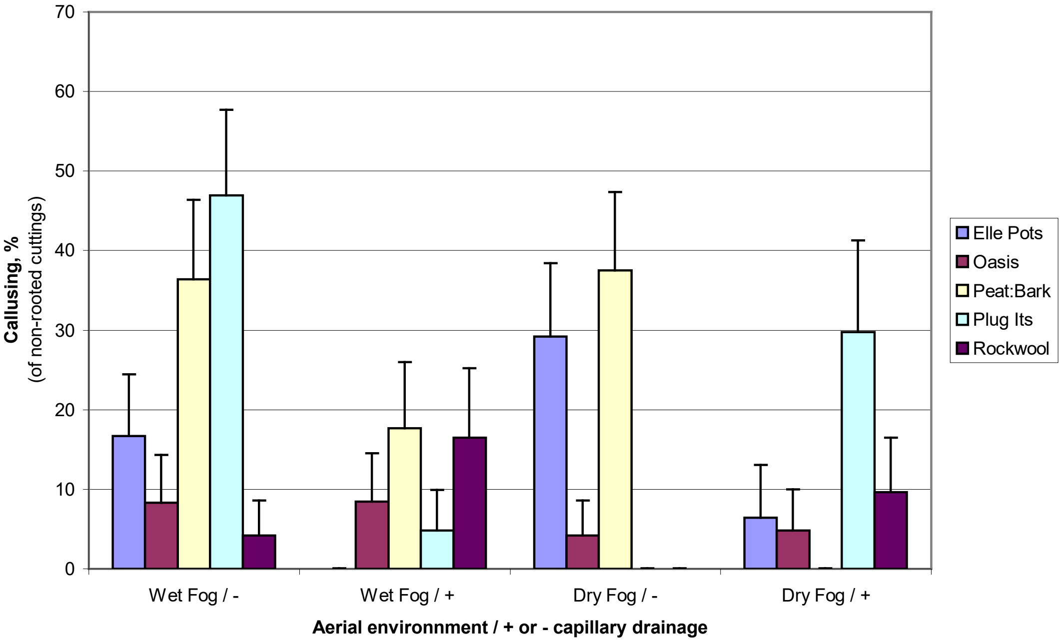


Figure 19. The percentage callusing amongst non-rooted cuttings of *Fremontodendron* ‘Pacific Sunset’ in Trial 2.

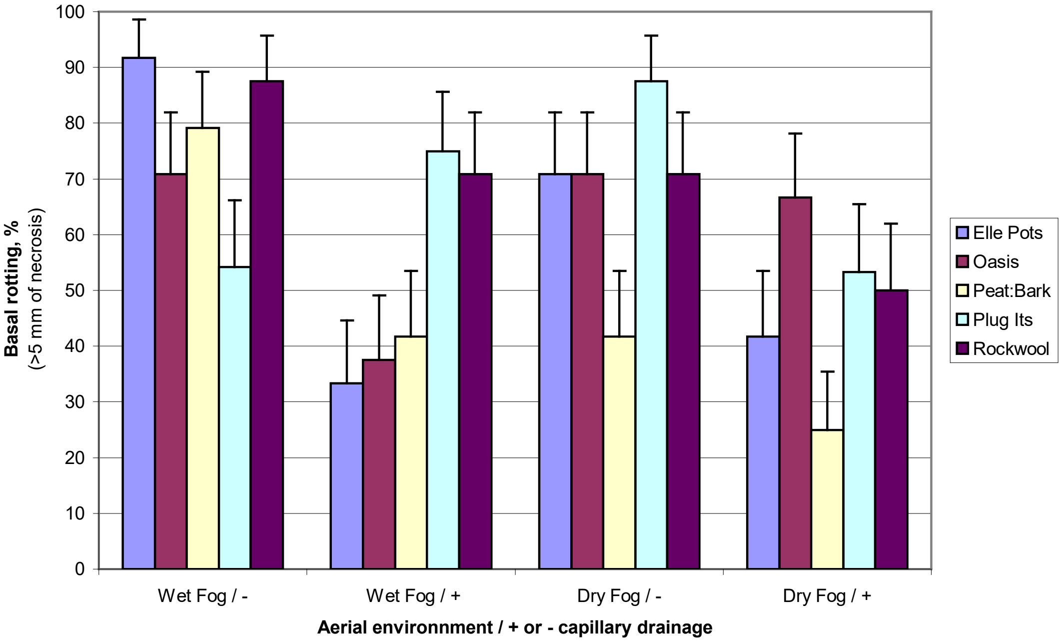


Figure 20. The frequency of basal stem rotting in cuttings of *Fremontodendron* ‘Pacific Sunset’ in Trial 2.

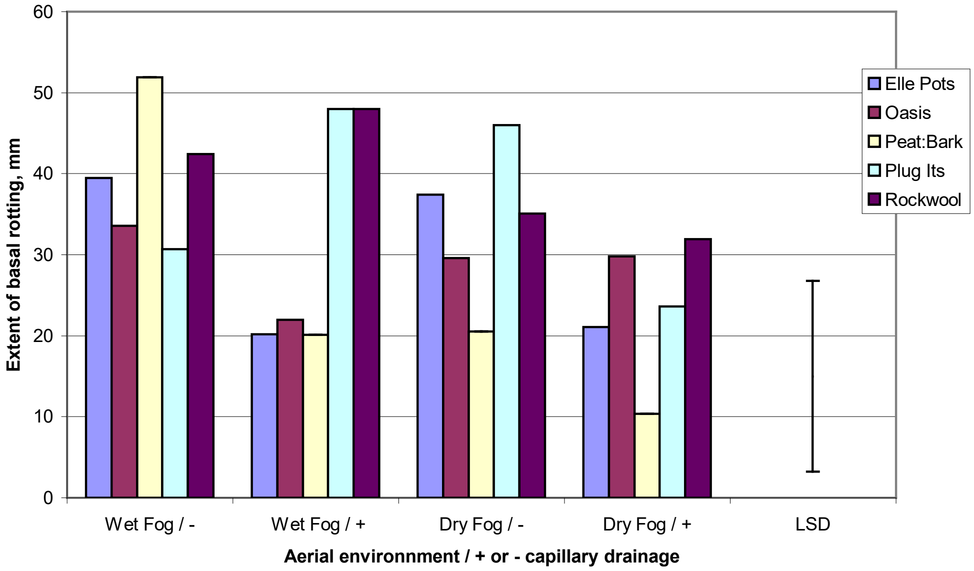


Figure 21. The extent of basal stem rotting on cuttings of *Fremontodendron* 'Pacific Sunset' in Trial 2.

Trial 3 – Garrya elliptica 'James Roof'

As expected, this very drought sensitive subject rooted better under the heavy water deposition of wetting zone W1 (Figure 22). It also showed much less benefit from capillary drainage than the other subjects in the rooting trials, particularly in the less heavily wetted zone (W3). Rooting percentage was consistently lower in peat:bark and in Plug-Its than in Elle Pots, Oasis or rockwool. In the absence of capillary drainage, this might be attributed to the particularly low air content of peat:bark and Plug-Its but that explanation cannot cover the capillary drained treatment.

As has been observed previously with *Garrya*, the highest rooting percentage obtained in the G-CPE was substantially lower than that of a batch of cuttings placed close to the fogger in the 'Agritech' ventilated fog house (97%). The reason for this difference is not known but is believed to reflect the penetration of fog beneath the leaves in the 'Agritech' house which improves the control of transpiration and thus more effectively avoids stress. This explanation is consistent with significant differences between the experimental blocks associated with reduced transpiration at lower light levels (Figure 23). However, these lower light levels were also associated with greater rotting, both above and below ground (Figures 25 and 28). This suggests that the reduction in light in blocks I and II was great enough to lead to a shortage of carbohydrates and other products of photosynthesis in these cuttings.

There was no consistent effect of the media or capillary drainage on rotting above or below ground (Figures 24, 26 and 28). On average there was slightly more rotting in W3 than in the more heavily wetted W1 zone.

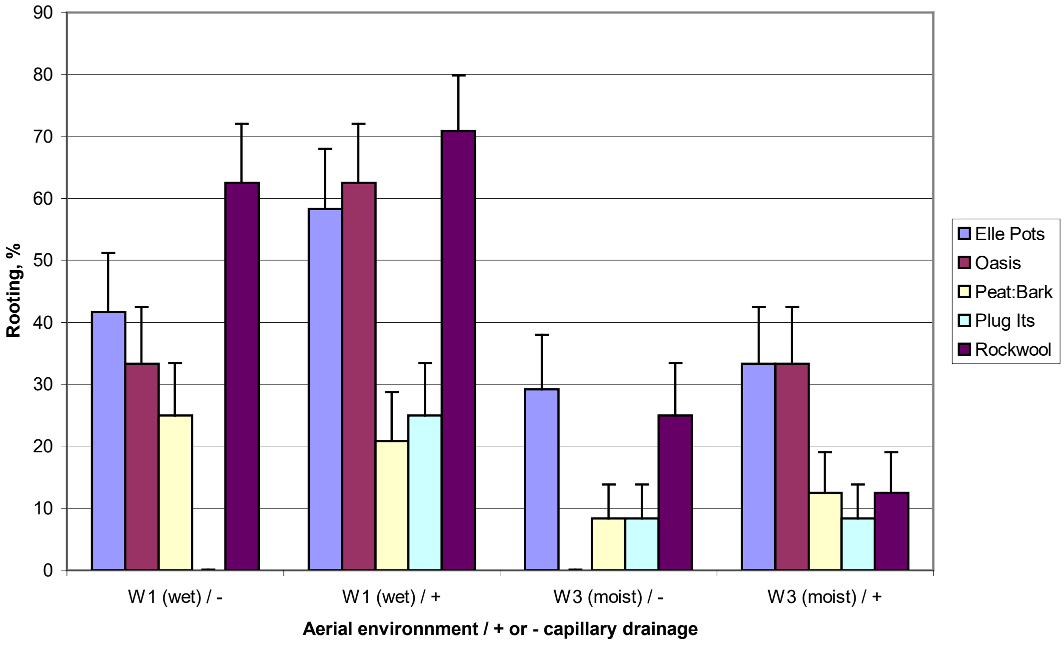


Figure 22. Percentage rooting of *Garrya elliptica* 'James Roof' cuttings in Trial 3.

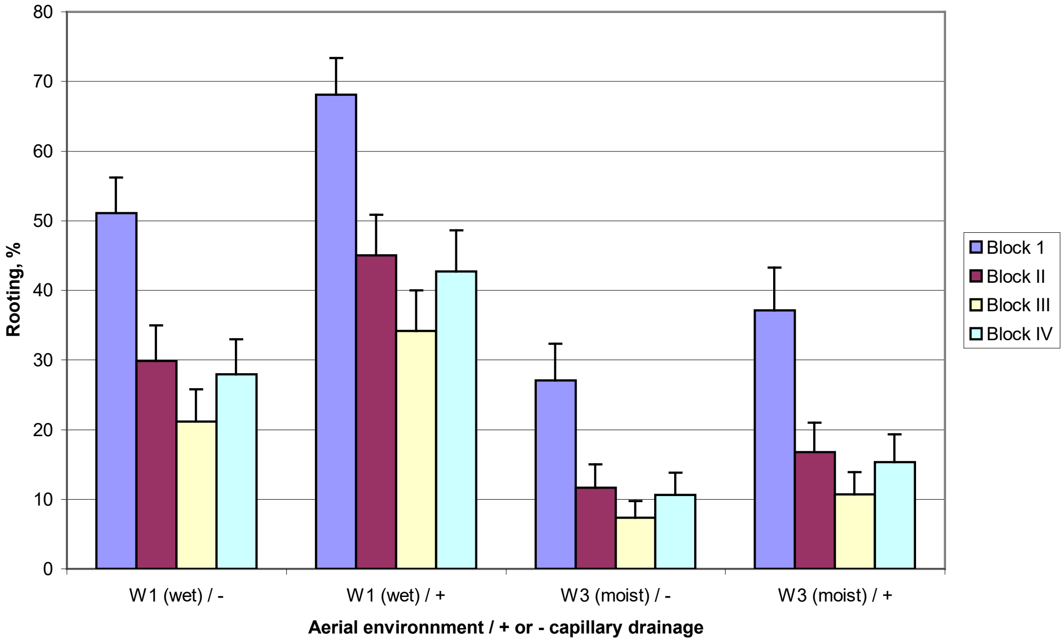


Figure 23. Block differences in rooting percentage of *Garrya elliptica* 'James Roof' in Trial 3. The probable explanation of these block effects is that light level increased from block I to block III.

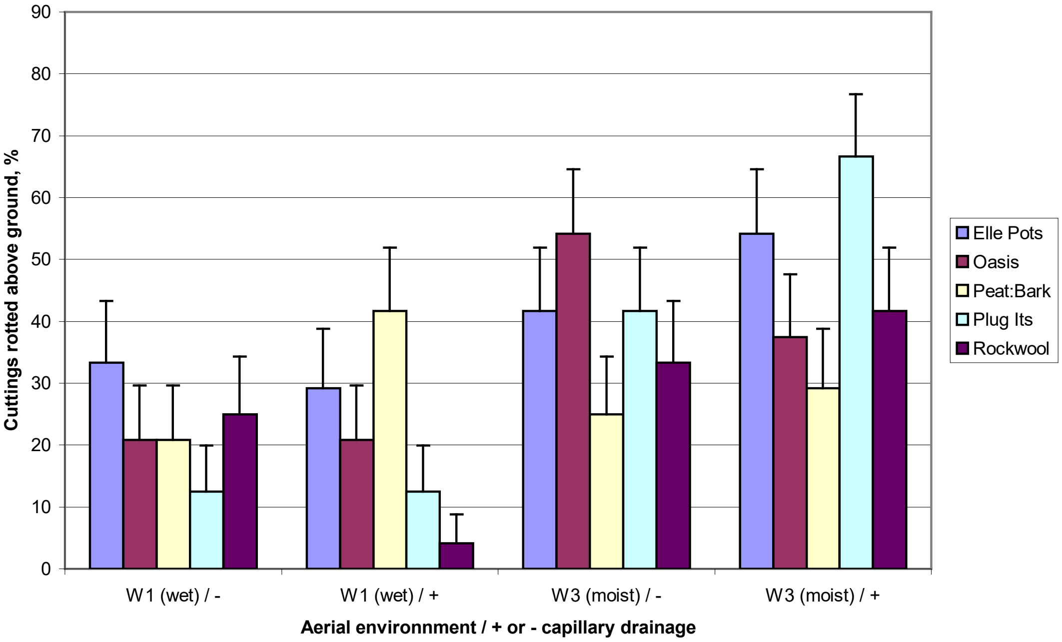


Figure 24. Percentage of *Garrya elliptica* 'James Roof' cuttings with severe rotting of the above ground stem and leaf tissues in Trial 3.

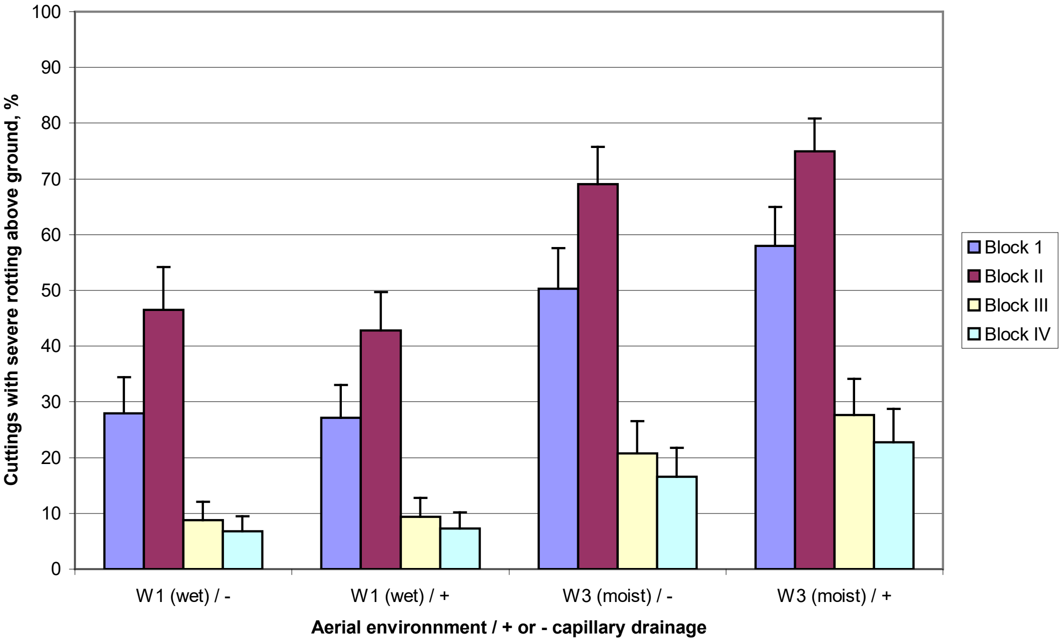


Figure 25. Block effect evident in the percentage of *Garrya elliptica* 'James Roof' cuttings with severe rotting of the above ground stem and leaf tissues in Trial 3.The probable explanation of these block effects is that light level increased from block I to block III.

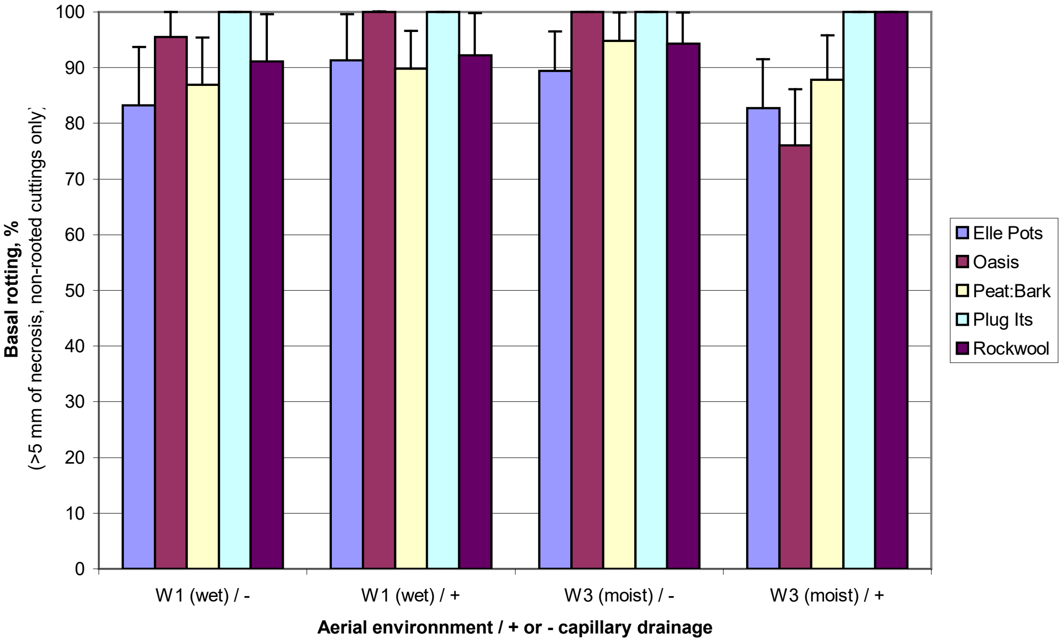


Figure 26. The percentage of *Garrya elliptica* 'James Roof' cuttings with substantial basal stem rotting in Trial 3.

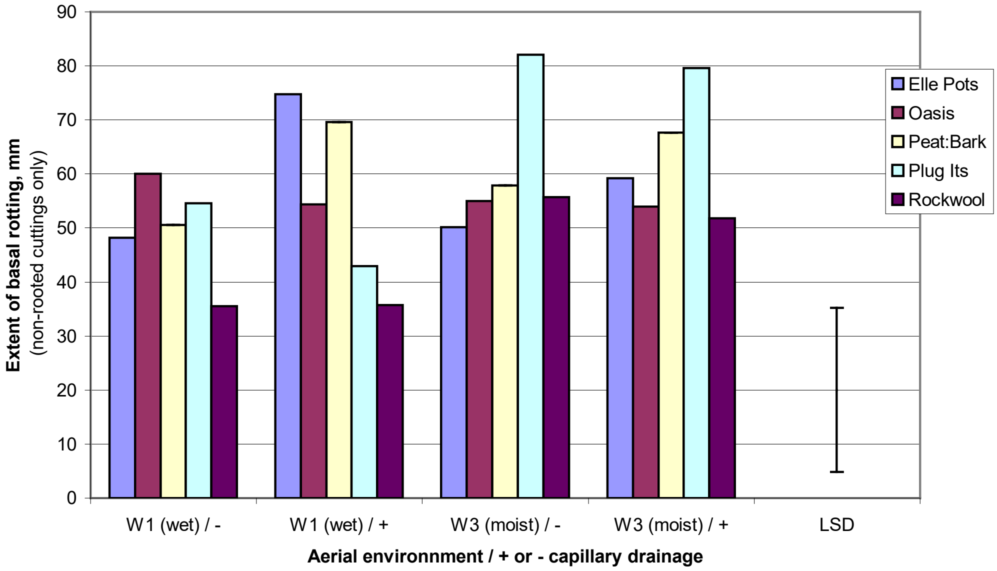


Figure 27. The extent of rotting at the stem base in cuttings of *Garrya elliptica* 'James Roof' in Trial 3.

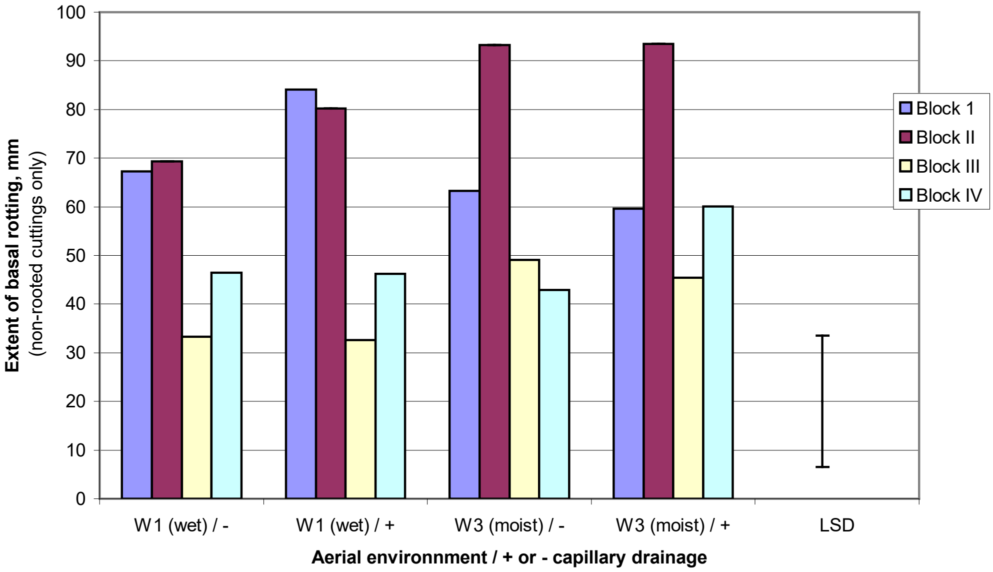


Figure 28. Block effects on the extent of rotting at the stem base in cuttings of *Garrya elliptica* 'James Roof' in Trial 3. The probable explanation of these block effects is that light level increased from block I to block III.

Trial 4 – Fremontodendron 'Pacific Sunset'

This trial incorporated two factors aimed to identify the cause of the unexpectedly poor rooting observed in trial 2:

- removal of flowers on the stock plants to stimulate more vigorous vegetative growth
- structured comparison of the Agritech ventilated fog house with the G-CPE environment.

Flower removal did not result in visibly more vigorous growth and had no effect on rooting of cuttings taken three weeks afterwards.

There was little difference in overall rooting percentage in the two environments (Figure 29). Compared to the earlier trial and to Experiment 2, rooting in the G-CPE was good (up to 75%), whereas it was lower in the fog house than it has been previously. This indicates that this subject has become much more sensitive to subtle differences in aerial environment than it was when studied as part of HNS 55, presumably because of some stock plant factor that we have not yet identified.

Rooting in Oasis and rockwool was again consistently poor compared with the peat based media (Figure 29). In contrast to all previous results, the results show no benefit from capillary drainage in terms of rooting (Figure 29) or avoidance of basal stem rotting (Figure 30 and 31).

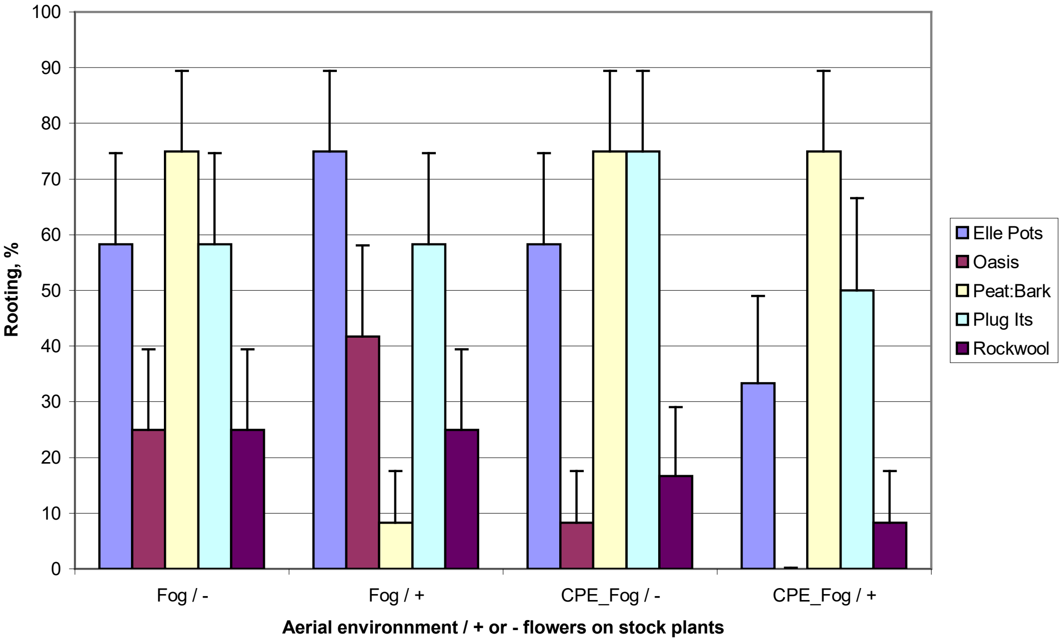


Figure 29. Rooting percentages for *Fremontodendron* 'Pacific Sunset' cuttings in Trial 4

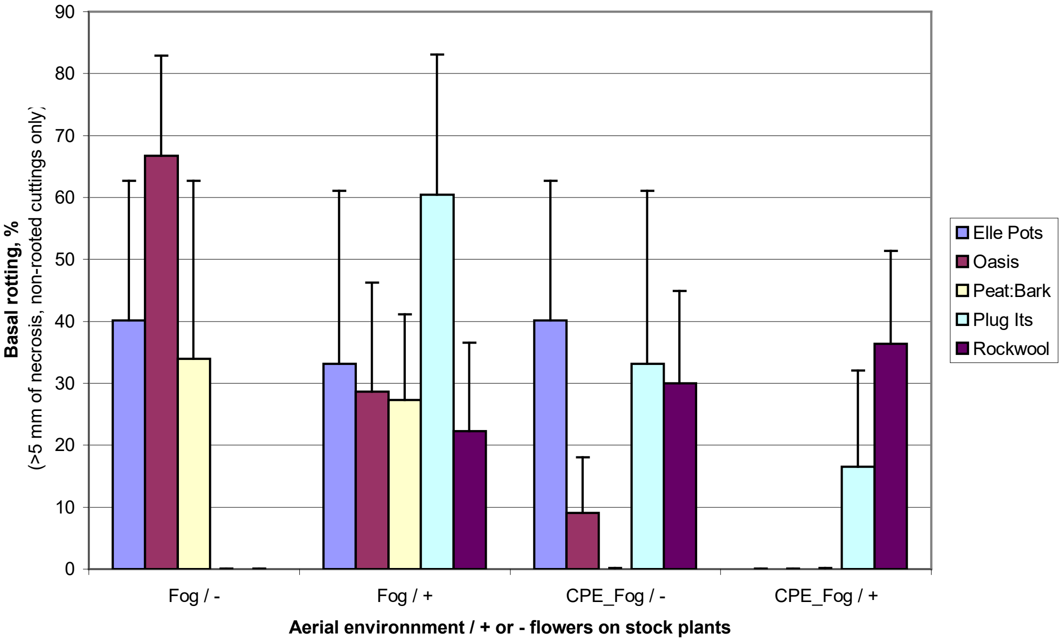


Figure 30. The percentage of *Fremontodendron* 'Pacific Sunset' cuttings with substantial rotting of the basal stem in Trial 4.

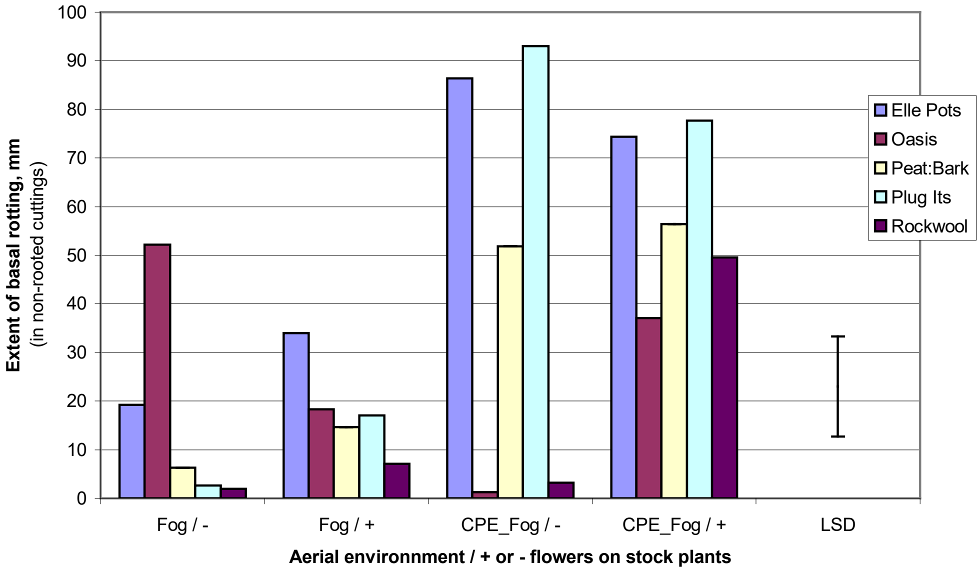


Figure 31. The extent of basal stem rotting on cuttings of *Fremontodendron* 'Pacific Sunset' in Trial 4.

Conclusions

The main conclusions at the end of the second year of this project are as follows:

- The continuous application of water in the form of mist or fog causes a small rise in water content of the rooting medium (and a corresponding decrease in air content) compared with the value predicted from the water release curve.
- This difference arises because, in a continuously wetted medium, the water content depends on a dynamic equilibrium whereas the water release curve depends on a static equilibrium.
- The difference is small enough that the water release curve provides predictions of air and water contents that are of practical value in the propagation context.
- Capillary drainage can have a major effect on the air content of rooting media, particularly those with a high proportion of peat.
- Capillary matting is much less effective than sand as a drainage medium, even when a hanging tail is used to increase tension at the surface of the mat.
- Contact between the medium and the capillary substrate may tend to limit its effectiveness. This may account for the relatively weak drainage effect observed with capillary matting. This area requires further investigation.
- 10 to 12 cm of fine sand, as used in most of the experiments in this project, increased rooting and decreased rotting of most subjects and in all media, particularly when combined with generous wetting.
- 3 cm of sand is sufficient to raise the air content of pure peat or a 50:50 peat:vermiculite mixture to above 10%, sufficient to keep the medium well aerated.
- No single parameter dominates the cutting's response to conditions in the rooting medium. There was evidence that water tension and air content have independent effects and that the proportion of peat in the medium can influence rooting and rotting in a way that is unrelated to its effect on air/water relations.
- In practical terms, most of the results suggest that the most reliable approach to managing the rooting medium is to combine sufficient wetting to avoid water stress with an open textured rooting medium and a layer sand to provide capillary drainage.

- There was no consistent difference in rooting between Elle Pots, Plug-Its, and a conventional 50:50 peat:bark mixture. For *Fremontodendron* only, Oasis and rockwool gave significantly poorer rooting than the peat-based media.
- Severe basal rotting was often associated with an environment in which cuttings suffered water stress, rather than an excess of water in the medium. It is important that nurserymen do not assume that rotting always indicates that the medium is too wet.

GLOSSARY : terms, abbreviations and products used

Agritech fogger - a machine in which large quantities of water (up to 135 L h^{-1}) are atomised by nozzles mounted on the ends of a pair of rotating arms, and which incorporates a powerful fan to distribute the resulting fog. It produces a mixture of droplet sizes, ranging from mist-sized drops to fine fog droplets. It is no longer manufactured but alternatives are available. It is used in a polytunnel with an extract fan, that is refered to as the 'Agritech' ventilated fog house.

apical cutting - one which includes the shoot tip

Bulk density - the density of the medium as a whole, including the pore space, i.e. the mass of a sample of the medium divided by its volume.

CPE - a 'Controlled Propagation Environment'.

'environmental fingerprint' - term coined for a 3D graph summarising the response of rooting to environment, in a particular species, cultivar, or type of cutting, based on results from the G-CPE (e.g. Figure 4 or 5).

evaporative demand - an imprecise term referring to the power of an environment to evaporate water. It differs from humidity in that it takes account of the many other factors which influence evaporation, such as irradiance. For a more precise definition it is necessary to specify a particular evaporative surface e.g. a leaf - see also potential transpiration.

evapo-sensor - an instrument invented at HRI - East Malling which provides an electrical signal approximately proportional to potential transpiration

G-CPE - the 'Gradient - Controlled Propagation Environment' in which gradients of two environment factors (currently light and wetting) interact to create a matrix of different environmental conditions.

g L^{-1} - grammes per litre.

IBA - indolyl butyric acid. This is a synthetic auxin used to stimulate rooting in cuttings and is the active ingredient in Seradix rooting powders.

necrosis - tissue death. Used in this report to refer to darkening of tissues that indicates that the cells have probably died so that the tissues will eventually break down.

($P < 0.05$, $P < 0.01$, or $P < 0.001$) - a statement of the statistical probability (P) that the observed differences could have been due to chance. The smaller the value of P, the more certain we can be that the result is 'real'. A value of 0.05 is conventionally taken as the threshold for accepting the result, i.e. that an effect is 'statistically significant'.

particle density - the density of the solid material making up the ‘particles’ of the solid in the rooting medium.

tension (or soil water tension) - a measure of the capillary forces holding water in the soil (or rooting medium), and therefore the force required to remove water from it. It is synonymous with ‘soil moisture suction’ and numerically equal to the soil matric potential (though of opposite sign). In the present context it is convenient to express it in centimetres of water, i.e. the height of a column of water which would create the same tension.

REFERENCES

Anon. (1998). Methods for optimising the hydraulic properties of growing media for HNS. Final report on MAFF project HH1208SHN.

Harrison-Murray, R.S., Howard, B.H. and Knight, L.J. (1998) Stategies for liner production designed to achieve high quality container plants. Horticultural Development Council Report for project HNS 55.

Thomas, A. and Harrison-Murray, R. S. (1995). What makes peat so good for growing. Grower, 124(21): 21-22.