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UNDERSTANDING THE ENVIRONMENTAL NEEDS OF LEAFY CUTTINGS DURING ROOTING

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Experiments in which a range of leafy cuttings was propagated in nine different rooting environments showed that leaf wetting was more effective than high humidity in preventing water stress and encouraging rooting, but that the combination of the two was more effective still. This combination enabled high success rates to be achieved with otherwise very difficult-to-root subjects and allowed the use of soft summer cuttings for species normally produced from ripe autumn cuttings (e.g *Garrya elliptica* 'James Roof'). It also had the benefit of reducing dependence on shade as a means of preventing water stress.

The required combination of conditions can be achieved either by enclosing mist so as to trap the humidity, or by fog. The advantage of fog is essentially that controlled ventilation is possible without humidity dropping so that the possibility of high temperature damage need not be a concern. However, it is very difficult to achieve uniform wetting with fog and it is technically more troublesome than mist. There is no single ideal solution and the factors to be considered are discussed.

Summary

It has been estimated that, of the 200 million HNS cuttings taken each year, approximately 40% fail to root. It is very likely that the majority of these failures are attributable to poor environmental conditions during rooting, as implied by the results of our survey of commercial nurseries (Thompson *et al.* (1993). Improvement of propagation environments, therefore, has the potential to prevent a great deal of wasted time and materials. It can also help bring new plants to the market place that otherwise could not be commercially viable.

The prime function of the propagation environment for leafy cuttings is to restrict transpiration. Once severed from the stock-plant the opportunity for the cutting to take-up water through the cut stem is very limited, so the emphasis must be on limiting water loss by transpiration if damaging water deficits are to be avoided.

The physics of evaporation from leaves is well understood and documented. To help nurserymen grasp the essential principles, this report includes a simple diagrammatic model of the process to help them interpret their own observations. However, theory alone cannot provide answers to many of the practical questions to which nurserymen are seeking answers because not enough is known about how plant factors, such as stomatal closure, interact with environmental factors.

This project aimed to bridge this gap between the basic theory and its application to propagation practice. Cuttings of a wide range of mainly difficult-to-root cultivars were propagated in nine different environments. The choice of environments was designed to separate the effects of the components of aerial environment which

propagators can influence: i.e. humidity, wetting, and light. For species with moderate to large leaves the following generalisations can be advanced:

1. Raising humidity close to saturation (i.e. greater than 95% RH) was not **on its own** effective in preventing stress sufficiently to allow many cuttings to root.

2. Leaf wetting on its own was more effective than high humidity alone.

3. The combination of leaf wetting and high humidity was more effective than either factor alone.

4. The effectiveness of the wetting + high humidity combination in reducing transpiration permitted some subjects to be propagated out of their normal season while still very soft (e.g. *Garrya elliptica* 'James Roof'). It also allowed shade levels to be reduced without evident stress. The additional light improved the rooting of some species.

It is concluded that fog must be seen essentially as an alternative to enclosed mist for achieving the combination of high humidity with wetting, not as a means of controlling transpiration without leaf wetting. As such its unique feature is that it can humidify incoming dry air quickly enough to make it possible to ventilate without any substantial drop in humidity around the cuttings.

In the worst environments (i.e. those providing only high humidity) on average between 65 and 70% of rooting potential was lost (i.e. rooting percentage was 65 to 70% less than the best achieved with the same subject).

For species with smaller total leaf area, and narrower leaves, such as *Berberis stenophylla*, wetting alone, as in open mist, was more effective than for larger leaved species. This is probably due, at least in part, to the ease with which excess water on the upper surface of the leaf can run round the edge and coat most of the lower surface as well. For this type of plant, the wetting + high humidity combination suppressed rooting unless shade was reduced. In a second year, in which the amount of water applied was increased, additional light was unable to completely offset the adverse effect. Nonetheless, the combination of wetting + high humidity + relatively light shade (about 30% of outside light reaching the cuttings) was the only environment that came close to a universally acceptable environment for all the subjects tested.

Repeated propagation of *Cotinus coggygria* 'Royal Purple', *Garrya elliptica* 'James Roof' and *Syringa vulgaris* 'Charles Joly' indicated that there was little or no change in environmental requirement through the season. In the case of *G. elliptica* the rooting of ripe cuttings was very similar to that of soft cuttings, even though the soft ones wilted in all but the most moist environments whereas the ripe cuttings were too hard to wilt at all.

An experiment with *Acer platanoides* 'Crimson King', as an example of a large-leaved diffcult-to-root subject, showed that water deficits incurred by exposure to drying conditions **during preparation** had no effect on final rooting providing that the stress was relieved either before sticking, or by virtue of a generously wet rooting environment.

An evaporimeter which was intended to mimic evaporation from a leaf proved to be of limited application because its reading did not correlate well with either visual evidence of stress or rooting. A newly developed electrical sensor offers better prospects as a monitoring device for use by growers. It also has great potential as a new type of controller, to be known as an 'evapostat', which is described in a separate report (Harrison-Murray *et al.* 1993).

EXPERIMENTAL SECTION

Introduction

Vegetative propagation, as a method of achieving trueness-to-type when multiplying desirable ornamental forms, is central to Hardy Nursery Stock (HNS) production. Of the various methods available, rooting of cuttings is usually the nurseryman's first choice and leafy cuttings under mist or polythene the most common method. For many otherwise desirable varieties, difficulty of propagation is the barrier that prevents the plant being offered to the public in commercially relevant quantities. However, leafy cuttings are very sensitive to environment and dramatic improvements in rooting of difficult-to-root cuttings can sometimes be achieved by quite small refinements in the way propagation facilities are managed. Of even greater commercial significance is the fact that improvements in the propagation environment can bring more consistent results with those-subjects that are already routinely produced from cuttings, but which often give very variable success rates. The objective of this project was to expand our understanding of the environmental requirements of leafy cuttings and thus to raise the efficiency with which the industry is able to propagate them.

Apart from extending the range of subjects that nurserymen are able to offer, there is another compelling reason to improve rooting environments. It has been estimated that of 200 million cuttings stuck each year, 40% fail to root. Most of these cuttings are of subjects which root sufficiently readily that 100% rooting is entirely possible. The figures therefore imply **avoidable** wastage on a scale that the industry can ill afford. Not only is the plant material itself wasted, but also labour, heating and propagation space. Furthermore, a cutting which roots well and quickly is likely to make a better liner and eventually a better quality, more saleable, plant than one which came close to death before it eventually rooted.

The sensitivity of leafy cuttings to their aerial environment is well established (e.g. Loach, 1988; Harrison-Murray and Thompson, 1988) but the results of earlier research provide little practical guidance to nurserymen wishing to improve their propagation facilities. The aim of project HO/9 was to bridge the gap between existing research programmes and the need of the practical plant propagator to be able to identify the weaknesses of his facilities. In particular, it was felt that there was a pressing need to establish whether fog offers the potential to create inherently better rooting environments than the technically simpler and well-established mist systems, and if so to specify how to achieve that potential. There were three distinct stages in achieving this aim:

1. Define the needs of the cutting in terms that nurserymen could apply to the management of their facilities : i.e. shading, humidification, and wetting.

2. Survey propagation environments in use in the industry today, to see how they compare with the ideals emerging from 1.

3. Identify improvements in equipment for creating and controlling the propagation environment. At the outset it was envisaged that this might involve a specification for a complete fog system, including improvements in the control system for regulating fog output.

This report relates to the first of these three stages. The others are the subject of separate reports (Harrison-Murray *et al.*, 1993, Thompson *et al.*, 1993).

A simple theoretical background

The key problem for a leafy cutting is that, detached from the roots that had previously supplied the shoot with water, its leaves make it acutely vulnerable to water stress. It is dependent on those leaves for the photosynthetic production of the carbohydrates needed for survival and rooting. Yet it is evaporation from those leaves that can so easily cause the cutting to lose so much water that it dies. The most obvious sign of water stress is wilting, but it is important to realise that physiological processes, including those leading to root initiation, may be impaired long before stress has reached the level at which visible wilting occurs. The rate at which lost water can be replaced by absorption through the cutting base is very limited. Initially, this is simply because its surface area is so small, but later the stem itself may become blocked by the entry of air, microorganisms, or other detritus. Wounding the base of the cutting can increase the surface area for uptake (Grange and Loach, 1983) but otherwise there is little that can be done to increase uptake from the rooting medium. Our efforts to avoid water stress must therefore concentrate on creating an aerial environment which minimises transpiration.

Unfortunately, there is no **single** environmental factor that determines the rate at which leaves lose water, but rather a complex of factors which interact strongly. This is not the place for a detailed theoretical treatment of the physics of transpiration, but the following outline of the basic principles is provided to help the reader understand the rationale behind our experiments. An understanding of these principles will also help propagators interpret what is going on in their own facilities.

The effect of raising humidity

Transpiration involves the diffusion of water out of the leaf. As such, it will only occur if the concentration of water vapour inside the leaf (i.e. in the tiny air spaces between the leaf cells) is greater than that in the air around the leaf. This situation can be illustrated by reference to a highly simplified "model" leaf which has just one large air space with just a single stomatal pore in the undersurface. Such a model is shown diagrammatically in Figure 1. The cell walls surrounding the air space are permanently moist and evaporation from them ensures that air within the leaf is always saturated (i.e. 100% RH). The air outside the leaf is not saturated so that there is a steep gradient of concentration of the water molecules (represented by the spots) across the stomatal pore. The molecules are constantly moving about at random and the concentration gradient results in more of these random movements carrying water molecules **out** of the leaf than in the reverse direction. As a result there is a net loss of water molecules from the leaf to the atmosphere. This in turn drives the whole transpiration process from the compost, through the water-conducting tissues of the stem (i.e. xylem) to the cell walls within the leaf.

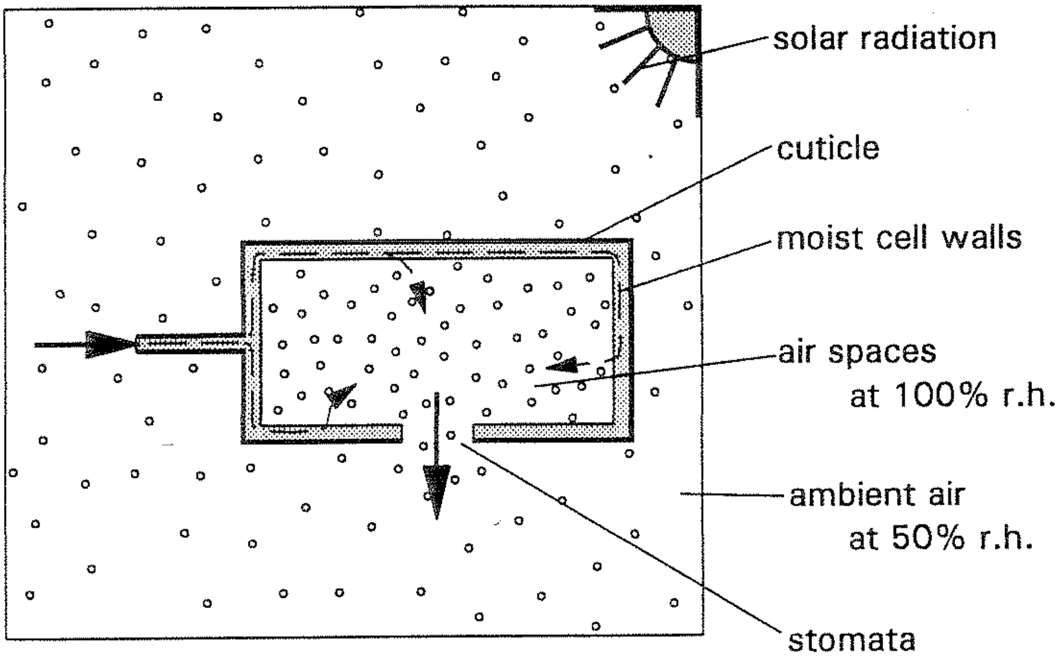

Figure 1. A diagram of the transpiration process in a simplified "model" leaf. Inside the leaf air is kept saturated with water vapour molecules (represented by the spots) by evaporation from the moist cell walls that border all the air spaces. Transpiration occurs through any open stomata as water vapour diffuses from the region of high concentration inside the leaf to the region of lower concentration outside it. Liquid water is drawn in from the stem to replace what is evaporating. Energy is used in the evaporation process so that the rate of transpiration depends strongly on the amount of solar radiation.

The model clearly suggests one way of reducing transpiration; raise the humidity of the air around the cuttings and thus reduce the concentration gradient that is driving the diffusion of water out of the leaf (compare Figure 2b with 2a).

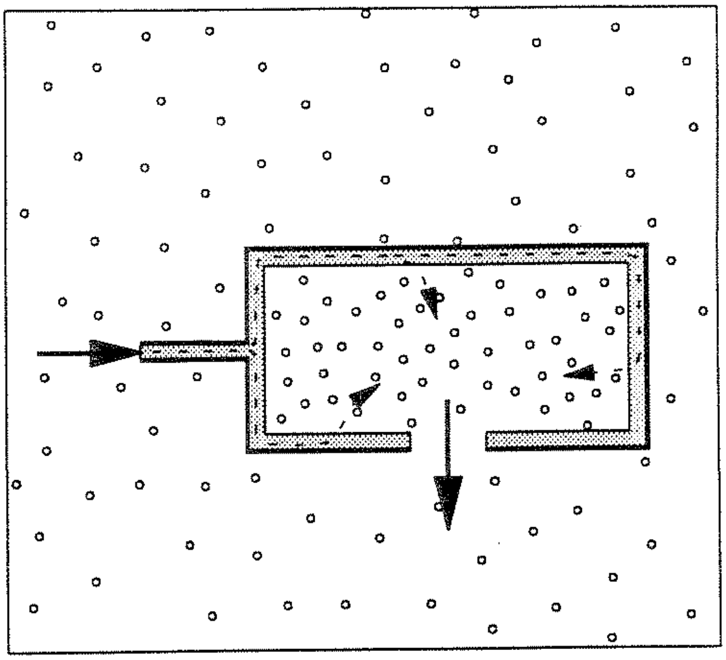

Figure 2. Using the model described in Figure 1 to illustrate how the environment affects transpiration rate:

(a) A leaf in a normal growing environment; high light intensity and low humidity create a large difference between the concentration of water vapour inside the leaf and that outside it (i.e. leaf-to-air vapour concentration difference or LAVCD).

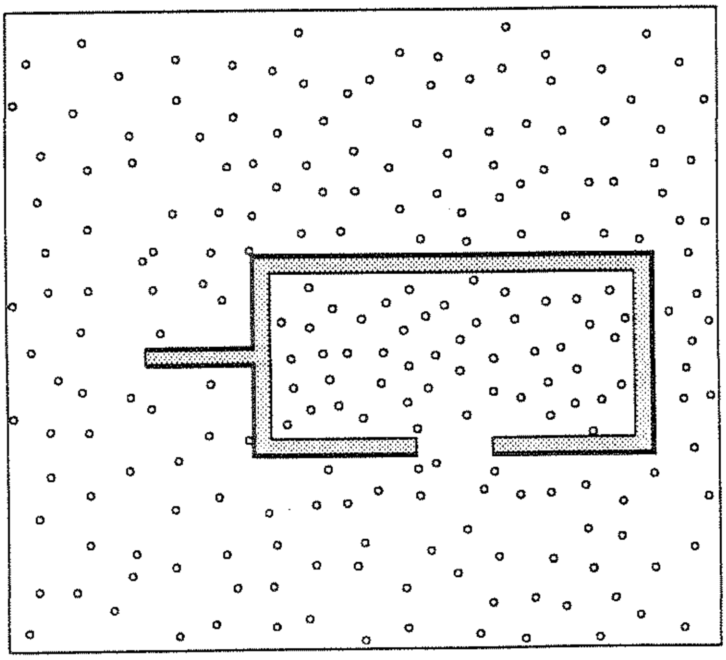

Figure 2(b). Raising the humidity around the leaves reduces the concentration difference and, if the light level is very low, transpiration is reduced, or may even stop.

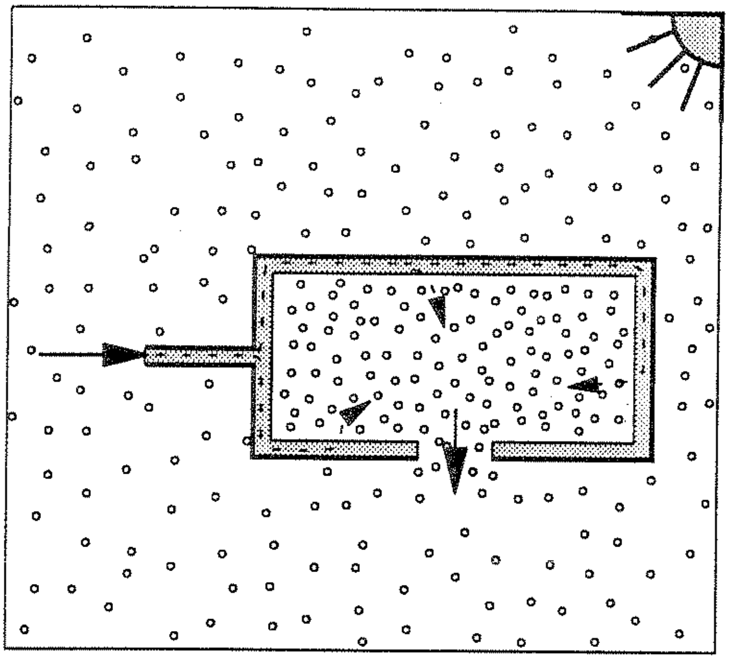

Figure 2(c). If light level is **not** very low, radiant energy absorbed by the leaf warms it, increases the water vapour concentration needed to saturate the air inside it, and so re-establishes a concentration difference which causes transpiration to restart even though the air around the leaf is saturated.

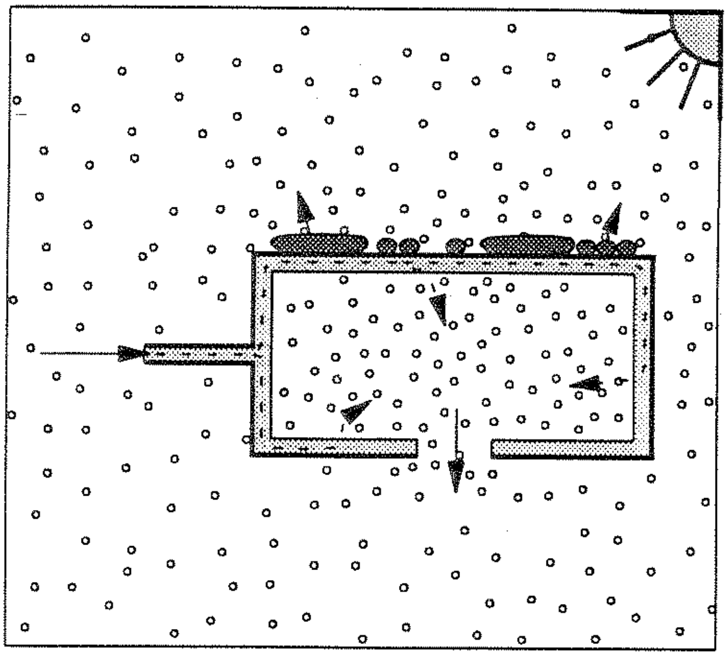

Figure 2(d). Wetting the leaves diverts much of the available energy into evaporating the external water. How much energy is diverted depends on many factors (e.g. how much extra resistance the stomata present to transpiration but not to evaporation of external water).

Unfortunately, however, even saturating the atmosphere around the leaves will only stop transpiration if the leaves are in darkness. The reason for this is as follows. In the light, absorption of radiant energy tends to warm up leaves compared to the air around them. This in turn means that the air inside the leaf can hold more water vapour before it becomes saturated so that the concentration of water vapour inside the leaf rises (Figure 2c). In other words, unless the air around the leaf is at the same temperature as the air inside it, it is physically impossible to prevent transpiration by humidification alone. This is important; people generally assume that if they can keep the air saturated then transpiration will cease, but, despite what is claimed in some manufacturer's literature, this is not the case. Even if the leaf is only 1°C warmer than the air around it, that is enough to drive transpiration into a **saturated** atmosphere. Indeed, with that temperature difference, the rate of transpiration would be roughly the same as if the air around the leaf was at only 95% relative humidity, with leaf and air at the same temperature.

The effect of shading

The last point suggests another practical way in which transpiration can be reduced, which is to use shading to reduce the level of radiation and thus limit leaf-warming. In fact, shading tends to reduce transpiration even where humidity is below saturation. "Latent heat of evaporation" is the technical term used to describe energy that must be transferred to water molecules for them to evaporate. Evaporation of water from the moist cell walls, replacing the water vapour that has diffused out of the leaf, therefore calls for a continuous supply of energy. The main source of this energy is normally the radiant energy received from the sun. By restricting the amount of sunlight reaching the leaves, shading puts an "energy brake" on the evaporation process. However, there is a conflict here because the amount of shade that can safely be applied is limited by the need to provide sufficient light for photosynthesis, the process that fuels the wound healing and rooting mechanisms.

The effect of wetting

Finally, the model also provides a reason to expect that applying water to the outside of the leaves, as with mist or fog, should reduce transpiration. Because transpiration depends on the supply of energy required for the evaporative process itself, it will be reduced by any other process that competes for the available energy. Evaporation of water from the **surface** of the leaf provides such competition and thus reduces evaporation from inside the leaf, i.e. transpiration (Figure 2d). This explanation is rather different from that commonly propounded. By avoiding any mention of evaporative cooling, it avoids the suggestion that wetting will only be effective under low humidity conditions. This is important because wetting is also effective even under saturated conditions, reducing the leaf warming effect referred to earlier (i.e. the leaves are cooler than they would be without wetting even though they remain above the temperature of the surrounding air).

It is also possible that wetting can reduce transpiration by covering the stomatal pores with a film of water. However, this is only likely to be important for subjects which have a significant number of stomata on the upper leaf surfaces. Most trees and shrubs do not fall into this category. Wetting may also allow for water **uptake** through leaves. Available evidence suggests that any such uptake makes a very minor contribution because of the impermeability of the cuticle (Grange and Loach, 1983).

We have seen that the water vapour concentration difference between the leaf and the air around it, maintained by the radiant energy from the sun, provides what might be thought of as the "driving force" for transpiration. However, the actual rate of transpiration depends also on the resistance to diffusion. This depends largely on the size of the stomatal pores and is thus under the control of the leaves themselves. However, stomatal closure does not completely prevent water loss, because the cuticle is not completely impermeable to water. Furthermore, complete stomatal closure is to be avoided because it would also prevent photosynthesis by blocking the uptake of carbon dioxide. The same is likely to apply to the various anti-transpirant materials that can be used to form an impermeable coating if applied by dipping to the underside of the leaf.

This outline of our present understanding of the physical processes controlling water loss from cuttings provides a sound basis for concentrating on three factors in the propagation environment:

(a) raising humidity close to saturation

(b) wetting the foliage

(c) reducing light levels as much as is compatible with adequate photosynthesis.

At present there is no sound theoretical basis for predicting the relative effectiveness of each of these factors. The effect of wetting is particularly difficult to integrate into an overall mathematical model of the process. Furthermore, the theory is restricted to effects on transpiration and cannot predict the ultimate effect on rooting of cuttings. In practice, other effects, such as leaching of nutrients from leaves, and wetting the compost may influence the benefit to rooting.

Experimental approach

The purpose of the experiments was to determine how, in practice, the three factors highlighted by the theory contribute to successful rooting of a range of cuttings. This involved creating a number of contrasting rooting environments which would allow the contributions of humidification, wetting, and shade level to be identified.

Materials and methods

The rooting environments

Year 1 (1988):

Nine environments were defined within the following four separate facilities:

A. Wet fog tunnel. Combined humidification and wetting was provided by a modified version of the Agritech spinning nozzle fogger. Located in the corner of a well-sealed 7 x 13 m PVC-clad tunnel it operated for 1 minute every 15 minutes during daylight hours. This type of fogger has a high output (about 135 *l*/h) so that one minute was sufficient to reduce visibility to a few metres, and some of this fog was always visible at the end of the 15 minute interval. The fogger also ran whenever a thermostat (set to 27.5 °C) brought on the exhaust fan. The fogger was positioned next to the air intake louvres to humidify the incoming air before it reached the cuttings. It was able to maintain dense fog even while the 18" exhaust fan was operating (4300 cfm). A fan was incorporated in the fogger itself to distribute the fog, and an oscillating mechanism rotated the machine through approximately 130° to help spread the fog throughout the house. Nonetheless, there was a marked decline in the amount of wetting of both cuttings and compost at increasing distance from the machine (See separate report - Harrison-Murray *et al.*, 1993).

B. Dry fog tunnel. Two fog nozzles (Sonicore type 052H from Lucas Dawe Ultrasonics, air pressure 70 psi, water flow rate 10 *l*/h) injected fog at one end of a 7 x 9 section of a PVC-clad tunnel. The designation "dry" fog refers to the fact that most of the water droplets from such nozzles are small enough to remain in suspension long enough to evaporate before they reach the floor or other surfaces, which therefore remain dry. However, in this facility there was minimal ventilation and the fog output was sufficiently high to keep foliage lightly wetted up to about 2 m from the nozzles. Outside this zone there was generally thick visible fog and the humidity was always close to saturation, but there was little or no wetting of leaves or compost. Fogging was controlled by the prototype of a new "evapostat", more details of which will be found in the separate report (Harrison-Murray *et al.*, 1993) which also considers further the technical aspects of fogging.

C. Dry fog under glass. One fog nozzle (Sonicore type 052H from Lucas Dawe Ultrasonics, air pressure 70 psi, water flow rate 10 *l*/h) injected fog at one end of a 2 x 5 m compartment equipped with computer-controlled vents and heating. Attempting to use the shade screen to contain the fog had proved unsatisfactory so the compartment was lined with polythene to contain the fog. Within this small enclosure steep gradients of wetting could not be eliminated. It operated under normal humidity control, generally set to 97.5% RH but adjusted, if it appeared necessary, to suit prevailing weather conditions.

D. Mist under glass. There were two independent 1 x 6 m mist beds, equipped with Macpenny nozzles and electric "leaf" wetness sensor controls, one bed being enclosed in a transparent polythene tent to raise the humidity. The position of the "leaf" was adjusted to give fairly generous misting, such that leaves were always well wetted. The glasshouse itself was small, unheated, with manually controlled roof vents set to provide moderate ventilation. A polythene curtain, about 1m high, surrounded the non-enclosed bed to prevent dry air blowing directly onto cuttings near the edge of the bed.

Within these facilities the following environmental treatments were defined:

1. In facility A, 2 m from the fogger, cuttings heavily wetted.
2. In facility A, 8 m from the fogger, cuttings lightly to moderately wetted.
3. In facility B, 1 m from a fog nozzle, cuttings lightly to moderately wetted.
4. In facility B, 5 m from a fog nozzle, virtually no wetting.
5. In facility C, 3 m from the fog nozzle, where wetting was generally light or absent.
6. In facility D, the polythene enclosed mist bed.
7. In facility D, the open mist bed.
8. In facility D, in a non-misted section of the polythene enclosure.
9. In facility A, 2 m from the fogger, cuttings heavily wetted but under reduced shade.

These environments will be referred to as E 1 to E 9, and are described in more conventional terms in Appendix 1.

Shading on each facility was adjusted so that cuttings in E 1 to E 8 received approximately the same amount of light, the target being 20% of outside light. Most shade was external so as to achieve the maximum reduction of air temperature (shade material is warmed up by the radiation it intercepts so that internal shade is less effective in keeping down temperatures). In one corner of the wet fog tunnel shade was reduced to allow about twice as much light to reach cuttings in E 9.

Year 2 (1989):

In the second year experiments were designed to examine more thoroughly the response to light and its interaction with humidity, wetting and ventilation.

Specially constructed shade structures created a continuous gradient of light level from 10% to 40% of available daylight, across a 2 m wide bed, in the heavily wetted part of the wet fog tunnel (facility A) close to the fogger (similar to E 1 in 1988). The shade structure was based on a Ludvig Svensson reflective thermal screen material (LS 11), the progressive decrease in shade being achieved by removal of an increasing proportion of the reflective strips. To avoid confounding with other factors that might vary across the bed (e.g. amount of leaf wetting) two replicate shade frames were mounted with the shade gradients running in opposite directions. They were mounted just above the cuttings so as to minimise changes in transmission with changing solar angle.

In the mist house (facility D), external shade was used to achieve light levels of about 20% and 40% of daylight. Open and polythene-enclosed mist beds were independently controlled by electric "leaf" in the less shaded zone. Water output in the more heavily shaded half of each bed was reduced by about half by using smaller nozzles. The controls were adjusted so that visible leaf surfaces were always wet.

Subjects propagated

The following subjects were selected, in consultation with the industry co-ordinators, to represent a range from "very difficult" to "troublesome", and also to provide a wide range of leaf size. They were propagated on the dates shown.

Table 1. List of material propagated in Year 1

Experiment	Dates	Subject
Year 1		
1a	22.5-22.6.88	*Syringa vulgaris* 'Charles Joly', apical cuttings from hedge and non-earthed-up stool sources
1b	14.6-12.7.88	" " " " "
1c	05.7-02.8.88	" " " " "
5	14.6-13.7.88	*Parrotia persica*, apical
6a	16.6-18.7.88	*Betula pendula* 'Dalecarlica', apical
6b	29.6-29.7.88	and non-apical nodal cuttings
7a	17.6-19.7.88	*Garrya elliptica* 'James Roof' apical
7b	30.6-01.8.88	" " " "
8a	21.6-20.7.88	*Cotinus coggygria* 'Royal Purple' apical
8b	23.6-28.7.88	" " " "
9	07.7-04.8.88	*Corylus maxima* 'Purpurea' apical

10	14.7-15.8.88	*Acer platanoides* 'Crimson King' apical
11	18.8-02.10.88	*Berberis stenophylla* - apical & semi-ripe nodal
15	23.8-29.9.88	*Cotinus coggygria* 'Royal Purple' apical
17	25.8-05.10.88	*Cytisus Burkwoodii* (clone 7) apical cuttings from lateral shoots
20	13.9-20.10.88	*Garrya elliptica* 'James Roof' apical
23	22.9-02.11.88	*Berberis stenophylla* - ripe nodal
27	26.10-14.12.88	*Garrya elliptica* 'James Roof' - soft apical
	"	*Garrya elliptica* (non selected) - ripe apical
22	21.9-02.11.88	*Ilex aquifolium* 'Handsworth New Silver'
25	12.10-24.11.88	" " "
28	8.11-20.12.88	" " "

Experiments where shortage of material limited replication to < 20 cuttings per treatment

12	16.8-28.9.88	*Photinia* 'Red Robin' - apical
		Photinia 'Red Robin' - proximal nodal
16	24.8-29.9.88	*Wisteria sinensis* non-basal, nodal
18a	31.8-11.10.88	*Arbutus unedo* - apical
18b	1.9-11.10.88	*Rhamnus alaterna* 'Argenteovariegata' apical
18c	1.9-11.10.88	*Ceanothus impressus* apical

The plants selected for more detailed study in the second year are shown in Appendix 3

Handling and treatment of cuttings

Cuttings were generally collected before 10:00 hours and prepared immediately in a cool damp room. They were dipped or sprayed with water if they showed signs of wilting. A standard auxin treatment was adopted which consisted of a 5 second dip in 1250 ppm IBA (i.e. 1.25 grams per litre of indolyl butyric acid in a 50:50 mixture of acetone and water). The hormone dip was allowed to dry on the cutting before they were handled further. The tops of all cuttings were then dipped in Benlate (2.0 g/*l*). The compost was a 50:50 mixture of peat (Irish medium grade) and pine bark (Cambark fine grade). No slow release fertiliser was added because the rate of both release and leaching would have varied between environments, complicating the interpretation of the results.

Experimental units and design

There was inevitably some variation within each notional environment, such as the variation in water deposition around mist nozzles. To minimise the impact of such local variation, cuttings were stuck in 11cm square pots rather than conventional trays so that the available cuttings could be spread over a wider area. From 4 to 8 cuttings were inserted per pot, depending on the subject. Each pot represented an experimental unit in a randomised block design. The blocks were used to absorb any variation associated with handling factors, such as might occur, for example, between the first and last batches to be stuck. In each environment the arrangement of blocks was designed to absorb effects of predictable variation in wetting and to accommodate all subjects in one design. Within each block, subjects were kept separate. There was generally 2 cm between pots, but this was increased if necessary to avoid excessive mutual shading with the larger cuttings.

Assessment of the rooting response

Year 1: After four weeks, or longer for slow rooting subjects, cuttings were removed from their pots to record root number, maximum root length, callusing, rotting at the base and/or shoot tip as appropriate to the subject. A few cuttings were potted-off for observation but the stress involved in the thorough recording prevented any realistic assessment of establishment ability.

Year 2: Recording of rooting was done in two stages. At four weeks after insertion (or more for slow subjects) half the cuttings from each treatment were removed for detailed recording of rooting, rotting, etc. and were then oven-dried to determine the net dry matter accumulation over the rooting period. The remainder were weaned, via the dry fog tunnel, over the course of about two weeks, before a simple rooting percentage record was made and representative cuttings were potted-up. This system was a compromise between the need to have accurate information on the initial rooting response, whilst beginning to extend the study to the effect on subsequent growth.

Environmental measurements

A data logging system was used to monitor the temperature of the air and compost, and the light level in each environment over the course of the whole season. It also provided records of humidity, but for most environments these had to be restricted to short representative periods. This was mainly because there is no instrument that reliably measures humidities near saturation without constant attention. Wet and dry bulb measurements are the most reliable and an electrical version was used in the present studies. However, in "wet" fog, the dry bulb tended to become wet so that only short-term spot measurements were possible.

Water deposition was measured by weighing the water which collected in plastic petri dishes. There is no way to prevent water collecting in the dish from subsequently evaporating, so that the method actually measures **net** water deposition. The evaporation is minimised by ensuring that the dish absorbs as little energy from its surroundings as possible (see the theoretical section for an explanation). Using a transparent dish, held clear of the compost on a transparent stand, minimised both radiation absorption and heat conduction from the compost.

Data were also collected using an evaporimeter designed to simulate evaporation from a leaf (Figure 3). This provided a way of estimating the combined effects of all the relevant environmental factors, but it is important to recognise that it has not been proved to match real leaves closely. In particular, it estimates the opportunity for water loss while stomata are fully open, it makes no allowance for any water that may be absorbed through the leaf cuticle, and it probably absorbs a higher proportion of the radiation falling on it than would a real leaf.

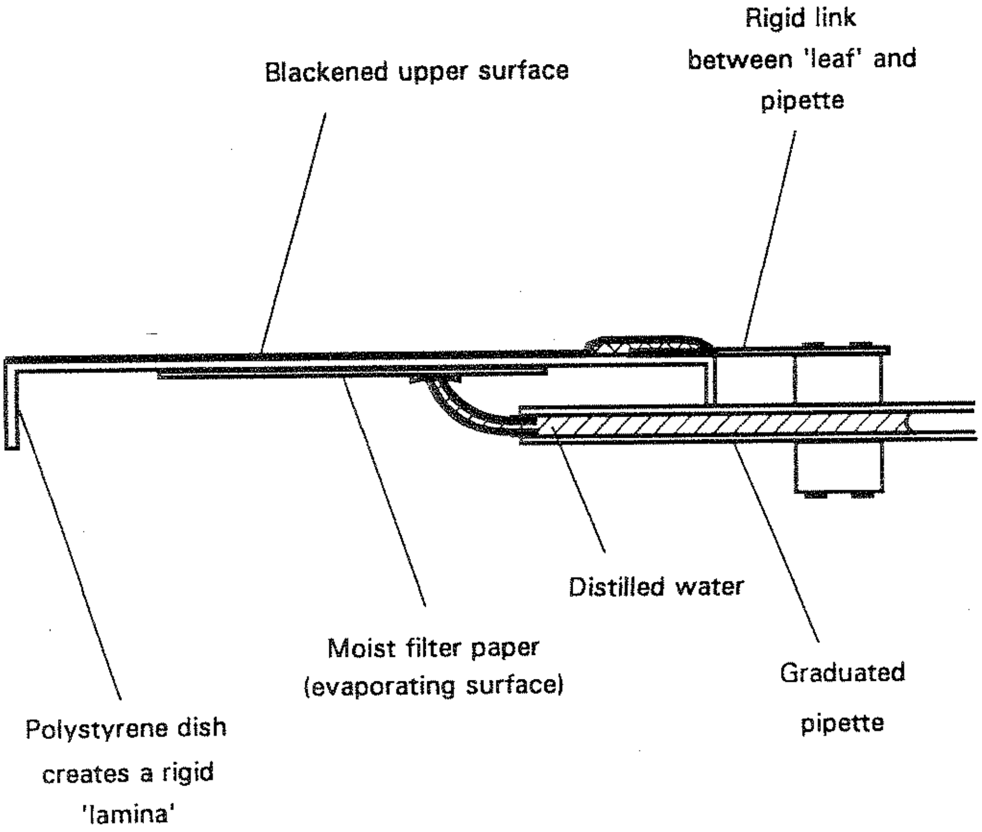

Figure 3. Diagram of the leaf-model evaporimeter.

Results

Year 1

Environmental measurements

Humidity

The presence of visible fog does not necessarily mean that the air between the droplets is saturated unless, as in the case of natural fog, it has formed by condensation when moist air has cooled to its dew point. Measurements in the wetter fog environments (i.e. environments 1, 2, 3, and 9) had to be limited to brief "spot" checks so that the dry bulb had little chance to become wet. From these data it was clear that the humidity in those environments could effectively be considered as 100% RH.

The other high humidity systems, in which wetting of the dry bulb did not occur, were monitored by automatic data logging equipment. Even in the "dry" fog environments, in which some fog was always visible, the average humidity was 2% below saturation (i.e 98% RH) but the deficit was twice this in the polythene tent (i.e. 96% RH, see Appendix 4a). For enclosed mist (E 6) this figure indicates the **lowest** humidity to which leaves would have been exposed between mist bursts, measurements being made well above the mist, not amongst the cuttings. For open mist (E 7), spot measurements indicated that humidities ranged from about 2 to 30% below saturation (i.e. about 70 to 98% RH) with an average of about 15% (85% RH), that is about seven times drier than "dry" fog and four times drier than the polythene tent.

Wetting

The amount of water falling on the leaves was estimated as the net water deposition (NWD) in a transparent dish (see methodology section for an explanation of the concept of NWD). Figure 4 shows that the environments fell into three categories as follows:

1. Heavy wetting of more than 1 mm per day. Both mist enclosed under polythene and open mist (E 6 and E 7) fell into this category. In general misting tended to be less frequent under polythene but, if leaves were to be kept wet **in all parts** of the bed, the average amount of water deposited was necessarily high.

2. Moderate wetting, in the region of 0.5 to 1 mm per day. This was characteristic of all locations in the ventilated wet fog tunnel and of locations close to the nozzle in the dry fog tunnel (E 1, E 2, E 3, E 9).

3. Light wetting of less than one tenth of a millimetre per day. This was characteristic of that part of the dry fog tunnel that was beyond a radius of about 2 m from one of the nozzles (E 4). Generally this area was still densely foggy for much of the day but it appeared that the majority of the water droplets were evaporating before they had a chance to settle, so that wetting was negligible.

In both dry fog under glass (E 5) and the simple polythene tent (E 8), NWD was negative, that is to say that evaporation exceeded deposition. The small negative value recorded in the polythene tent (E 8) can be taken as an indication of the rate of evaporation from the **transparent** dishes, since there was no wetting in that treatment. This indicates that, for the humid environments, gross water deposition would have been close to the measured net value.

Evaporation of water from the surface of **leaves** would generally have been faster than from the dishes because they absorb more of the incoming radiation, increasing the vapour concentration gradient and with it evaporation rate, as explained in the theoretical section; just how much faster was estimated by blackening the base of some dishes. The size of the reduction in NWD in these dishes compared to the transparent ones is a measure of this additional evaporation and is shown by the line in Figure 4 . There are no data for the two mist environments because large point-to-point variations in wetting obscured the comparison of the differently coloured dishes.

In the light wetting category, evaporation greatly exceeded net water deposition. This implies that although some water might be deposited on the leaves, the potential for it to evaporate was greater than the rate of deposition. Under such circumstances, one would expect that a layer of water could never build up on the leaves so that they would always appear dry. However, the plotted values are averages of measurements made over many days and at many locations within each environment, so that it is not surprising that in fact, from time to time, light wetting of the foliage was evident.

In the moderate wetting category, net water deposition generally exceeded evaporation and leaves consequently appeared wet most of the time. The higher light level in E 9 approximately doubled evaporation but this was still less than deposition.

The amount of water deposited varied from point to point within all the environments. Variation was greatest in mist, the amount collected in dishes less than one metre apart sometimes differing three-fold. By comparison, in the wet fog tunnel variation within the defined environments rarely approached two-fold. However this must be seen in the context of the larger scale gradient of wetting within the house as a whole that had made it possible to define "dry" and "wet" zones as separate environments within it.

Potential transpiration

A physical model of a leaf (a leaf-model evaporimeter) was used to try to measure the combined effects of all the factors influencing water loss from leaves. It was designed to measure the maximum transpiration rate that could possibly be observed from a real leaf under the same conditions, that is the rate that would occur if the stomatal pores offered no resistance whatsoever to water vapour loss. This will be referred to as the potential transpiration rate and is related to the well-established concept of potential evapo-transpiration as applied to field crops.

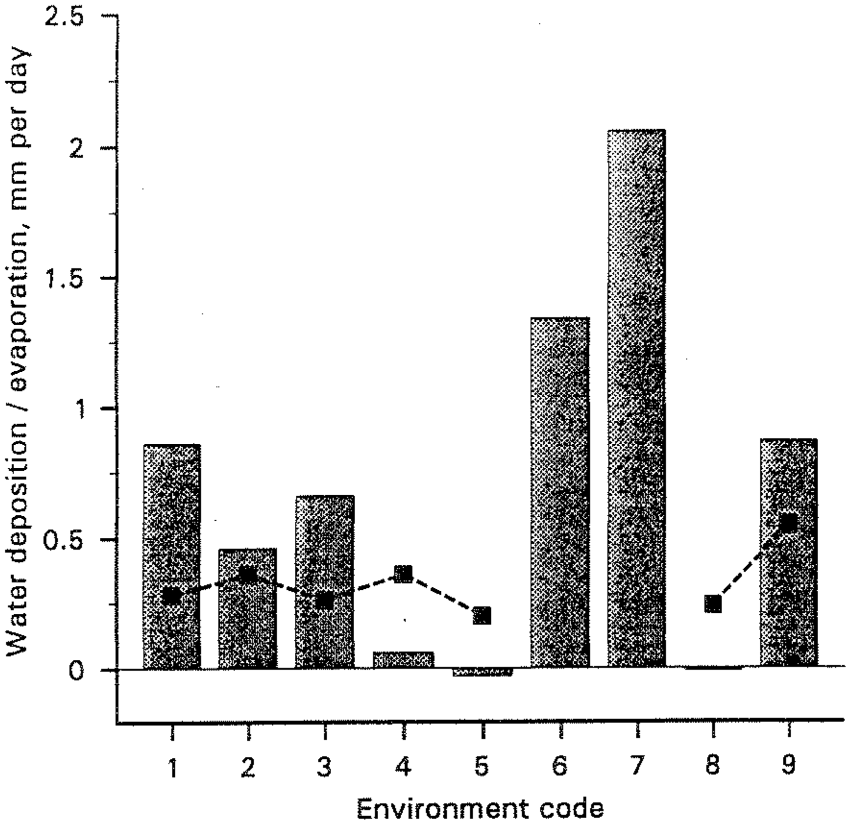

Figure 4. Average rates of net water deposition recorded in June and July of year 1, shown by the bars, together with a rough estimate of potential evaporation based on the additional evaporation of water from a **blackened** dish (broken line).

The comparison of the different environments is shown in Figure 5. Potential transpiration was greatest in open mist and in the simple polythene tent environment (E 7, E 8). However, by comparison, even the wettest fog environment (E 1) reduced potential transpiration by less than half. By contrast, the reduction in potential transpiration overnight (i.e. generally the period from 17:00 to 09:00 hours) averaged about 85%. This emphasises the important role of solar radiation in driving water loss from leaves, that applies particularly under humid conditions. The overnight reduction was smallest in open mist because the relatively low humidity in that environment (E 7) reduced the dependence on radiation.

The importance of radiation is seen even more clearly in Figure 6 which also illustrates important differences between the environments. In the polythene tent and wet fog high humidity systems, potential transpiration approached zero at low light levels and the difference between the sophisticated wet fog and the simple polythene tent lay in the rate at which it rose as light level increased. On the other hand, under open mist, potential transpiration was higher than in any other system at low light levels but did not rise as rapidly as in the polythene tent. The line for polythene-enclosed mist did not show the same tendency for water loss at low light, indeed it was barely distinguishable from that for wet fog and was omitted for the sake of clarity.

Some of these results, particularly the overriding sensitivity to light level and the modest response to wetting, led us to doubt whether the leaf-model evaporimeter was behaving sufficiently like a real leaf to give useful information. For example, the difference between the two zones in the dry fog tunnel (E 3 and E 4) seemed too small to account for severe wilting of subjects such as *Cotinus coggygria* 'Royal Purple' at the drier end but not in the wetter zone around the nozzles. Water loss from *Cotinus* cuttings was therefore measured in these two environments, in parallel with further measurements of potential transpiration. The cuttings were freshly collected and sealed into bottles of water so that water loss could be measured as the change in weight of the bottle plus cutting. Figure 7 shows that differences in water loss from the cuttings broadly paralleled that from the leaf-model evaporimeter though the actual rates were much slower. Some discrepancy in actual rates was to be expected due to the restriction imposed by the stomatal pores of the real leaves. What is less obvious, but of greater significance, is that wetting reduced transpiration from the real leaves proportionately more than that from the leaf-model evaporimeter (Table 2).

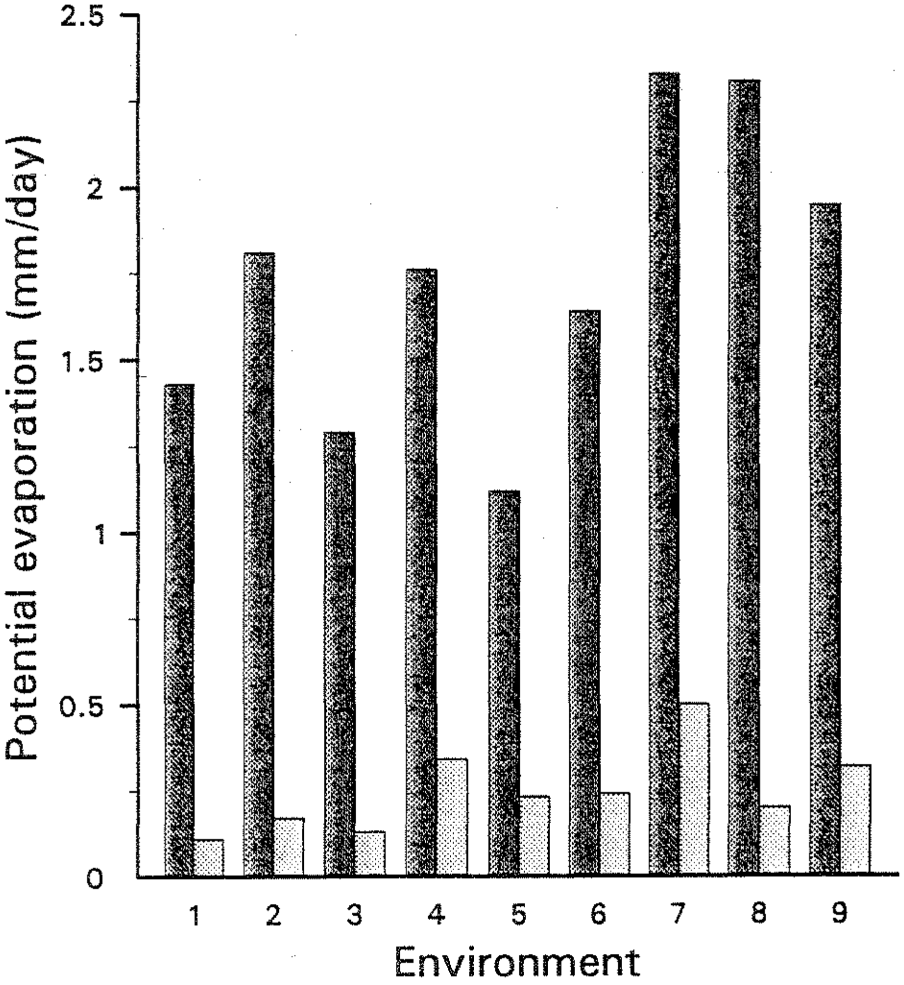

Figure 5. Potential evaporation as estimated by the leaf-model evaporimeter (see Figure 3). Data were collected from 27.7.88 to 11.8.88; "day" (dark columns) and "night" (light columns) relate to the working day (approximately 09.00 to 17.00 h).

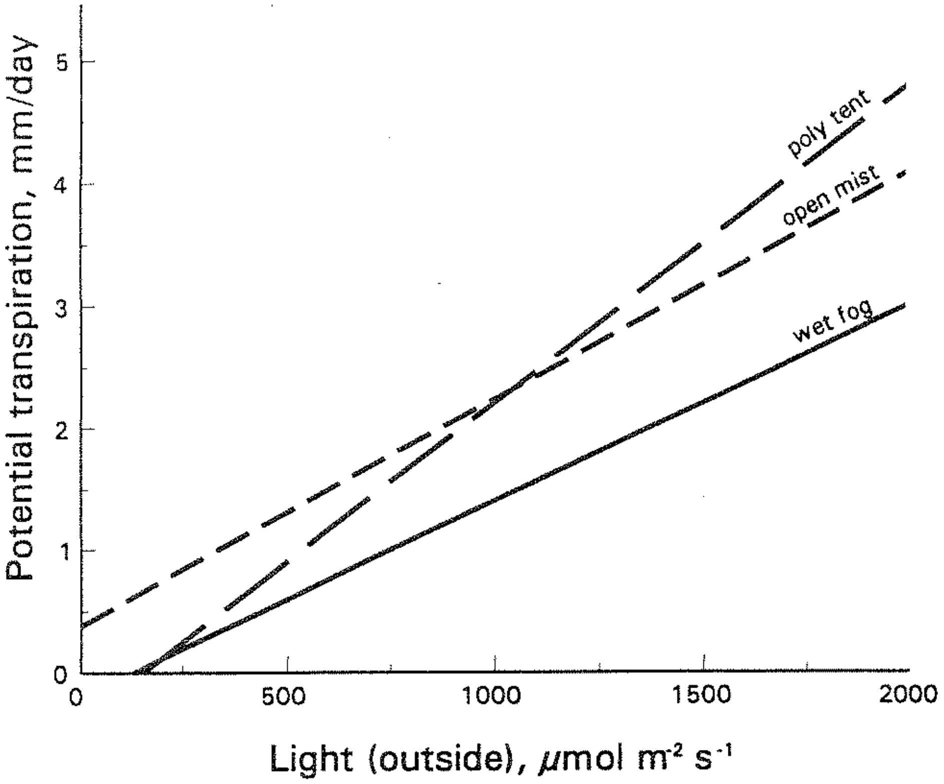

Figure 6. The relationship between potential transpiration (from the leaf-model evaporimeter - see Figure 3) and light level in three contrasting environments. The lines were fitted by linear regression. Light at cutting level would have been about 20% of that outside.

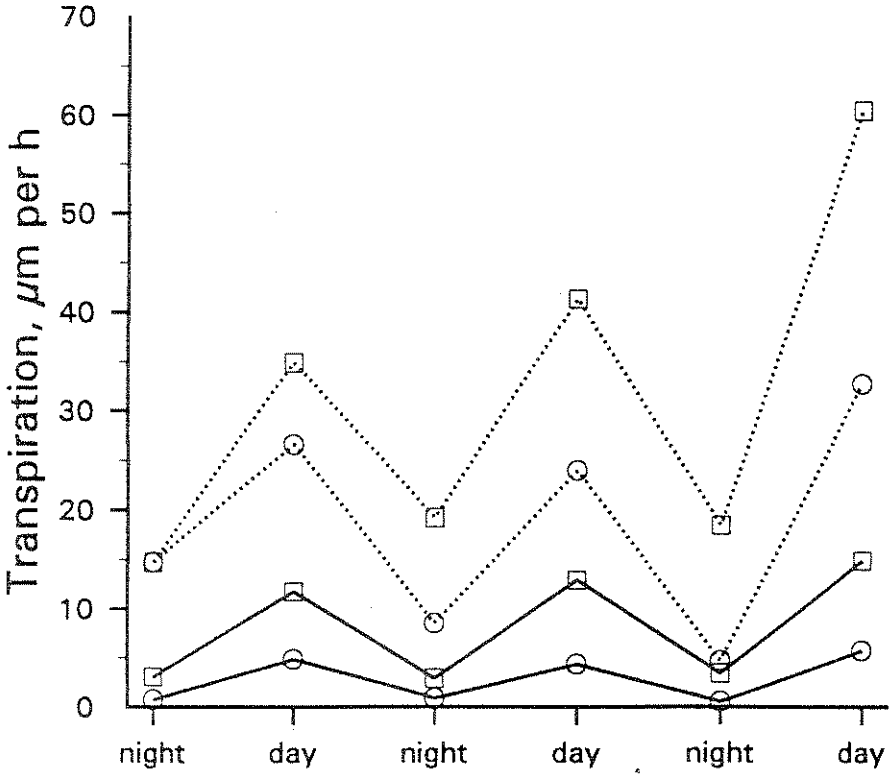

Figure 7. Comparison of actual transpiration from *Cotinus* leaves (circles) with potential transpiration estimated by the leaf-model evaporimeter (squares) at the wet (solid lines) and dry (dotted lines) ends of the "dry" fog tunnel, i.e. E 3 and E 4. Data collected from 11.10.88 to 14.10.88.

Table 2. Effect of wetting on water loss from a real cutting of *Cotinus coggygria* (**actual** transpiration) compared to the leaf-model evaporimeter (**potential** transpiration) in a high humidity environment. Day and night relate to a working day of 09:00 to 17.00 h.

	Transpiration rate, μm per h		
	Environment 3 (moderate wetting)	Environment 4 (light wetting)	Reduction due to additional wetting
	Daytime		
Actual	4.9	13.2	63%
Potential	27.8	45.6	39%
	Overnight		
Actual	0.7	3.1	77%
Potential	9.3	17.5	47%

This comparison illustrates the difficulty of relying on **potential** transpiration as a means of distilling the "cutting's eye view" of the dryness of the environment into a single figure. The fact that actual transpiration was lower than potential transpiration is of less concern than the differences in **relative** values when environments are compared.

Such mismatching of the response of the artificial leaf to the real one could have many causes. For example, the stomata in a real leaf impede the evaporation of water from inside the leaf in a way that does not apply to evaporation of external water. There are reasons to believe that this would make transpiration from real leaves, particularly those whose stomata were partially closed, more sensitive to wetting than the leaf-model evaporimeter, which has no such resistance. Since stomatal resistance varies both within and between species, no leaf-model can ever match all real leaves, and it is likely that the present model provides a useful basis for environmental comparisons provided that it is considered along with other data and interpreted with caution.

Air temperature

During the summer, average air temperatures differed little between environments: they were highest in enclosed mist (average daily maximum 31.3°C) and lowest in open mist, but the difference was less than 3°C (Appendix 4b). Even the highest temperature recorded was only 4.1°C cooler in open than closed mist, reflecting the fact that ventilation of the mist house was not generous. By contrast, the forced ventilation integral to the ventilated wet fog system kept it more than 10°C cooler.

In autumn, average temperatures were all below 20°C (Appendix 4c), dropping rather more in those environments under polythene than those under glass, despite the polythene being wet with condensed water, which is expected to act as a thermal screen.

Compost temperature

In all cases minimum compost temperature was close to 20°C, the set point for the compost heating (Appendix 4d). Maximum temperatures paralleled air temperatures closely, though absolute values were about 3°C lower. The additional light in E 9 increased the maximum by about 3°C.

Light

The light reaching the cuttings depended partly on the ambient light level and partly on the amount of shade. Continuous measurements showed that 18% to 20% of outside light was penetrating the shade in all but two environments. In E 9 the reduced shade allowed 32% light transmission, while in E 5 the integral glasshouse shade allowed 13% of outside light to reach the cuttings.

Figure 8 shows that solar radiation levels were broadly stable for much of the period covered by the experiments, but that after the end of August, shortening days and lower solar angle are reflected in reduced average light levels and air temperatures. Substantial short-term variation is also evident. For example, cuttings propagated on June 19 would have received nearly 3 times more light over the first 5 days than cuttings inserted on June 8. Such variations could account for the large differences sometimes seen between batches of similar cuttings collected just a few days apart, especially where the propagation system cannot respond to changes in weather (e.g. a polythene tent, or timer-controlled mist).

Up to the end of October, light levels were generally sufficient to provide at least 1.5 MJ per m^2 per day, the level below which rooting is likely to be impaired (Loach and Whalley, 1978), in all treatments except E 5. Therefore, of the main experiments, only in the last of the *Garrya* propagations (experiment 27), would any treatments have fallen below this threshold.

Rooting responses of individual subjects

Rooting of all the subjects examined was affected by environment, and in many cases varied from almost 0% in the least favourable environment to near 100% in the most favourable (e.g. *Corylus maxima*, *Cotinus coggygria*, and *Garrya elliptica*). Not all subjects responded in the same way, as can be seen by comparing the graphs of rooting percentage results (Figures 9 to 17). In these graphs the environmental treatments are referred to by their treatment codes (see page 12) but instead of being in numerical order they are arranged according to the gradation of environmental conditions that they provided. These varied from high humidity + heavy leaf wetting (on the left and labelled "wet"), to high humidity without any leaf wetting (on the right and labelled "dry"). Open mist (E 7), with generous wetting but comparatively low humidity, was placed between these extremes. Arranged in this way, it is clear that rooting was generally favoured by generous leaf wetting, and virtually prevented in the absence of wetting, but there were important differences between subjects. Detailed rooting data, including measures of root length and number as well as basal rotting, are given in Appendix 2; also included are those subjects for which shortage of material restricted the number of environments which could be tested.

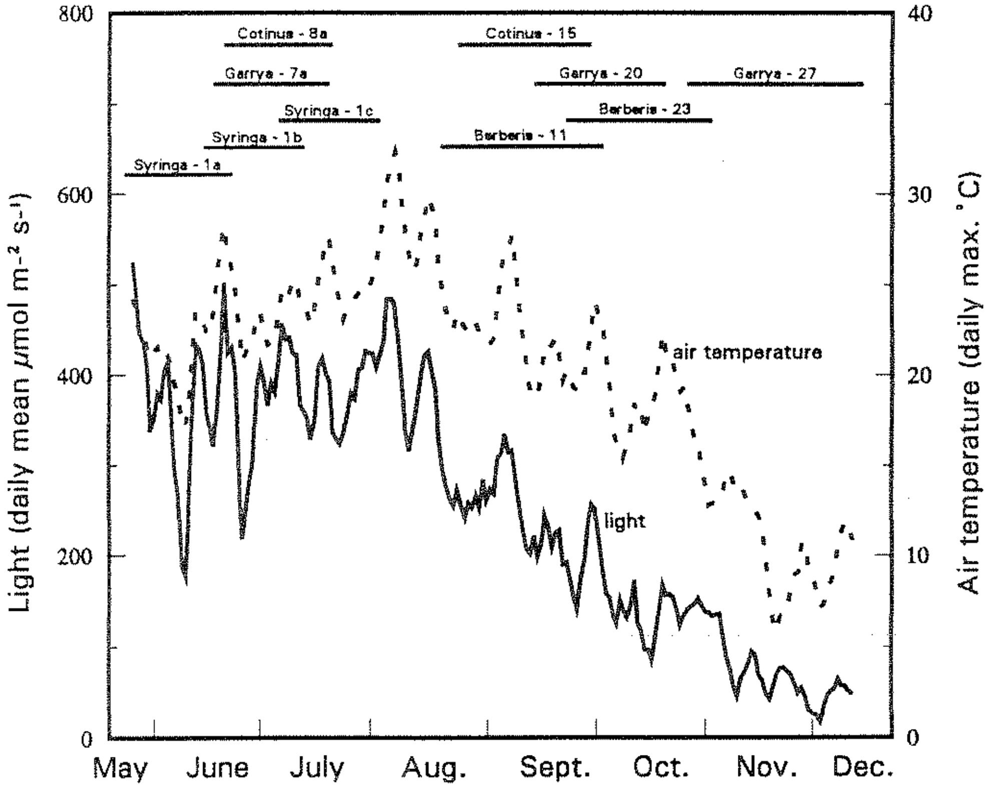

Figure 8. Summary of weather conditons for year 1 experiments. The horizontal bars indicate rooting periods for each of the main experiments. Plotted values of light (solid line) and temperature (broken line) are 5-day running averages, so as to emphasise medium term variations and filter out most of the day-to-day fluctuations. The date indicated is the start of each averaging period.

The light values are 24 hour averages, and therefore take into account the effect of daylength on total radiation received. The units used (photosynthetic photon flux density) can be approximately converted to lux by multiplying by 54, or to MJ per m^2 per day of total solar radiation by dividing by 21.5.

For example, Figure 10 shows that soft apical (tip) cuttings of *Garrya elliptica* 'James Roof' rooted well under the very wet and humid conditions of E 1 (wet fog, close to the fogger) but failed completely in open mist (E 7), whereas similar cuttings of *Parrotia persica* rooted well in both (Figure 15), and *Berberis stenophylla* generally preferred mist (E 6 and E 7 - Figure 16). Some rather more subtle differences are also evident; for example, there was little difference between the open and closed mist as far as *Berberis* cuttings were concerned (Figure 16), whereas, for *Garrya*, open mist (E 7) was one of the poorest environments and closed mist (E 6) one of the best (Figure 10). Some of the distinctions could reflect changes in what was notionally the same environment, as a result of changes in the weather, but results of repeated propagations, discussed in more detail in a later section, suggest that this is unlikely.

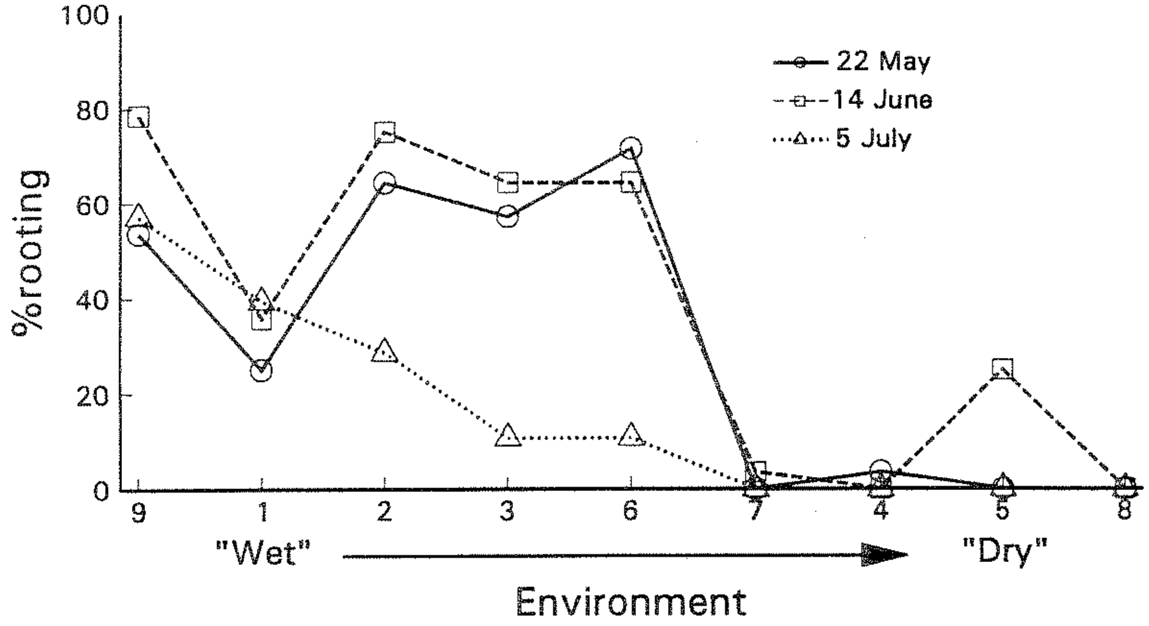

Figure 9. The rooting response of *Syringa vulgaris* 'Charles Joly'

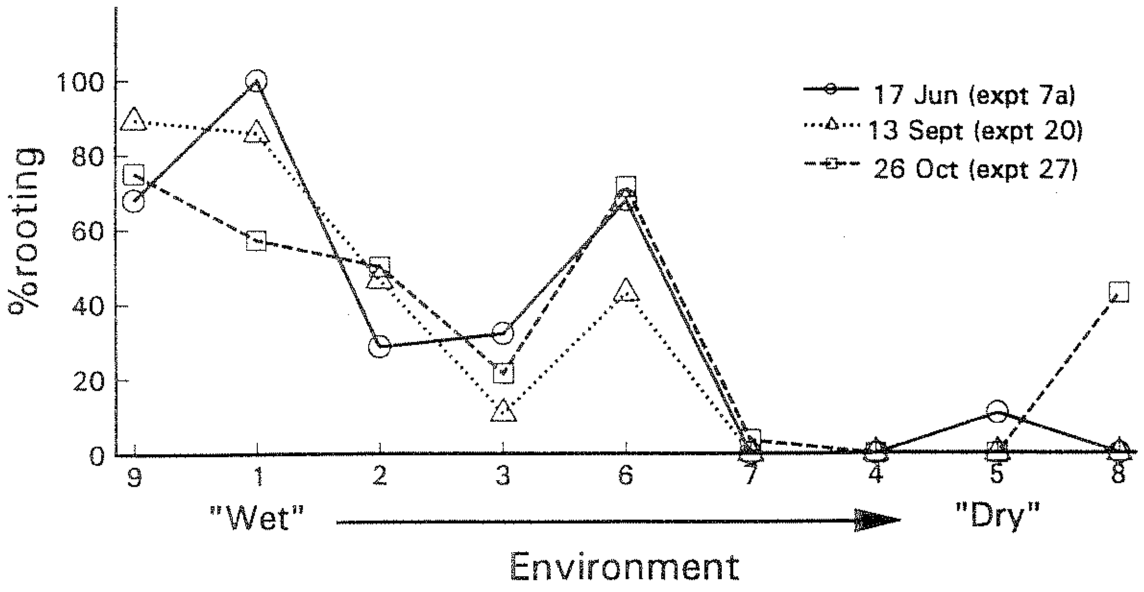

Figure 10. The rooting response of soft apical cuttings of *Garrya elliptica* 'James Roof'

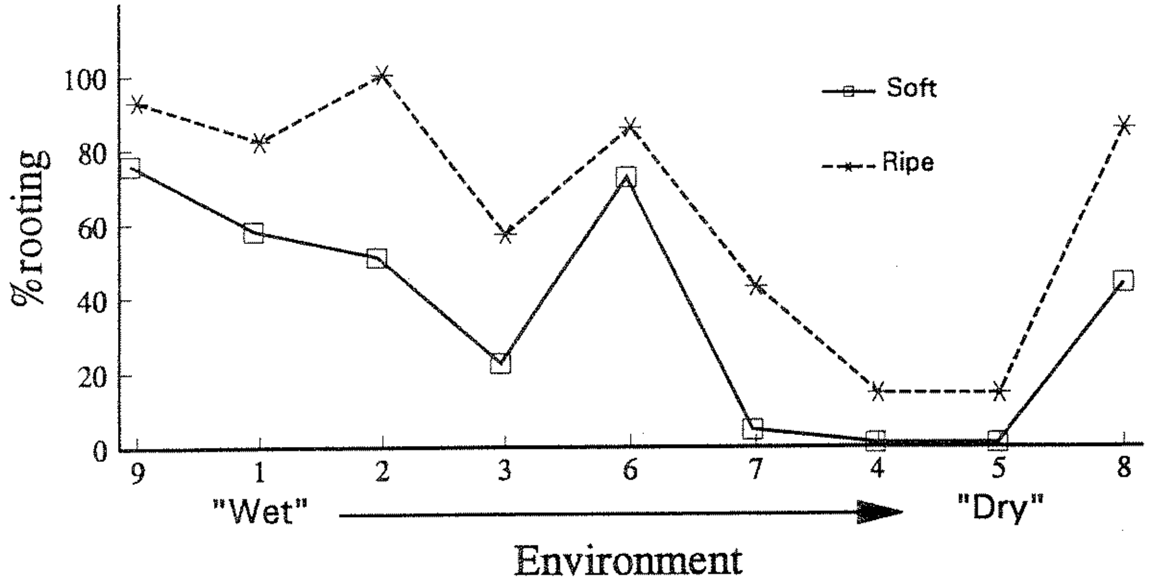

Figure 11. Comparison of the rooting response of ripe *Garrya elliptica* cuttings propagated in late October with soft cuttings from a different source propagated at the same time.

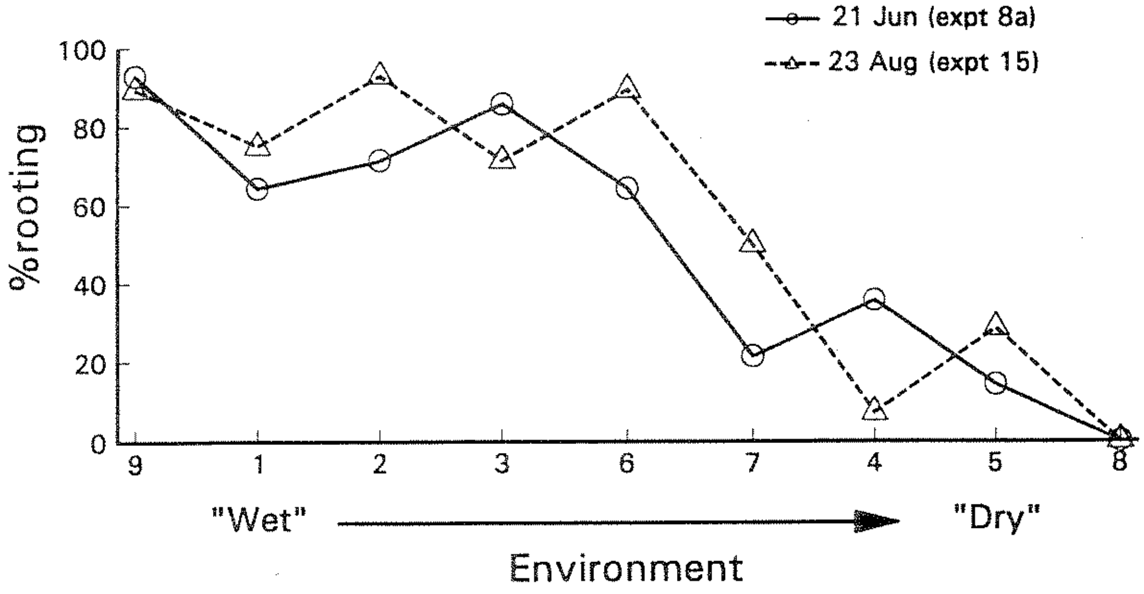

Figure 12. The rooting response of *Cotinus coggygria* 'Royal Purple'.

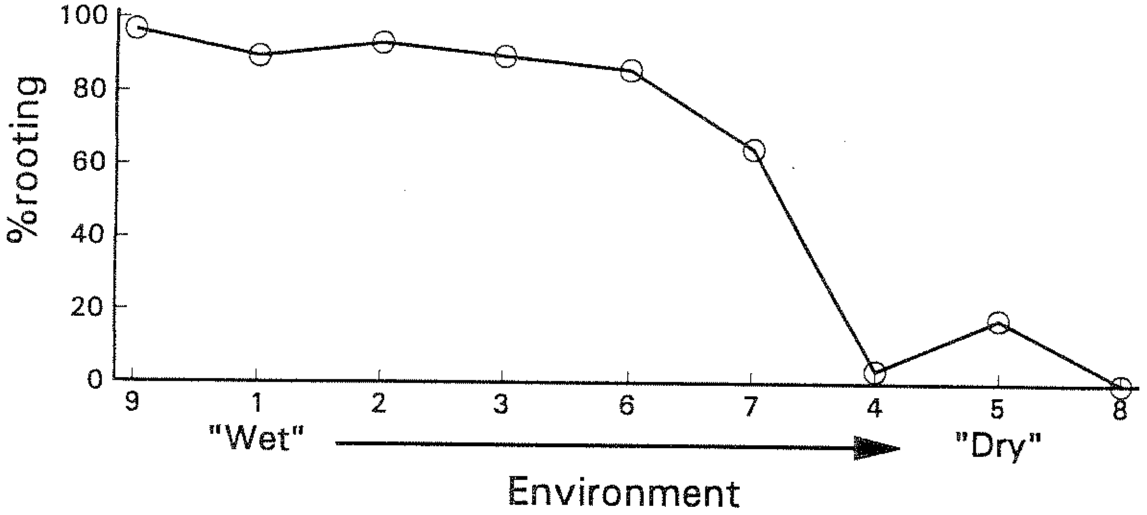

Figure 13. The rooting response of *Corylus maxima* 'Purpurea' propagated on 7 July.

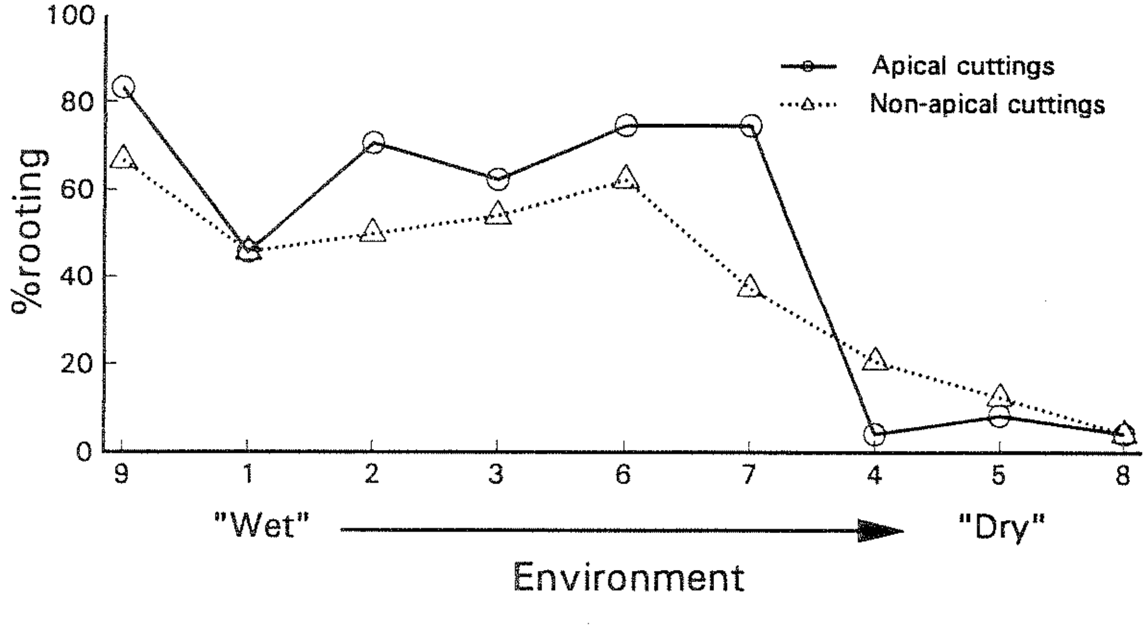

Figure 14. The rooting response of *Betula pendula* 'Dalecarlica' propagated in June (data for 16th and 29th combined)

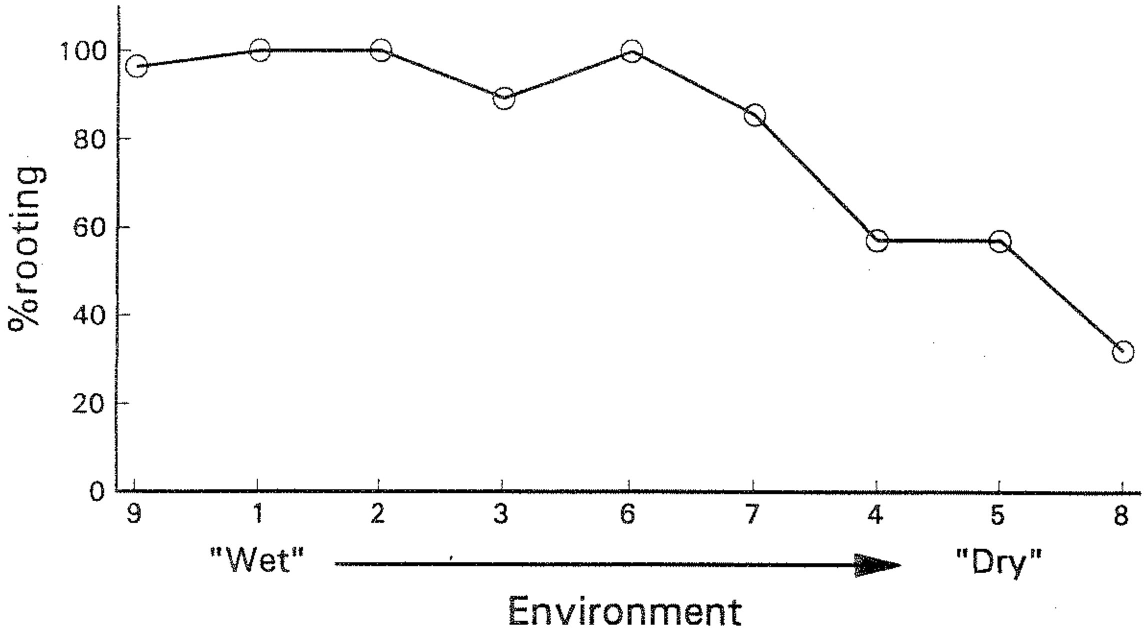

Figure 15. The rooting response of *Parrotia persica* propagated on 14 June.

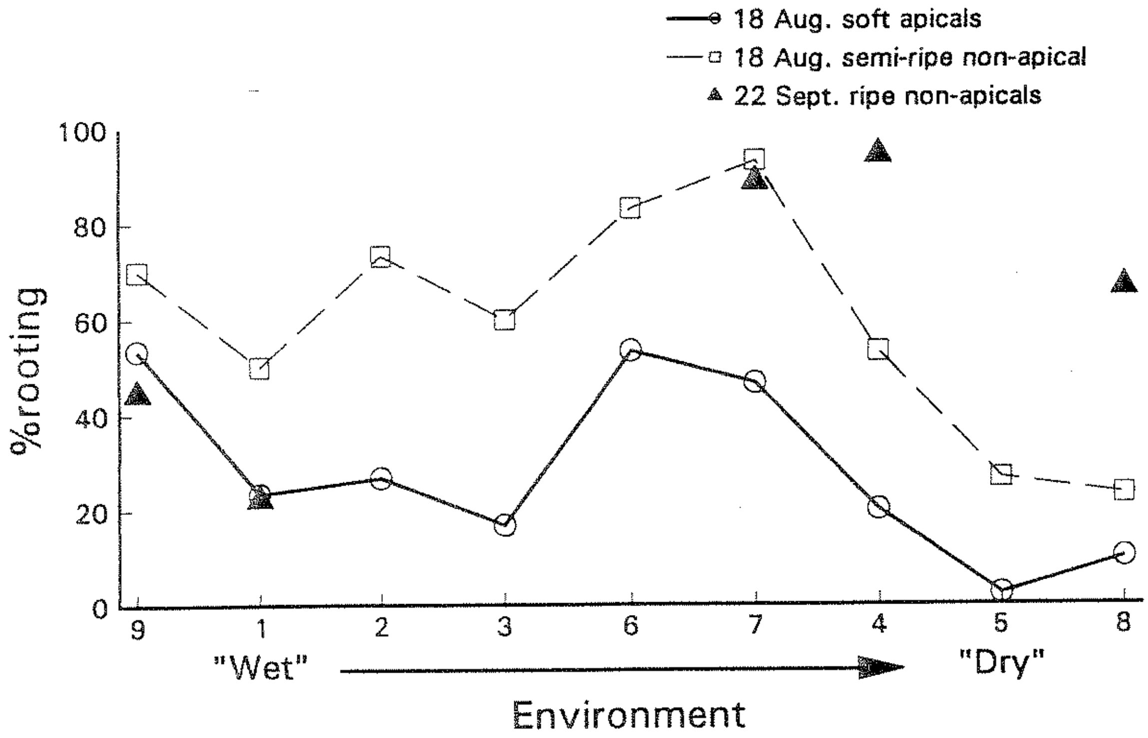

Figure 16. The rooting response of *Berberis stenophylla*.

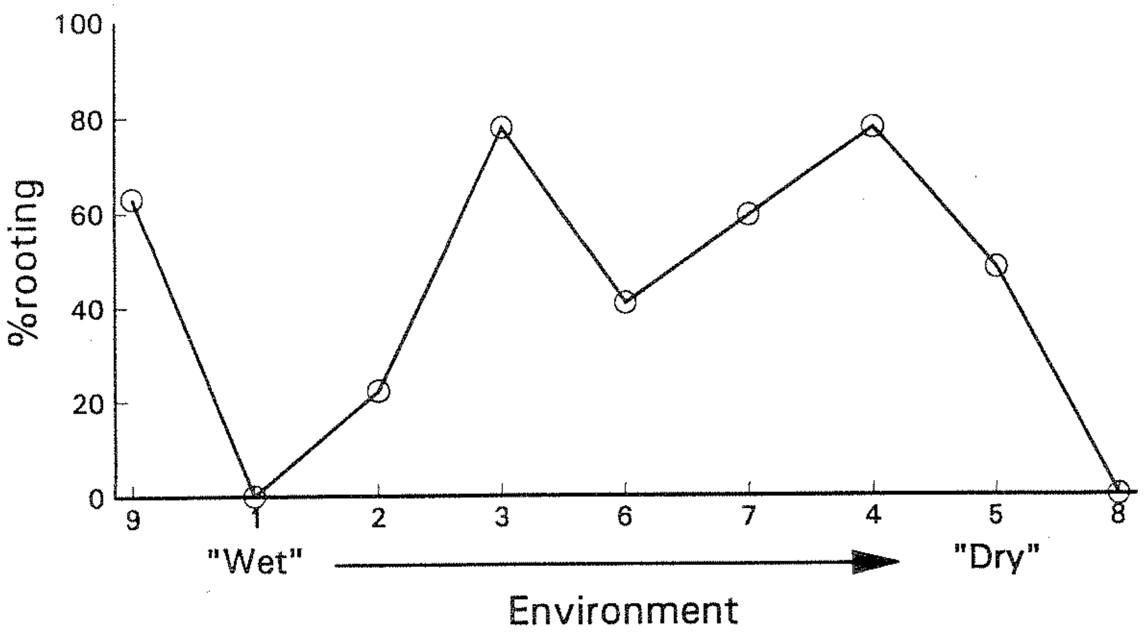

Figure 17. The rooting response of *Cytisus Burkwoodii* (clone 7) propagated on 25 August.

For soft cuttings there was a strong link between wilting and loss of rooting potential. For example, with the acutely wilt-prone soft apical *Garrya* cuttings, definite signs of wilting in E 2 and E 3 compared with virtually none in E 1 was reflected in a loss of about 70% rooting (Figure 10), while cuttings often collapsed completely in the drier environments. In less sensitive subjects, such as *Corylus*, any wilting was always more severe in the environments which provided only high humidity, such as "dry" fog (E 4), than in open mist, (E 7) where humidity was much lower but cuttings were kept wet (Figure 13).

When examining the results of individual experiments, the reader needs to be aware of a fundamental difficulty in achieving high precision data for rooting percentage. It is a difficulty which applies to all information relating to the **proportion** of a sample which either passes or fails a test of some sort. A familiar example is the proportion of "heads" obtained when a coin is repeatedly tossed. To be reasonably sure whether the coin has any bias to fall to one side, it must be tossed hundreds of times. Similarly, no amount of care in the design or execution of experiments can avoid the need to test very large numbers of cuttings if rooting percentage is to be measured with high precision. For this project, with many subjects, many environments, and many propagation dates, it was impractical to use routinely more than 30 cuttings for each treatment. With this number there is a 1 in 20 chance of an error as large as 18% if the true rooting percentage is 50% (i.e. if 50% of an **infinite** number of similar cuttings would have rooted). If the true rooting percentage is 90% then this error reduces to 11%. Statistical analysis confirmed that the variation actually observed was consistent with these predictions. Potential errors in estimates of **differences** between treatments are of similar order.

Clearly then, the grower looking at the detail of the results for an individual subject, perhaps with a view to changing the way he manages his propagation environments, should not rely too heavily on the smaller differences between treatments, particularly those less than 20%. On the other hand, in the absence of any other data, **the values shown represent the "best available" information, and the environment in which the highest rooting was observed remains the one most likely to be genuinely optimal for the subject concerned.**

Overall responses to humidity, wetting and light

In practice, few nurserymen will be in a position to hone their propagation environment to the precise requirements of a single subject. Instead, they have to propagate a wide range of plants and need an environment that will suit all of them reasonably well. To assess the environments against this need for versatility, the results of all the experiments were combined, with the subjects divided into just two categories as follows:

(i) Those with narrow leaves and small total leaf area (*Berberis*, *Cytisus*, and *Ceanothus*),

(ii) Those with relatively broad leaves (i.e. all the other subjects, with leaf size ranging from the very large leaves of *Acer platanoides* and *Corylus maxima* to the smaller and dissected leaves of *Betula pendula* 'Dalecarlica').

There were two reasons to expect these groups to behave differently. First, narrow leaves are liable to become wetted on **both** surfaces by mist and fog, so that transpiration is more effectively suppressed, but with the danger that photosynthesis may also be restricted if stomatal pores are blocked by water. Second, the narrow-leaved group presented a much smaller total leaf area per cutting, thereby directly limiting the opportunity for transpiration. Since the narrow-leaved type were outnumbered in these experiments it would have been an artificial oversimplification to have averaged responses over all experiments.

In trying to see these results in terms of the practical value of improving propagation facilities, it is not the percentage of cuttings which rooted that is important but the number that had the **potential** to root but were **prevented** from doing so by a less than ideal environment. Therefore, for each batch of cuttings stuck, the highest rooting percentage observed in any one environment was taken as the best available estimate of their inherent potential to root. Using this estimate rooting was expressed in terms of the percentage of cuttings which **failed** to root because of suboptimal environment, referred to below as %loss of rooting, or **wasted rooting potential**.

The response of the broad leaved group is show in Figure 18, with the environments arranged in order of decreasing loss of rooting. Losses were greatest in the environments relying mainly, or entirely, on high humidity, that is in most of the dry fog facilities (E 4 and E 5) and in the polythene tent (E 8). These environments prevented more than 65% of cuttings from rooting. By contrast, both wet fog and enclosed mist (E 1, E 2, E 6), which combine high humidity with leaf wetting, reduced losses to less than 25%. Losses in open mist (E 7) were intermediate, at about 50%, indicating that heavy leaf wetting alone, without any attempt to retain humid air, provided a more effective propagation environment than high humidity with minimal wetting. Losses were lowest, at less than 10%, where the shade level was reduced in a generously wetted part of the wet fog tunnel (E 9).

There was no significant difference between enclosed mist (E 6) and wet fog at the same shade level (E 1 and E 2). There is therefore no evidence of any benefit from two of the distinctive features of the ventilated wet fog system: namely, control of maximum air temperature and blowing of fog amongst the cuttings.

The distinctly different behaviour of the narrow leaved subjects is evident from Figure 19, in which similar environments have been grouped as follows:

(A) High humidity, light wetting (environments 4, 5, 8)

(B) Low humidity, heavy wetting (environment 7)

(C) High humidity, moderate to heavy wetting (environments 1, 2, 3, 6)

(D) Reduced shade but otherwise like Group C (environment 9).

Statistical analysis of data combined in this way identified significant effects of leaf type ($P < 0.05$), environment type ($P < 0.001$), and their interaction ($P < 0.001$). For the broad-leaved subjects, all differences amongst the plotted values are significant ($P < 0.05$); for the narrow leaved subjects losses in B and D environments were significantly lower than losses in type A environments.

Seasonal changes in response to environment

Some subjects were propagated on more that one occasion to see whether their need for environmental support changed as shoots hardened.

(a) *Syringa vulgaris* 'Charles Joly'

Figure 9 includes results from three propagation dates, starting when shoots reached about 20 cm, and finishing as extension growth ceased in early July. On all occasions this subject required a highly supportive environment to root, there being virtually no rooting in open mist for example, and the results suggest that the need for wet and humid conditions actually increased as the cuttings became less soft by the time of the final propagation. Reducing shade (E 9) appeared to be particularly beneficial at this time, despite high ambient light levels (Figure 8).

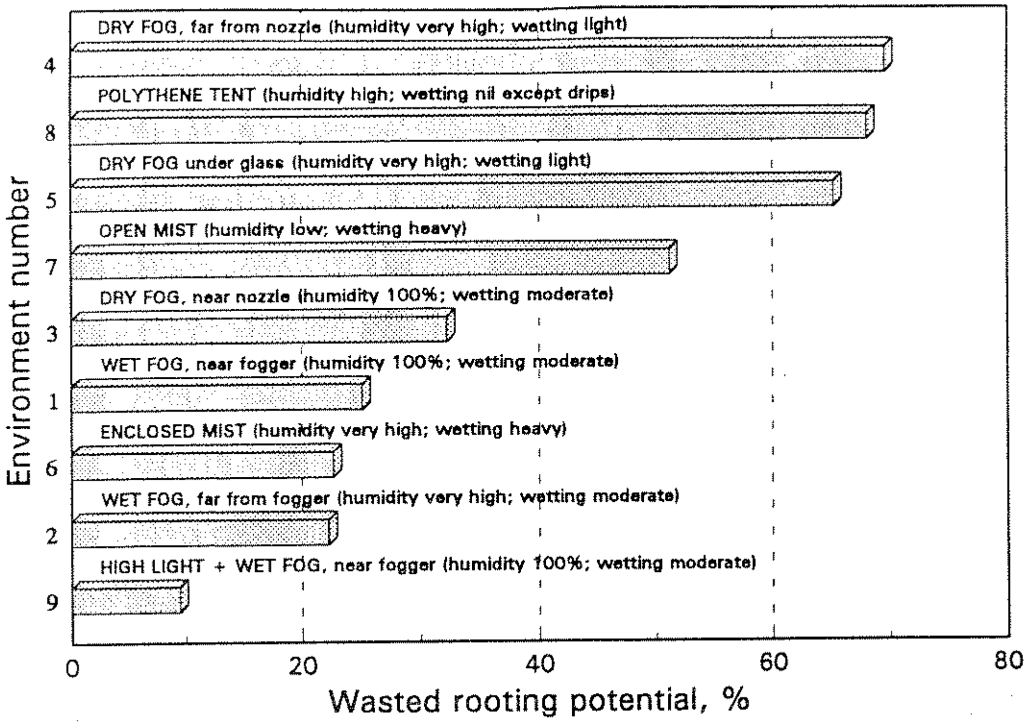

Figure 18. Effect of the rooting environment on the wastage of rooting potential of all the large leaved subjects included in the main first year experiments.

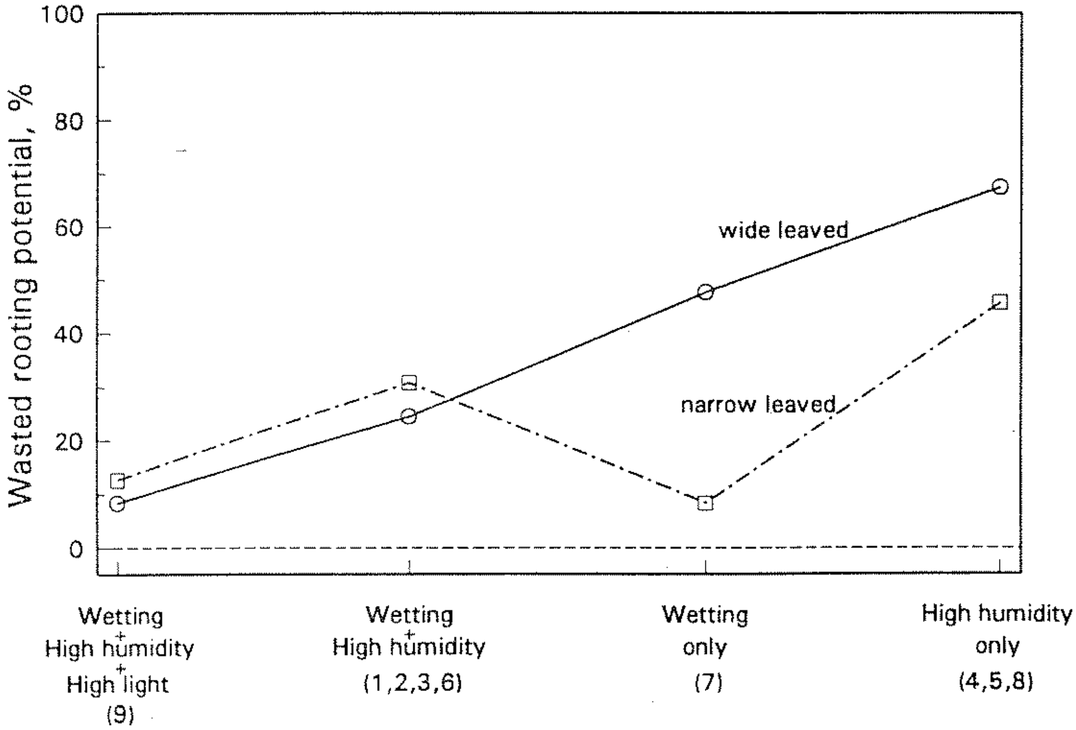

Figure 19. The apparent effect of leaf shape and/or size on the response to rooting environment seen in the first year.

(b) *Garrya elliptica* 'James Roof'

Garrya was also propagated on 3 occasions, these spanning its much longer growing season. The benefit of a supportive environment was again very great, but in this case the time of propagation had remarkably little effect on the response (Figure 10), despite a much greater range of ambient conditions (Figure 8). The fact that some rooting was achieved in the polythene tent (E 8) on the last occasion is an exception. It can probably be attributed to increasing significance of condensation dripping from the polythene onto cuttings as radiation and temperature declined while bottom heat encouraged evaporation from the compost.

For the autumn propagation, in addition to the cuttings from a young vigorous hedge at East Malling, which even in October were soft over at least the apical 7 cm, ripe cuttings from terminated lateral shoots were obtained from a more mature hedge at Hadlow College (Figure 11). Because the difference in cutting ripeness was confounded with the many other differences associated with their different source, including the genetic difference between 'James Roof' and the species, the greater rooting percentage of the ripe cuttings in all environments is of less interest than the broad parallel in their response to environment. Thus, although the ripe cuttings were too firm to wilt in response to stress, severe stress in E 4 and 5 (humid/non-wetting) is indicated by minimal rooting (i.e. 86% loss of rooting potential). Rooting of the ripe cuttings was not influenced by whether they were basal, with a small heel, or cut to a node a few centimetres from the base.

(c) *Cotinus coggygria* 'Royal Purple'

There was no significant difference in response to environment of cuttings taken in early or late summer (Figure 12).

(d) *Ilex aquifolium* 'Handsworth New Silver'

Following a suggestion from earlier work at HRI Efford, this subject was propagated on three occasions in early winter. At that time, for this evergreen subject, the lighter wetting of E 2 and E 3 gave higher rooting percentage than the wetter environments E 1 and E 6, but trends were less clear than with other species. No significant change in rooting ability or in response to environment was evident on the different dates, despite the final propagation (in December) coming after the first frosts. Instead, a very large difference between two sources was observed. There was virtually no rooting in any environment of cuttings from a hedge on a light soil that was growing poorly, probably as a result of summer drought.

Water stress during cutting preparation

Water loss during collection and preparation of cuttings can mean that cuttings are already stressed before they reach the rooting environment. *Acer platanoides* 'Crimson King', was used to investigate whether stress at this stage is likely to affect rooting potential or the response to rooting environment. Cuttings were stressed by allowing them to dry out gradually on the bench for 5 hours, by which time they had lost on average 5.6% of their initial fresh weight and were obviously wilted. Half of these stressed cuttings, together with the non-stressed controls, were then stood in water overnight in a dark and fogged enclosure to rehydrate them, while the remainder were placed in a humid chamber to prevent further water loss. Following rehydration the weight of both the stressed and control cuttings was on average 9% more than when freshly collected. This is indicative of the substantial water deficits that can develop either on the stockplant or in the normal process of cutting collection. Cuttings had been placed under damp hessian as they were collected and collection was completed by 0945 hours, but bright and breezy conditions favoured rapid water loss.

The results in Table 3 indicate that there was no long term effect of the 5 hour stress period, but that if the stress was maintained overnight rooting dropped by 10% even if subsequently rooted in the most favourable environment for this subject (E 1). The benefit of relieving the stress before sticking the cuttings was most marked for cuttings provided with an intermediate level of support (i.e. E 2), in which the relatively light wetting reduced the rate at which they could recover once in place. Open mist (E 7) was itself so stressful that the pre-treatments were irrelevant.

Clearly, it is essential to ensure that cuttings which become stressed during preparation are placed in an environment where they will recover as rapidly as possible. For example, it would be unwise to place cuttings under mist at the end of the day if overnight mist was very infrequent.

Table 3. Percent rooting of *Acer platanoides* 'Crimson King' cuttings in response to water stress pre-treatments (roots per rooted cutting in brackets)

	Rooting environment		
Pre-treatment	1	2	7
Non-stressed + rehydration	77 (11)	53 (6)	10 (6)
Stressed + rehydration	77 (11)	57 (8)	3 (3)
Stressed - rehydration	67 (9)	20 (4)	10 (2)

Year 2

These experiments were designed to examine the response to light intensity in more detail. It was realised from the outset that it would be difficult to separate the effect of high light from the effect of additional wetting required to prevent stress developing at high light. As more external shade was removed from the ventilated fog house, the intensity of fogging was doubled (to 2 minutes every 15 minutes) resulting in heavier wetting of cuttings in all shade treatments. In the mist treatments some compensation was possible by fitting lower output nozzles in the heavily shaded sections of the bed while controlling misting with an electric "leaf" in the lightly shaded section. A further complication was that shade levels changed substantially over the course of the season, as a result of changing solar elevation, so only results for the early summer propagations are reported.

Despite these difficulties the results with the larger-leaved subjects confirmed the benefit of increasing light level up to about 40% of outside light, if humidity and wetting are sufficient (wet fog and enclosed mist) to prevent stress (Figure 20). However, at 20% of outside light, rooting was better (i.e. wasted potential less) in enclosed mist than in the wet fog environment, and doubling light intensity merely enabled the results from fog to match those in enclosed mist. This suggests that additional light was mainly counteracting an adverse effect of over-wetting, rather than being beneficial to the rooting process in its own right.

Reducing shade over enclosed mist resulted in alarmingly high temperatures, the highest recorded being 41°C and the average daily maximum being 37°C. However, the results do not indicate any substantial effect on rooting.

In open mist lower humidity resulted in almost 40% wastage of rooting potential at the lower light level. Surprisingly, increasing light reduced this wastage slightly. This suggests that the heavier application of mist more than compensated for the increased evaporative demand imposed by the extra solar radiation. The fact that radiation has **proportionately** less effect on evaporative demand in open mist than in high humidity environments (Figure 6) is consistent with this explanation.

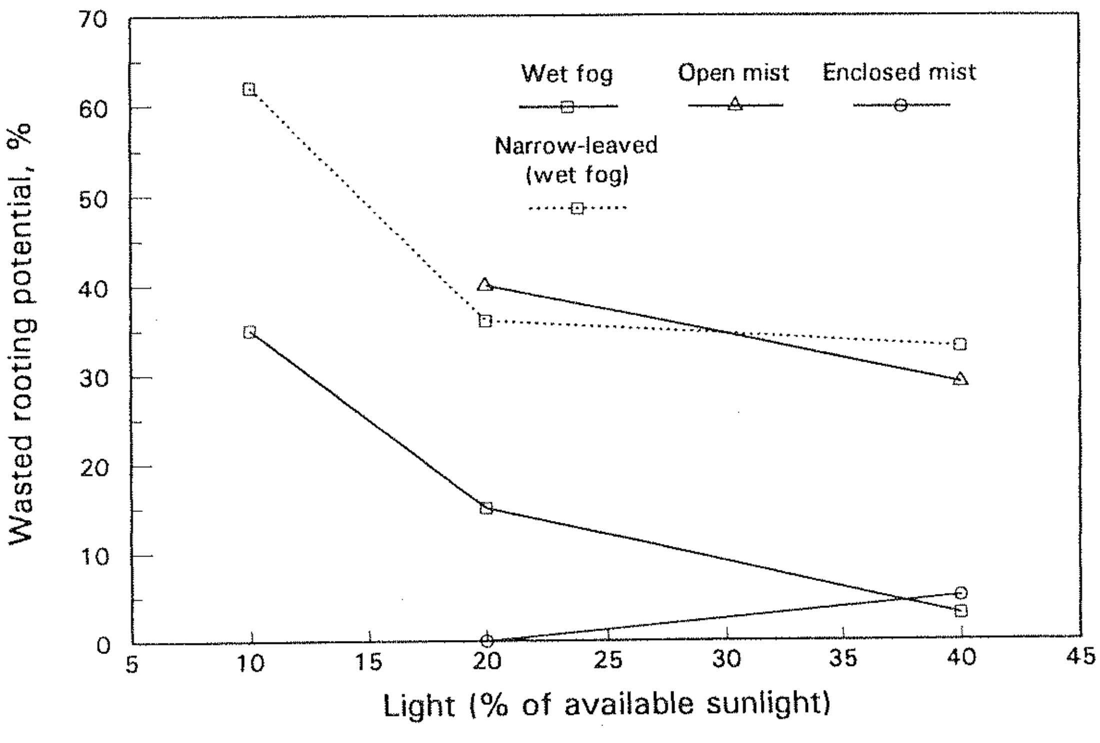

Figure 20. The effect of shade level on wastage of rooting potential seen in the second year. Data for the narrow leaved cuttings in mist are ommitted for the sake of clarity; wastage varied from 0 to 7%

The results with narrow-leaved subjects also point to an adverse effect of the heavier fogging than in year 1. Although rooting benefited from increased light as in year 1, more than 30% of rooting potential was lost even at the highest light level. Furthermore, there was no requirement for increased light to achieve more than 80% rooting in enclosed mist.

Conclusion

The aim of this project was to bridge the gap between existing knowledge of the physics of evaporation from leaves, and the practical need of plant propagators to control water loss from their cuttings. The physical principles were well established, at least for natural environments, and research at East Malling and elsewhere had already drawn attention to the powerful influence of environment on the rooting of leafy cuttings (e.g. Harrison-Murray *et al.*, 1988). What seemed to be needed was to relate the basic principles to the practical context in a way that would assist nurserymen seeking to upgrade or extend facilities, and to help them get the best from existing facilities. High on the list of priorities was to clarify whether fog offered important new opportunities not shared by mist, and if so how to exploit it to maximum advantage.

Some unexpected conclusions emerge simply from applying the underlying theoretical principles to the propagation context. For example, most people are surprised that putting cuttings into a fully saturated atmosphere will **NOT** generally stop them transpiring. The explanation provides valuable insight into the influence of solar radiation on cuttings. On the one hand, light is essential for the process of photosynthesis which provides the carbohydrate resources on which the survival and rooting of the cutting depend. On the other hand light, together with the other non-visible parts of the solar radiation spectrum, is a source of heat energy which tends to make leaves warmer than the air around them and drive out water vapour, even when the air around them is saturated. This stimulation of transpiration is distinct and separate from the tendency to raise temperature and decrease humidity in the house as a whole. This understanding highlights the importance of the choice of shade level.

Another particularly important conclusion from the theoretical analysis is that "evaporative cooling", due to evaporation of water on the outside of the leaf, will continue to reduce water lost from within the leaf **even when the surrounding atmosphere is saturated.** It follows that the benefit of misting does not depend on the mist house being well-ventilated, as is often supposed, and leaf wetting will continue to have an important role even in high humidity propagation systems.

The brief section devoted to putting this theory into user-friendly terms (Figures 1 and 2) is included in the belief that growers will find that it helps them to understand what is happening in their own facilities and thus improves management decisions.

However, the theory has its limitations, particularly concerning the **relative** effectiveness of the various environmental factors in reducing transpiration, and the way these factors **interact** with the response of the stomata. The rooting experiments were designed to fill this gap.

Experiments were designed to compare the effects of humidity, leaf wetting, and light, environmental factors over which the propagator can influence some control, rather than compare different systems such as mist versus fog. This decision reflects an important distinction; a system such as mist is a means of creating a propagation environment, it is not an environment in itself. The environment achieved depends partly on the equipment for atomising water, be it mist or fog, but largely on the structure in which it operates and the way in which it is controlled. It also depends on the precise location within the structure, since local variations mean that what is usually achieved is not one environment but a number of different mini-environments.

The conclusions from these trials are broadly as follows:

1. High humidity (i.e. RH above about 95%) does not **on its own** suppress transpiration enough for most species to be able to root. This was true of both the high technology "dry" fog environment and for the simple polythene tent system. In soft cuttings severe wilting provided clear evidence of the resultant stress, but rooting was also inhibited in more mature cuttings which were too hard to wilt.

2. Leaf-wetting on its own, as in open mist, was more effective that high humidity alone. In practice it is impossible to wet leaves without also tending to humidify the air around them, but without measures to trap that humid air, relative humidity in open mist can fall to as low as 70% between mist bursts.

3. The combination of leaf-wetting and high humidity is much more effective than either alone and allows large cuttings of difficult subjects to be maintained without wilting, resulting in unprecedentedly high rates of rooting.

4. The combination of leaf-wetting and high humidity can suppress rooting of some species. Such species tend to be those with rather narrow leaves such as *Berberis stenophylla*. Since the same species tolerate heavier leaf wetting when humidity is lower, the result cannot be attributed to leaching. Rather, it seems likely that rooting suffers if transpiration is suppressed too much. Narrow-leaved subjects are likely to be sensitive to leaf-wetting because any excess water deposited on the upper surface may easily run round the edge of the leaf and cover most of the lower surface. A leaf completely covered with water will not transpire at all.

5. The combination of wetting and high humidity permits a useful reduction of shade without causing stress. Such an increase in light level stimulates rooting of some subjects and also has the effect of making narrow-leaved subjects tolerant of the same wet and humid conditions that suit other species. This sort of combination therefore offers the best hope that it may eventually be possible to specify a rooting environment that is satisfactory for almost any type of cutting.

The cuttings on which these conclusions are based were mainly quite large cuttings of difficult-to-root species and as such particularly prone to water stress. When wilting provided visual evidence of water stress (especially *Garrya* but also *Cotinus, Parrotia, Betula* and *Syringa*), suppression of rooting was strongly related to the severity of wilting. The principles which emerged therefore relate strongly to the prevention of water stress, largely through restricting water loss, and as such apply to virtually any type of cutting.

Practical application

For nurserymen interested in propagating some of the more troublesome species such as *Cotinus coggygria* or *Corylus maxima* 'Purpurea', the potential benefit of improvement in propagation environment is large; in the worst environments an average of about 70% of cuttings failed to root because of the unfavourable conditions (Figure 18). Equally, it is clear that careful choice of new facilities is critical since the most high-tech. (that of generating dry fog) achieved one of the worst environments. Even for those more interested in ready-rooting "bread and butter" subjects, it is reasonable to expect that the same principles apply, but that the advantages would be seen in terms of speed and quality of rooting, which should feed through into improved plant quality later. Alternatively, use of more supportive environments may open up management opportunities, such as the use of larger cuttings with more leaf area to shorten the production process.

What then is the best way to achieve the required combination of high humidity and generous leaf wetting? There are essentially two options: use mist to wet the cuttings while enclosing it in polythene to trap the humidity, or use fog to provide both humidification and wetting. It may also be worth considering a hybrid of the two options in which mist would operate in a house where fog provided background humidification, but this concept is as yet untested.

Enclosed mist

To ensure that humidity is close to saturation, and never falls below about 95% RH the enclosure needs to be virtually air tight, particularly if operating in a draughty house. The system relies on evaporation from wet leaves and compost, because the mist settles out too quickly for evaporation of suspended droplets to make a large contribution. This limits the rate at which dry air leaking in can be humidified so that leaks must be kept to a minimum. It is also vital that the unused parts of the bed remain wet by leaving mist nozzles open and using a water retentive substrate below the rooting modues or trays, such as sand or capillary matting.

The need for such tight sealing creates the system's main problem. As well as retaining humidity the enclosure act as a heat trap; energy arriving in the form of solar radiation, absorbed by the cuttings and compost, must be lost by conduction through the polythene to the surrounding air, there being no opportunity for evaporative cooling. Extra shading avoids the problem by reducing the amount of energy getting in , but also limits the light available for photosynthesis. Automatic shading solves this conflict but is expensive.

The problem is made worse by uncertainty about how far temperatures can rise before significant damage is done to cuttings. The present experiments provided no evidence of substantial damage from average maximum temperatures of 34°C and an extreme of 41°C, recorded in lightly shaded enclosed mist in the second year. In the absence of more precise information, a reasonable rule of thumb would be to aim to keep temperatures below 35°C but be prepared to see them occasionally go up to 40°C. One thing to be beware of is that water in overhead mist lines may become much **hotter** than the air around it if exposed to incoming radiation. Shielding with aluminium foil or aluminised plastic film should be an effective cure.

Another area of some uncertainty is the effect of the shape and size of the polythene enclosure. It is normal to make it just large enough to enclose one mist line and any attempt to scale-up beyond this should be done with the following dangers in mind. Increasing the width is likely to exacerbate high temperature problems because it increases the ratio of area covered, and therefore energy absorbed, to area of polythene over which the energy can be lost. Increasing the height may increase the opportunity for humidity gradients within the enclosure which could mean lower humidity around the cuttings despite saturated conditions next to the polythene. The inconvenience of small polythene enclosures as opposed to walk-in ones may therefore be an inherent feature of this system. Further research to examine this question is required.

Fog

The fundamental advantage of fog is that it provides a way of humidifying incoming air so that some ventilation is possible without exposing cuttings to low humidity. The problem of energy trapping in a tightly sealed enclosure is thus avoided. Ventilation should be no more generous than is necessary because complete humidification of incoming air before it reaches the cuttings cannot be guaranteed. Forced-fan ventilation is preferable to passive venting; the point of air entry is clearly defined and ventilation rate can be controlled to match the capacity of the fogging equipment.

Even when weather conditions are such that high temperature is not a problem, there are reasons to expect fog to restrict transpiration slightly more that enclosed mist. Firstly, the suspended fog droplets act as a reservoir of water ready to evaporate and maintain saturation as the air is warmed by contact with leaves and compost that are being warmed by the radiation they are absorbing. Secondly, some fog droplets may be deposited on the **under**surface of leaves, inaccessible to mist droplets which fall rapidly downwards. However, only in exceptional circumstances is enough water deposited for the undersurface of leaves to become visibly wet (e.g. close to a fan-assisted fogger such as the Agritech).

The fundamental problem of fog is that, while its humidifying effect is uniform, its wetting effect is not. Despite the built-in fan to aid distribution there is a marked gradient of wetting away from the Agritech fogger in our ventilated "wet" fog system.

Moreover, a wet zone also forms around so-called "dry" fog nozzles except in applications where the desired humidity is well below saturation so that droplets evaporate rapidly after they have left the nozzle. The feasibility of combining the small droplet size of "dry" fog with the fan-assisted distribution of the Agritech is examined in a separate report (Harrison-Murray *et al.* 1993).

Just as for mist, it is important that a fog house is well drained. If not the problem of wet spots is made worse and, in hot weather, it may not be possible to apply enough water to keep leaves wet without saturating the compost. The substrate under the trays must make capillary contact with the rooting medium to drain out excess water. A few centimetres of sand is ideal. Since paths will also be wetted, it is useful if they are porous. At East Malling we have found that a thin layer (2-3 cm) of a coarse granular water-retentive material (e.g. mulch-grade bark) works well. It is laid on a sheet of Mypex, with gravel filled drainage channels beneath the Mypex if the soil is not well drained.

It is not possible here to discuss **all** the practical aspects of fog, and the authors would welcome enquiries from individual growers who are either considering installing fog or experiencing problems with an existing fog system.

Control systems

The control system is a critical component of a propagation system because its response to changing weather conditions affects the environment the cuttings are exposed to at least as much as the choice between enclosed mist and fog. A timer is simple and reliable but, unless frequently readjusted by experienced personnel, must be set to apply too much water most of the time if stress is to avoided in the sunniest periods. Provided drainage is adequate, this can be an acceptable way of ensuring that transpiration is suppressed as much as possible all of the time, and it was on this basis that it was used to control the Agritech fogger for this project. However, the rooting results provide evidence that this approach can adversely affect rooting of some subjects, not because the excess wetting physically damaged the cuttings, for example by leaching, but because transpiration was reduced too much. The ideal propagation system needs both the capacity to restrict transpiration enough to prevent stress on the hottest day of the year but also a control system that will ensure some transpiration on the dullest day. To perform this function a controller needs to sense the environment in a way that parallels transpiration from the leaves of a cutting. None of the existing controllers does this because none responds to all three of the relevant factors, namely, light, wetting and humidity. For example, it is illogical to control fog on a humidity controller when that will not be directly sensitive to light and when the aim is to achieve leaf wetting as well. Over the course of the project a sensor was developed to fill this need which has since been used to regulate a number of systems most successfully. Further detail is provided in a separate report (Harrison-Murray *et al.* 1993) but efforts to find a manufacturer to develop and market it have so far proved unsuccessful. In the meantime, a conventional mist controller, either the electric "leaf" wetness or the radiation integral type, would probably be an improvement on either timer or humidistat.

Methods of assessing propagation facilities

Results with a leaf-model evaporimeter, intended to provide a "cutting's eye view" of the drying power of an environment, did not correspond well with rooting results, apparently because it was less sensitive to wetting than real leaves. The electrical sensor mentioned above offers a better prospect as an instrument that could be useful to growers. Until something of that sort is available commercially the best that growers can do is probably to use a few relatively soft and "wilty" cuttings as a visual bioassay of how stressful conditions are. As the results with *Garrya* show, the fact that the normal production cuttings are not wilting does not necessarily mean that they are not under stress.

Shade level is often worth measuring directly, rather than trying to calculate it from manufacturer's specifications, because it is difficult to make the correct allowances for the framework of the house, dirty glass, etc. For this purpose it does not matter whether the light meter is calibrated in illumination units (e.g. lux), or energy units (e.g.watts per m^2) because the shade value is calculated by comparing the average reading obtained at cutting level in the house, with the average reading outside. The sensor should be horizontal for all measurements, and it is easiest to make the measurements on a uniformly cloudy day when the effects of solar angle and shadows will not need to be taken into account.

Remaining questions

The efforts made here to understand the way that light interacts with what might be called the "moistness" of the environment, that is the combination of wetting and humidity, were hampered by the difficulty of varying them independently using conventional propagation facilities. A more fundamental problem is the need to separate the effect of light on photosynthesis from the accompanying effect of total radiant energy on water loss. This is now the subject of a MAFF-funded project in which it is being studied under the more controlled conditions of our "Controlled Propagation Environment" (CPE) facility. It is being combined with further efforts on behalf of HDC to understand the differences in environmental preferences between species, such as the distinct requirements of narrow leaved species which became evident in this project.

In this project we have emphasised the aerial environment because, for leafy cuttings, its influence seems to be paramount. However the effect of the above-ground environment on the rate of water loss must be seen in relation to the opportunity for water to be taken-up by the cutting base. Factors affecting the resistance to water movement through the rooting medium to the cutting base are the subject of another MAFF project, in the course of which we expect to examine whether some of the response to wetting reported here may be attributable to re-wetting of the rooting medium immediately around the cutting base.

The ultimate objective, towards which these are all important steps, is to be able to specify the environmental requirements of all important groups of plants, recommend how those requirements can be met, and provide the methods to measure whether they are.

In this last respect the HDC fogger provided an excellent experimental test rig that helped us understand the factors governing the distribution of fog in relation to the output required for adequate leaf wetting (Harrison-Murray *et al.*, 1993). However, the use of expensive Sonicore-type nozzles, and the need for a large compressor to drive them, means that it is unlikely that nurserymen would find it an economic solution in its own right. New equipment continues to come on to the market and, to exploit the insights gained in this project, the HDC may need to support further work which would be aimed at identifying cost-effective high performance systems based on commercially available equipment.

Among the possibilities that would need to be examined are:-

Upgrading mist systems by adding dry fog to raise the background humidity level in the house, or compartment.

Using a battery of high pressure fog nozzles, combined with a fan, as an alternative to Agritech-type equipment, for nurserymen who wish to exploit wetness gradients.

Improving the uniformity of fog distribution achieved in large scale installations of overhead nozzles by introducing an oscillatory movement of some sort to blur the local variation associated with each individual nozzle.

Glossary

Agritech fogger - a machine from the USA, in which fog is produced from two simple nozzles mounted on the ends of rotating arms. The rotation serves to pressurize the water and to create air movement around the nozzle which breaks up the water into a wide range of droplet sizes. It incorporates a fan, which in some versions shares the same motor as the nozzles, to distribute the very large output (up to 135 *l*/h).

Evaporative demand - an imprecise term referring to the power of an environment to evaporate water. It differs from humidity, in that it also takes into account the many other factors which influence evaporation, such as wind. For a more precise definition it would be necessary to specify a particular evaporative surface.

Evaporimeter - A device which measures the rate of evaporation from a specified surface. In the present context the surface was a model of an idealised leaf (Figure 3).

Net water deposition (NWD) - The difference between the rate at which water is applied by a fog or mist system, and the rate at which it evaporates. By measuring NWD in such a way as to minimise the evaporation component (e.g. using transparent dishes) the data can provide a good indication of the amount of water applied by different systems.

Potential evapo-transpiration - The rate of evaporation from a large area of uniform vegetation, this being made up of water evaporating direct from the soil, combined with water passing through the plants before being evaporated from their leaves (i.e. transpiration).

Potential transpiration - the maximum rate at which leaves could be losing water under prevailing environmental conditions. To achieve this maximum rate, water supply would be unrestricted and stomata would be fully open. Since stomata vary considerably even within one plant, it can only be given a precise value for a particular leaf.

($P < x$) - An expression of statistical precision referring to the probability that the observed differences between treatments could have been due to chance. The smaller the value of x, the more certain we can be that the result is real, 0.05 being equivalent to the "5% probability level" conventionally taken as an acceptable threshold for considering the results to be "statistically significant".

Radiation - the form in which energy can be transferred between bodies without involving the material between them. For example, it is the only form in which energy from the sun can reach us across the vacuum of space. Its properties depend on wavelength, about half of the energy we receive from the sun (**solar radiation**) falling within the range of wavelengths that plants can use for photosynthesis and our eyes can detect, namely **light**. The visible waveband is only a small segment of the total spectrum of radiation which also includes ultraviolet, infra-red, radio, microwave, and many other wavebands.

Relative humidity (RH) - A measure of the water vapour present in the air. It is expressed as a percentage of that which would be present if the air was saturated and at the same temperature.

Stomata - the pores in the outer layers of the leaf through which gas exchange takes place between the air spaces inside the leaf and the air around it. The size of the pore orifice varies in response to various factors including light, water shortage, and carbon dioxide. In this way the plant exercises some control on its transpiration rate.

References

Grange, R.I., and Loach, K., 1983. The water economy of the unrooted cutting. *Journal of Horticultural Science*, **58**, 9-17.

Harrison-Murray, R.S. and Thompson, R., 1988. In pursuit of a minimum stress environment for rooting leafy cuttings: comparison of mist and fog. *Acta Horticulturae*, 227, 211-216.

Harrison-Murray, R.S., Howard, B.H. and Thompson, R., 1988. Potential for improved propagation by leafy cuttings through the use of fog. *Acta Horticulturae*, 227, 205-210.

Harrison-Murray, R.S., Thompson, R., Knight, L.J., and Howard, B.H., 1993. Development of equipment to meet the environmental needs of leafy cuttings during rooting. *Horticultural Development Council HNS Sector, Final Report*, pp 19.

Loach, K., 1988. Towards the ideal system. *Horticulture Week*, 11 November, 23-25.

Loach, K., and Whalley, D.N., 1978. Water and carbohydrate relationships during the rooting of cuttings. *Acta Horticulturae*, **79**, 161-168.

Thompson, R., Harrison-Murray, R.S., Knight, L.J. and Howard, B.H., 1993. Environmental comparison in commercial propagation houses. *Horticultural Development Council HNS Sector, Final Report*, pp 24.

Appendices

Appendix 1

Key to environments used in the first year experiments

1. Ventilated wet fog tunnel; heavy wetting zone
2. Ventilated wet fog tunnel; light wetting zone
3. Dry fog tunnel; light wetting zone
4. Dry fog tunnel; almost no wetting
5. Dry fog under glass; light and variable wetting
6. Polythene enclosed mist; heavy wetting
7. Open mist; heavy wetting
8. Polythene tent humidified by adjacent misted area; no wetting
9. As (1.) but with shade reduced by about half.

"Wet" fog refers to fog generated by an Agritech spinning nozzle machine, "dry" fog to that from Sonicore-type compressed air nozzles. Shade was adjusted so that about 20% of outside light reached the cuttings, except in environments 5 (13%) and 9 (32%).

Appendix 2. Detailed results for Year 1 : %rooting

Expt	Dates	Subject	Environment 1	2	3	4	5	6	7	8	9
1a	22.5-22.6	*Syringa vulgaris*, hedge	25.0	64.3	57.1	3.6	0.0	71.4	0.0	0.0	53.6
		" " stool	42.9	*	*	0.0	*	96.4	0.0	*	*
1b	14.6-12.7	" " hedge	35.7	75.0	64.3	0.0	25.0	64.3	3.6	0.0	78.6
1c	05.7-02.8	" " hedge	39.3	28.6	10.7	0.0	0.0	10.7	0.0	0.0	57.1
		" " stool	53.6	*	*	0.0	*	39.3	0.0	*	*
5	14.6-13.7	*Parrotia persica*	100.0	100.0	89.3	57.1	57.1	100.0	85.7	32.1	96.4
6a	16.6-18.7	*Betula pendula* 'Dalecarlica'	58.3	58.3	66.7	8.3	8.3	66.7	100.0	0.0	100.0
		" nodal	41.7	58.3	58.3	0.0	25.0	66.7	33.3	8.3	50.0
6b	29.6-29.7	*Betula pendula* 'Dalecarlica'	33.3	83.3	58.3	0.0	8.3	83.3	50.0	8.3	66.7
		" nodal	50.0	41.7	50.0	41.7	0.0	58.3	41.7	0.0	83.3
7a	17.6-19.7	*Garrya elliptica*	100.0	28.6	32.1	0.0	10.7	67.9	0.0	0.0	67.9
7b	30.6-01.8	'James Roof'	100.0	50.0	*	0.0	*	8.3	0.0	*	*
8a	21.6-20.7	*Cotinus coggygria*	64.3	71.4	85.7	35.7	14.3	64.3	21.4	0.0	92.9
8b	23.6-28.7	'Royal Purple'	66.7	100.0	*	8.3	*	100.0	8.3	*	*
9	07.7-4.8	*Corylus maxima* 'Purpurea'	89.3	92.9	89.3	3.6	17.9	85.7	64.3	0.0	96.4
10	14.7-15.8	*Acer platanoides* 'Crim.King'	76.7	53.3	*	*	*	*	10.0	*	*
11	18.8-2.10	*Berberis stenophylla*	23.3	26.7	16.7	20.0	2.3	53.3	46.7	10.0	53.3
		" " nodal	50.0	73.3	60.0	53.3	26.7	83.3	93.3	23.3	70.0
12	16.8-28.9	*Photinia* 'Red Robin'	25.0	12.5	25.0	0.0	12.5	12.5	25.0	0.0	12.5
		" " nodal	44.4	22.2	0.0	0.0	11.1	0.0	0.0	0.0	66.7
15	23.8-29.9	*Cotinus coggygria* 'R.Purp.'	75.0	92.9	71.4	7.1	28.6	89.3	50.0	0.0	89.3
16	24.8-29.9	*Wisteria sinensis*	0.0	25.0	12.5	12.5	12.5	62.5	37.5	0.0	37.5
17	25.8-5.10	*Cytisus Burkwoodii*	0.0	22.2	77.8	77.8	48.2	40.7	59.3	0.0	63.0
18a	31.8-11.10	*Arbutus unedo*	16.7	*	33.3	16.7	*	16.7	0.0	*	50.0
18b	1.9-11.10	*Rhamnus alaterna*	8.3	*	0.0	0.0	*	8.3	8.3	*	16.7
18c	1.9-11.10	*Ceanothus impressus*	0.0	*	83.3	61.1	*	0.0	55.6	*	16.7
20	13.9-20.10	*Garrya elliptica*	85.7	46.4	10.7	0.0	0.0	42.9	0.0	0.0	89.3
23a	22.9-2.11	*Berberis stenophylla* nodal	22.2	*	*	94.4	*	*	88.9	66.7	44.4
27	26.10 -	*Garrya elliptica*, soft	57.1	50.0	21.4	0.0	0.0	71.4	3.6	42.9	75.0
	14.12	" " , ripe	82.1	100.0	57.1	14.3	14.3	85.7	42.9	85.7	92.9
22+25+ 28	21.9+12.10 +8.11	*Ilex aquifolium* 'Handsworth New Silver'	17.0	50.0	67.0	17.0	25.0	8.0	42.0	33.0	42.0

All apical cuttings except where noted otherwise. * = not tested, usually because of shortage of cuttings.

Year 1 : Roots per rooted cutting

Expt	Dates	Subject	Environment 1	2	3	4	5	6	7	8	9
1a	22.5-22.6	*Syringa vulgaris*, hedge	3.6	4.9	6.6	1.0	*	6.7	*	*	4.0
		" " stool	1.8	*	*	*	*	10.1	*	*	*
1b	14.6-12.7	" " hedge	4.5	4.4	8.8	*	5.1	10.2	3.0	*	9.9
1c	05.7-02.8	" " hedge	7.6	8.9	2.3	*	*	5.3	*	*	10.1
		" " stool	6.7	*	*	*	*	4.2	*	*	*
5	14.6-13.7	*Parrotia persica*	13.5	15.6	14.3	4.6	7.9	13.0	14.0	6.1	15.6
6a	16.6-18.7	*Betula pendula* 'Dalecarlica'	8.1	6.1	7.9	5.0	1.0	8.3	7.6	*	8.5
		" nodal	2.6	1.4	2.7	*	1.7	3.0	3.8	1.0	2.0
6b	29.6-29.7	*Betula pendula* 'Dalecarlica'	5.0	8.3	3.6	*	1.0	10.2	7.0	2.0	7.0
		" nodal	2.2	2.6	4.7	2.0	*	2.1	2.8	*	2.2
7a	17.6-19.7	*Garrya elliptica*	44.5	28.8	27.0	*	36.7	37.3	*	*	47.1
7b	30.6-01.8	'James Roof'	42.3	31.3	*	*	*	3.0	*	*	*
8a	21.6-20.7	*Cotinus coggygria* '	3.9	4.6	5.3	3.0	3.3	8.2	3.5	*	7.6
8b	23.6-28.7	'Royal Purple'	4.4	6.8	*	1.0	*	11.0	1.0	*	*
9	07.7-4.8	*Corylus maxima* 'Purpurea'	19.2	19.5	16.8	3.0	9.6	20.3	9.7	*	27.1
10	14.7-15.8	*Acer platanoides* 'Crim.King'	10.9	6.2	*	*	*	*	6.3	*	*
11	18.8-2.10	*Berberis stenophylla*	4.4	7.4	6.0	2.8	1.0	6.2	7.4	5.0	7.9
		" " nodal	3.9	4.0	3.8	5.4	3.4	6.7	6.8	5.0	4.0
12	16.8-28.9	*Photinia* 'Red Robin'	2.0	2.0	2.5	*	2.0	1.0	3.5	*	1.0
		" " nodal	6.3	2.5	*	*	2.0	*	*	*	4.3
15	23.8-29.9	*Cotinus coggygria* 'R.Purp.'	5.4	5.5	5.8	1.0	6.1	8.0	3.1	*	6.0
16	24.8-29.9	*Wisteria sinensis*	*	1.5	2.0	2.0	4.0	2.6	2.3	*	6.7
17	25.8-5.10	*Cytisus Burkwoodii*	*	1.8	2.6	3.3	2.9	2.9	4.1	*	3.3
18a	31.8-11.10	*Arbutus unedo*	4.0	*	3.0	1.0	*	3.0	*	*	4.0
18b	1.9-11.10	*Rhamnus alaterna*	1.0	*	*	*	*	1.0	2.0	*	10.0
18c	1.9-11.10	*Ceanothus impressus*	*	*	4.7	4.8	*	*	7.1	*	3.0
20	13.9-20.10	*Garrya elliptica*	28.3	26.2	27.0	*	*	22.1	*	*	29.4
23	22.9-2.11	*Berberis stenophylla* nodal	1.8	*	*	5.8	*	*	9.7	7.6	5.5
27	26.10 - 14.12	*Garrya elliptica*, soft	23.7	22.3	17.7	*	*	29.5	16.0	28.0	32.1
		" " , ripe	10.3	13.6	7.0	5.5	7.3	10.9	7.5	12.8	10.4
22+25+ 28	21.9+12.10 +8.11	*Ilex aquifolium* 'Handsworth New Silver'	8.5	6.5	4.3	2.0	8.7	4.0	7.7	2.7	8.3

All apical cuttings except where noted otherwise

Year 1: % necrosis (> 5mm)

Expt	Dates	Subject	Environment								
			1	2	3	4	5	6	7	8	9
1a	22.5-22.6	*Syringa vulgaris*, hedge	7.1	3.6	21.4	21.4	17.9	3.6	32.1	17.9	14.3
		" " stool	25.0	*	*	14.3	*	3.6	10.7	*	*
1b	14.6-12.7	" " hedge	*	*	*	*	*	*	*	*	*
1c	05.7-02.8	" " hedge	7.1	0.0	7.1	0.0	3.6	0.0	25.0	17.9	7.1
		" " stool	57.1	32.1	50.0	39.3	42.9	60.7	85.7	67.9	82.1
5	14.6-13.7	*Parrotia persica*	46.4	*	*	50.0	*	46.4	82.1	*	*
6a	16.6-18.7	*Betula pendula* 'Dalecarlica'	50.0	57.1	60.7	82.1	78.6	75.0	78.6	64.3	71.4
		" nodal	100.0	100.0	91.7	100.0	100.0	91.7	75.0	100.0	100.0
6b	29.6-29.7	*Betula pendula* 'Dalecarlica'	25.0	16.7	16.7	100.0	41.7	25.0	50.0	100.0	25.0
		" nodal	100.0	91.7	83.3	91.7	100.0	91.7	91.7	66.7	100.0
7a	17.6-19.7	*Garrya elliptica*	33.3	33.3	33.3	50.0	75.0	33.3	25.0	41.7	25.0
7b	30.6-01.8	'James Roof'	85.7	82.1	89.3	96.4	85.7	89.3	100.0	89.3	78.6
8a	21.6-20.7	*Cotinus coggygria*	33.3	33.3	*	58.3	*	66.7	91.7	*	*
8b	23.6-28.7	'Royal Purple'	7.1	17.9	21.4	82.1	60.7	7.1	67.9	50.0	3.6
9	07.7-4.8	*Corylus maxima* 'Purpurea'	8.3	8.3	*	8.3	*	0.0	33.3	*	*
10	14.7-15.8	*Acer platanoides* 'Crim.King'	25.0	28.6	28.6	100.0	82.1	39.3	46.4	100.0	39.3
11	18.8-2.10	*Berberis stenophylla*	83.3	83.3	*	*	*	*	60.0	*	*
		" " nodal	80.0	86.7	86.7	86.7	100.0	100.0	83.3	96.7	93.3
12	16.8-28.9	*Photinia* 'Red Robin'	70.0	76.7	80.0	96.7	90.0	83.3	73.3	100.0	76.7
		" " nodal	25.0	12.5	25.0	0.0	12.5	0.0	0.0	0.0	25.0
15	23.8-29.9	*Cotinus coggygria* 'R.Purp.'	22.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	24.8-29.9	*Wisteria sinensis*	0.0	3.6	10.7	53.6	67.9	7.1	64.3	75.0	7.1
17	25.8-5.10	*Cytisus Burkwoodii*	37.5	37.5	25.0	37.5	25.0	12.5	37.5	87.5	37.5
18a	31.8-11.10	*Arbutus unedo*	100.0	25.9	3.7	3.7	3.7	14.8	3.7	29.6	14.8
18b	1.9-11.10	*Rhamnus alaterna*	33.3	*	16.7	0.0	*	16.7	0.0	*	16.7
18c	1.9-11.10	*Ceanothus impressus*	0.0	*	16.7	16.7	*	0.0	0.0	*	8.3
20	13.9-20.10	*Garrya elliptica*	66.7	*	16.7	33.3	*	100.0	44.4	66.7	*
23a	22.9-2.11	*Berberis stenophylla* nodal	53.6	82.1	85.7	100.0	96.4	71.4	92.9	100.0	21.4
27	26.10 -	*Garrya elliptica*, soft	0.0	*	*	0.0	*	*	5.6	22.2	5.6
	14.12	" " , ripe	71.4	78.6	82.1	96.4	96.4	71.4	96.4	92.9	50.0
22+25+	21.9+12.10	*Ilex aquifolium*	7.1	17.9	7.1	0.0	0.0	10.7	3.6	0.0	0.0
28	+8.11	'Handsworth New Silver'	8.3	25.0	0.0	0.0	8.3	0.0	0.0	0.0	16.7

All apical cuttings except where noted otherwise

Year 1: Length of longest root per cutting

Expt	Dates	Subject	Environment								
			1	2	3	4	5	6	7	8	9
1a	22.5-22.6	*Syringa vulgaris*, hedge	1.4	1.5	2.0	0.3	*	2.5	*	*	2.1
		" " stool	1.7	*	*	*	*	3.0	*	*	*
1b	14.6-12.7	" " hedge	0.9	1.4	2.7	*	2.8	2.7	1.0	*	2.8
1c	05.7-02.8	" " hedge	1.5	1.4	0.9	*	*	2.1	1.5	*	2.4
		" " stool	1.4	*	*	*	*	*	*	*	*
5	14.6-13.7	*Parrotia persica*	1.7	2.1	1.9	0.9	1.6	2.4	2.2	0.7	2.9
6a	16.6-18.7	*Betula pendula* 'Dalecarlica'	5.3	9.8	8.8	10.0	8.0	9.6	9.9	*	6.1
		" nodal	6.0	6.5	7.8	*	10.3	8.4	9.5	8.0	10.8
6b	29.6-29.7	*Betula pendula* 'Dalecarlica'	9.5	9.0	7.7	*	1.0	8.9	9.5	11.0	9.6
		" nodal	8.3	11.2	11.8	6.7	*	10.4	4.6	*	10.1
7a	17.6-19.7	*Garrya elliptica*	3.8	2.6	2.7	*	4.4	4.7	*	*	3.6
7b	30.6-01.8	'James Roof'	4.6	3.5	*	*	*	0.1	*	*	*
8a	21.6-20.7	*Cotinus coggygria*	5.4	4.8	3.0	0.2	0.8	7.6	3.8	*	8.9
8b	23.6-28.7	'Royal Purple'	8.5	8.1	*	0.2	*	10.4	0.8	*	*
9	07.7-4.8	*Corylus maxima* 'Purpurea'	2.2	2.4	1.8	2.0	1.3	3.1	1.9	*	2.6
10	14.7-15.8	*Acer platanoides* 'Crim.King'	6.1	3.8	*	*	*	*	7.0	*	*
11	18.8-2.10	*Berberis stenophylla*	4.4	6.8	8.2	4.0	7.0	7.6	9.3	5.3	6.6
		" " nodal	5.2	7.1	8.6	9.3	6.1	8.7	10.5	5.3	6.3
12	16.8-28.9	*Photinia* 'Red Robin'	4.5	3.0	4.6	*	14.0	6.0	7.5	*	3.0
		" " nodal	9.3	6.5	*	*	5.0	*	*	*	9.2
15	23.8-29.9	*Cotinus coggygria* 'R.Purp.'	9.2	11.5	11.9	0.2	12.1	8.8	4.4	*	13.2
16	24.8-29.9	*Wisteria sinensis*	*	4.1	8.0	14.0	9.0	4.7	5.3	*	9.3
17	25.8-5.10	*Cytisus Burkwoodii*	*	2.1	1.9	4.3	3.2	2.8	8.2	*	2.3
18a	31.8-11.10	*Arbutus unedo*	2.5	*	5.8	1.0	*	6.0	*	*	3.8
18b	1.9-11.10	*Rhamnus alaterna*	1.0	*	*	*	*	0.5	2.5	*	2.5
18c	1.9-11.10	*Ceanothus impressus*	*	*	5.8	4.8	*	*	3.5	*	0.5
20	13.9-20.10	*Garrya elliptica*	6.2	4.0	2.1	*	*	3.1	*	*	3.7
23a	22.9-2.11	*Berberis stenophylla* nodal	2.4	*	*	8.0	*	*	9.5	7.8	6.0
27	26.10 - 14.12	*Garrya elliptica*, soft	7.9	6.7	7.6	*	*	4.4	8.0	4.7	4.4
		" " , ripe	3.9	6.9	2.3	1.6	2.0	2.4	2.3	3.5	3.8
22+25+ 28	21.9+12.10 +8.11	*Ilex aquifolium* 'Handsworth New Silver'	5.0	3.8	3.3	1.8	3.1	3.0	2.7	1.8	3.8

All apical cuttings except where noted otherwise

Appendix 3 % rooting data for June and July propagations. Figures in brackets are for dry weight growth during rooting (%).

System	Shade level (% of daylight at cutting level)		
	10	20	40
Parrotia persica :-			
WF	97 (+64)	100 (+113)	100 (+127)
OM		65 (+81)	94 (+103)
EM		100 (+116)	100 (+121)
Syringa vulgaris 'Charles Joly' ;-			
WF	35 (-4)	63 (+18)	66 (+38)
OM		13 (+13)	37 (+27)
EM		72 (+22)	87 (+46)
Corylus maxima 'Purpurea' apical :-			
WF	63 (+12)	81 (+38)	100 (+75)
OM		89 (+34)	96 (+66)
EM		85 (+41)	91 (+70)
Corylus maxima 'Purpurea' nodal :-			
WF	47 (+26)	75 (+25)	100 (+44)
OM		91 (+32)	91 (+50)
EM		87 (+33)	88 (+41)
Garrya elliptica 'James Roof' :-			
WF	53 (+6)	73 (+41)	97 (+80)
OM		3 (+58)	19 (+92)
EM		97 (+54)	69 (+91)
Cotinus coggygria 'Royal Purple' :-			
WF	59 (-12)	94 (+54)	100 (+85)
OM		94 (+59)	97 (+112)
EM		100 (+75)	94 (+109)
Acer palmatum 'Aureum' nodal :-			
WF	65 (+15)	75 (+23)	81 (+26)
OM		31 (+43)	31 (+23)
EM		75 (+29)	53 (+33)
Berberis stenophylla nodal :-			
WF	35 (+1)	59 (+12)	63 (+24)
OM		75 (+23)	75 (+20)
EM		84 (+27)	79 (+23)
Cytisus 'Burkwoodii' :-			
WF	22 (+6)	50 (+15)	53 (+27)
OM		97 (+114)	91 (+94)
EM		97 (+54)	91 (+86)

WF=Ventilated Wet Fog; OM=Open Mist; EM=Polythene-enclosed Mist

Appendix 4(a) Relative humidity in some of the high humidity rooting environments during the first summer (June to August). Numbers in brackets are the lowest values observed over the entire period.

Facility/Environments	Average daily:- Max.	Min.	Mean
Dry fog under polythene, dry end (environment 4)	100 (99.1)	90.4 (73.4)	97.5
Dry fog under glass (environment 5)	100 (97.5)	94.1 (70.6)	97.7
Closed mist, and polytent (environment 6 & 8)	100 (98.2)	89.0 (72.1)	95.7

Appendix 4(b) Air temperatures in different rooting environments during the first summer (June to August).

	Averages			Extremes	
Facility/Environments	Max.	Min.	Mean	High	Low
Ventilated wet fog (environments 1,2, & 9)	28.3	13.9	20.1	30.9[1]	9.3
Dry fog under polythene (environments 3 & 4)	30.5	14.7	21.1	37.8	10.3
Dry fog under glass (environment 5)	28.2	17.7	21.8	40.1	15.2
Closed mist, and polytent (environment 6 & 8)	31.3	16.7	22.1	41.6	12.0
Open mist (environment 7)	28.9	13.8	19.5	37.5	9.5
Outside[2]	24.2	10.1	15.9	31.9	3.6

1. Excluding a value of 37.2°C recorded during machine maintenance.

2. Measuring sensor was screened, but not fan ventilated, 2m above the ground close to the wet fog tunnel. The average maximum observed in this sheltered location was 5°C higher than at the East Malling meteorological station.

Appendix 4(c) Air temperatures in different rooting environments during the first autumn (Sept. to Dec).

Facility/Environments	Averages			Extremes	
	Max.	Min.	Mean	High	Low
Ventilated wet fog (environments 1,2, & 9)	23.1	10.7	15.6	31.4	2.8
Dry fog under polythene (environments 3 & 4)	24.0	11.1	16.2	37.8	2.9
Dry fog under glass (environment 5)	27.2	15.8	19.7	37.7	10.9
Closed mist, and polytent (environment 6 & 8)	25.3	14.6	18.5	39.5	10.3
Open mist (environment 7)	24.1	11.1	15.9	35.4	2.7
Outside	18.5	5.6	11.0	31.4	-5.8

Appendix 4(d) Compost temperatures in different rooting environments during the first summer (June to August).

Facility/Environments	Averages		
	Max.	Min.	Mean
Ventilated wet fog (environments 1,& 2)	25.8	19.3	22.6
(environment 9 - reduced shade)	28.6	20.3	24.2
Dry fog under polythene (environments 3 & 4)	27.2	20.7	23.5
Dry fog under glass (environment 5)	25.9	20.1	22.5
Closed mist, and polytent (environment 6 & 8)	27.1	19.9	23.2
Open mist (environment 7)	24.1	19.8	21.8

Appendix 4(e) Summary of environmental data for late June, 1989 (20.6 to 4.7.89).

	Air temperature, °C		Humidity, % RH		Saturation deficit (vpd), Pa	
Environment	Max.	Mean	Min.	Mean	Max.	Mean
WF	27.8	20.8	99.5	100	19	0
OM	26.9	19.1	78.3	89.4	775	233
EM:20%light	28.6	22.0	98.6	99.3	54	18
EM:40%light	33.7	23.7	94.8	97.8	270	64

WF = Ventilated Wet Fog
OM = Open Mist
EM = Polythene-enclosed Mist
(separate enclosures for each shade level)