Project title:	Horticultural Water Use in a Changing Environment
Project number:	CP 011
Project leader:	William J Davies
Report:	Final Report 2002
Previous reports:	None
Key workers:	Mark A Bacon and Dawn K Oliver
Location of project:	Lancaster University
Project co-ordinator:	
Date project commenced:	
Date completion due:	
Key words:	water, environment, efficiency, irrigation, evapotransipation,

Contents

APPENDIX 1

SUMMARIES OF HDC FUNDED RESEARCH ON HORTICULTURAL WATER USE

Including summary of Independent water audits for container grown nursery stock producers (Briercliffe, Hewson & Brough)

Horticultural Water Use in a Changing Environment

Foreword

This document has been written for those working for and within commercial UK horticulture, to provide an up-to-date view of the current research and technology under development in the broad area of horticultural water use.

This subject was the focus of a two-day workshop sponsored by the Horticultural Development Council (HDC) which allowed growers, consultants and researchers to explore this important and increasingly relevant issue within horticulture. The sessions held within the workshop and the resulting discussions over the two days form the basis to this document. More than twenty growers attended the two-day course held at Lancaster University, representing a significant cross-section of the industry. Several consultants joined the growers and applied researchers working within this general area to form a unique group focused on one issue.

The document is split into two parts. Part 1 discusses the recent advances in understanding within the general area of horticultural water use, reflecting the author's expertise and understanding of plant science research nationally and internationally and its potential impact on UK horticultural production. Each chapter considers a particular aspect of plant water use in horticulture and sets potential research priorities for the future to exploit the fundamental understanding discussed. Part 2 reviews international and national research in the light of a cross-sector perspective on water use and concludes with a proposed action plan for future research to assist those responsible for funding horticultural research.

The Plant Sciences for Industry Unit at Lancaster University undertook this project with funding from both the Horticultural Development Council and the Biotechnology and Biological Sciences Research Council.

PART 1

CAN PLANT SCIENCE HELP TO DELIVER ENHANCED HORTICULTURAL WATER USE EFFICIENCY IN A CHANGING ENVIRONMENT?

1. INTRODUCTION

SUMMARY
This chapter places the document in context by discussing the legislative changes which will place increasing emphasis on the efficient use of water within UK horticulture.

Why worry about water?

In many countries where substantial horticultural production takes place, the development of businesses is limited by the amount of water available for irrigation. In such areas, increases in water use efficiency has increased the capacity for commercial enterprises to establish and develop. Although labour costs remain the one major limiting factor in UK horticulture, many parts of the UK now experience summer droughts with increased frequency and are often faced with severe disruption in water supplies. It is now well accepted that climate and population changes will make increased demands on water and there is no doubt that much needs to be done to ensure that that water is used in a manner to guarantee sustainable production for many years.

We are all aware that the plants we produce to use or sell are largely made up of water. The horticultural industry is highly dependent on water and consideration of its use is justified on the basis of this importance and the clear profitability to be had from its efficient application.

If water abstraction licences were withdrawn could you continue in business? How many staff or local village communities are at risk if you have to cease trading? The recently published draft Water Bill is of importance to growers and all amenity users of ground water. However, the driving force behind current legislation is the increasing demand for potable water as population size and wealth increases. Of the 77 million cubic metres of water, which falls on England and Wales each year, only 13 million cubic metres (17%) is abstracted, although in dry periods this has been known to rise to 50%.

The new legislative proposals will be far reaching and will cover permits, consents and licences for abstraction. Central to this will be the issue of rights and liabilities. The proposals allow abstractions to change ownership irrespective of the land ownership from which the water is abstracted. Unused licences will be reviewed in a shorter period than the current 7 years and where only small amounts of water are used from a large licence a test of beneficial use would be applied to determine future licensed volumes. In modern crop rotations it is quite normal for land to grow crops needing irrigation and then to go through a period when they do not. The reduction of non-use time periods to below seven years could be problematic.

Damaging effects on buildings, land and other abstractions and similar environments are currently immune from legal action, but this immunity is likely to be lost under the new proposals. An abstractor would be legally liable for any financial losses resulting from damage. Growers of roses and trees for instance, often rotate on a twelve-year cycle to avoid specific re-plant problems. To lose that licence on a parcel of land because of good husbandry would be nonsensical. In some areas of the UK we have had four wet years in a row and irrigation needs have been minimal – under new legislation, will this count against an abstractor? The final draft of legislation needs to ensure that these considerations are taken into account.

Another quite different aspect to the use of water within the industry, is the potential to manipulate various properties of the plant to control water loss and increase plant and yield quality, by varying the amount and frequency of water applied. Although deficit irrigation methods are tried and tested in various sectors of the industry, re-appraisal of this tool, together with new developments in this field may allow us to reduce our water input and receive unexpected and valuable gains.

Legislation, Water Usage and Implications for the Grower

CAMS - Catchment Abstraction Management Strategies

A CAM is a situation report on the water resources for each catchment, together with a strategy on how to manage those resources and measures that may need to be taken in the interests of long-term sustainability within the catchment area. Presently there will be a total of 129 designated CAMS areas. Attention will be focused on the:

- balance of water resources
- sustainability status
- licensing practices in operation
- areas for change

- time limits of licences and strategy
- trading of licences

A summary of the strategy to be adopted by each region is available from the Environment Agency, which growers may find to be of benefit.

The draft *Water Bill* followed by a document entitled *Managing Water Abstraction* (due in April) provides further information on the above. A review of CAMS will be conducted every 6 years to ensure that the strategies are in harmony with the European Framework Directive on water.

<u>*Time Limiting of Licences*</u>

All abstraction licences will be issued subject to a time limit. Each catchment area will have a common expiry date. To renew a licence three tests will be employed on:

- environmental sustainability
- reasonable need on an on-going basis
- efficiency of water use, or how effectively water is used

A licence will be reviewed every 12 years, with longer periods applied to water storage schemes (possible 24 years). Shorter time limits may also be used, where deemed appropriate. There will be a fixed end date for the licences for each CAMS area. A notice period of 6 years will be given for licences that will not be renewed by the licensing authority.

Over Abstraction and Sustainability

The Environment agency has the remit to take steps in order to provide solutions due to over abstraction. Compensation may become available for those where abstraction licences are withheld.

Trickle Irrigation

Presently, abstraction licences are not required for trickle irrigation. Under the proposals in the Water Bill, trickle irrigation will no longer be exempt and no `grandfather rights` will apply.

Exemptions

Currently abstractions of up to $20m^3$ (4500 gals) per day may be taken for specific requirements, without a licence. This exemption will be extended for all irrigation purposes and may be subject to variation, as required. Licences will not be required for quantities of water less than this amount abstracted on a daily basis.

Changes to abstraction licences

The status of licences is also subject to change and may include:

- Defense against damage to third parties may be removed
- Compensation for the loss of permanent licenses may be phased out in 2012
- Alterations may be made to the specification of land on which water is used
- The only qualification for applying for a licence will be the right of access

Consequently:

- All unsustainable abstractions may be at risk
- Responsible abstractors may wish to find sustainable solutions and discuss the opportunities with the Environment Agency.
- Licence status is also subject to the requirements of the Habitats Directive and timely action may be required to ensure the time-scales are met.

The most recent information, obtained from the publication of the House of Commons Select Committee concerning the draft Water Bill identified several issues:

- Non time-limited abstraction licences would be revoked without compensation after 2012 (Clause 17 of the draft bill refers)
- Potential challenges may be made under the Human Rights Act 1998 (in respect of licences that may be taken way without any from of redress by the licence holder)
- No plans have yet been formalised to provide automatic licences for trickle irrigators

The European Habitats Directive

UK Environmental legislation has responded to the European Habitats Directed by making legislative changes. In essence, the Habitats Directive seeks to ensure that biodiversity is maintained through the conservation of natural habitats of wild plants and animals. The Directive is implemented through the Conservation Regulations 1994. The maintenance and restoration of selected habitats will be included. A network of sites under the Natura 2000 network will be formed and the designated sites will be selected. These will include special areas for conservation, special protected areas and wetlands of international importance.

The Directive has two main areas, which may affect those abstracting water. These are

- The Review of Consents (Regulation 50)
- The Assessment of New Plans and Permissions (Regulation 48)

It is the duty of competent authorities such as English Nature, Scottish Natural Heritage, Countryside Council for Wales and the Environment Agency to assess the effects of all plans, permissions or consents which may impact on the Natura 2000 sites. There must be no adverse effect on the integrity of the specified sites.

Consequently, those licences likely to have a negative impact on European sites will be subject to review and may not be renewed on application. The Environment Agency will continue to work with the Competent Authorities to undertake risk assessments in this respect. The assessment will comprise four key stages:

1. the identification of relevant permissions e.g. abstraction licences for the wetlands.
2. The likely significance of the abstraction having adverse effects on site integrity either alone or as a combination of effects.
3. For those where a negative impact is likely, an appropriate assessment is made. Should there be no adverse affect on the integrity of the site then licensing may be approved. However, if adverse effects are reported then the licence may be revoked unless there is an overriding concern of public interest.
4. Permission may be granted subject to satisfactory results.

Which abstractors are likely to be affected? Those that are likely to effect designated habitats. These habitats are likely to be the Fens, Peatbog areas and sites adjacent to lakes and rivers. Applications for new abstraction licences that may impinge on designated sites will also be considered under the Conservation Regulations. Such abstractors are recommended to consult the Environment Agency at the earliest opportunity.

Trading of Licences

The DETR issued a consultation paper on Economic Instruments in Relation to Water Abstraction (May 2000) regarding abstraction licences and the potential for trading licences as an effective means of achieving the optimal distribution of water resources. Any UK system to trade would be voluntary and assume that current licence conditions would apply, but would not be permitted if it led to environmental damage. The DETR is likely to issue further information on licence trading in the very near future.

Grant Aid

Growers and those in agriculture who are seeking to build winter storage reservoirs or similar may have access to grant aid under the Rural Enterprise Scheme as part of the England Rural Development Programme. The programme establishes how the UK Government will implement the Rural Development Regulation (RDR) which is referred to as the "second pillar" of the Common Agricultural Policy in the next six years. There are two priority areas for funding covering schemes to conserve and enhance the environment to those enabling the development of rural business, farming and forestry. The Rural Enterprise Scheme is just one of the four schemes outlined in the programme which is mainly funded by the European Union with UK Government support.

To be eligible, farmers, growers, rural businesses and communities must be non-public sector. Reservoirs that are built jointly as a shared scheme may attract 30-50% of the funding, with individual storage reservoir projects attracting 15-30% of the cost, providing all the relevant criteria for application is met. There is the potential for making a case for the inclusion of trickle irrigation and irrigation scheduling projects and advice should be sought from the Environment Agency or MAFF. Submissions are on an `open call` basis and can be made at any time.

Tips for making a successful application include the production of a high quality, innovative project that complements existing initiatives (such as LEAF, Countryside Stewardship etc), enhances the environment and stimulates co-operation and collaboration. Other key points include: -

- Linking the proposal to current Environment Agency Key Actions (such as A13 and A17)
- Highlighting the importance of irrigation to the local economy and the country as a whole
- Outlining the demand for water in your area especially if the region is located in an area that is particularly low in water
- Point out how the scheme would reduce pressure on local water resources

- Show that the importance of water and its uses for other activities within the area is understood
- Highlight the sustainability of having water available all year round thus relieving peak periods during the summer when the water resources in certain catchment areas would be 'stretched'.

Naturally, these key points are only a guide to accompany a full business plan outlining the aims, project costs, funding arrangements and the benefits to be derived from implementing the scheme.

How can science help?

The primary focus of this document is to provide information on the latest research and technological developments with the potential for significant future impact on the UK horticultural industry. In particular, the document aims to demonstrate how much of the basic plant science research underway in the UK and overseas, may impact on UK horticultural production. This first section is structured to consider water from the moment of application to the point at which it is lost to the environment via transpiration. We start with a consideration of water movement within substrates and how we might go about measuring this, before investigating the pathways of water uptake, the resistances to such uptake, and the relevance of this understanding to commercial production. Part I introduces a basic understanding of how plants function in relation to the supply of water and considers how we might actually use a plants' response to water supply to monitor crops. Using this information part I demonstrates how this information can be used to make irrigation decisions. A main feature of part I is to introduce recent applied research which demonstrates the significant commercial benefits being realised by taking a distinctly plant physiological approach to horticultural research. The main areas considered in the section include:

- Understanding water behaviour in substrates
- Measuring water in substrates
- Understanding plant water uptake and transport
- Using water to manipulate plant growth and yield
- Using the plant to monitor water status and schedule irrigation

Each chapter synthesises the current international understanding of the subject, provided by the author's expertise and that of those scientists who contributed towards the delivery of the course, around which this document is based. Many of the commercial opportunities for exploiting an increased understanding of plant physiology remain relatively unreleased by UK horticulture. This section therefore suggests, where relevant, potential areas in which future applied research and development may yield significant benefits for the UK industry.

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1. 'An eye on water'. *The Grower*, August 2001, p 20.

2. 'CAMS are coming'. *The Grower*, July 2001, p 19.

3. 'Tightening the taps'. *Horticulture Week*, May 2001, p 22

4. Tompkins J. Laws of irrigation. *The Grower*, Oct. 2000, pp. 13 - 14.

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6. Briercliffe T. Water margin. *Horticulture Week*, Aug 6th 1998, 28 - 31.

* *

2. HOW DOES WATER BEHAVE IN SUBSTRATES?

SUMMARY

This chapter gives a brief background understanding to the major properties and behaviour of water in horticultural substrates and the implications of such an understanding for production.

Introduction

The roots form the major means by which plants take up water. The form of the root system of any plant will differ depending upon the species and the situation and media in which it is grown. The supply of water to the plant from the media will be governed by:

- Root penetration (i.e. the ability of the root to push through the media)
- Container shape
- The method by which plants are watered
- The physical properties of the substrate

Water in substrates – terms

The two main properties of any substrate which determine its overall function as a water holding substrate are its **water holding capacity** (i.e. its ability to *store* water) and its **hydraulic conductivity** (i.e its ability to *transmit* water). The capacity of a substrate such as soil is a function of the pore spaces created by the constituent solid material and as such will be dependent on the actual substrate properties (Fig. 2.1). The **capacity** of a specific container is seen as the amount of water retained in a containerised substrate after drainage from saturation, but before evaporation. **Field water capacity** is defined as the amount of water retained within a soil with a pressure head of 300mm, which corresponds to –0.3 bars.

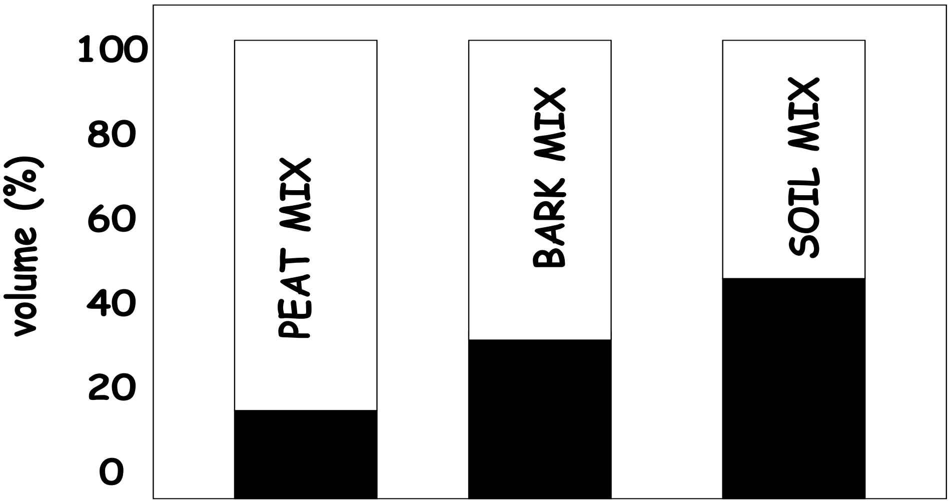

Figure 2.1. Typical proportions of pore space in different substrate mixes (the solid shaded area indicates pore space).

Properties of water in substrates

The ability of a substrate to hold onto water can be measured in terms of water potential. A potential is a negative pressure and is therefore given the units of pressure (Megapascal – Mpa). As substrate water content declines, the water potential of a substrate will increase (i.e. it will become more negative, give up water less easily and take water up more readily. Fig. 2.2 shows this in diagrammatic form for typical substrate mixes. The significance of water potential in describing substrate water status, is the fact that it is this variable, which the plant actually senses and responds to. Many commercial substrate water status monitors have been developed to estimate soil water content, as opposed to water potential (Chapter 3). The relationship between the two is far from straight forward (Fig. 2.2) and significantly affected by the level of dissolved nutrients in solution. Future technological developments should consider the development of a low cost, robust monitoring device to measure substrate water potential, not content.

How is this potential generated? Water is held on the surfaces of substrate particles. The surface tension created by the water on the substrate particles will increase as water content declines. Consequently, a greater amount of energy is required to overcome this surface tension as the substrate dries. As well as an increase in soil water potential, the hydraulic conductivity of a substrate will also change as soil water content declines (Fig. 2.3).

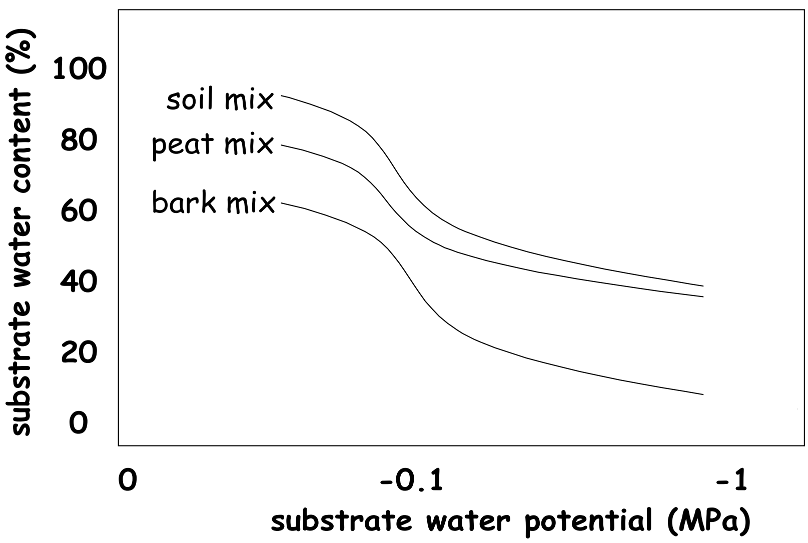

Figure 2.2. The typical relationship between substrate water content and substrate water potential in different substrate mixes.

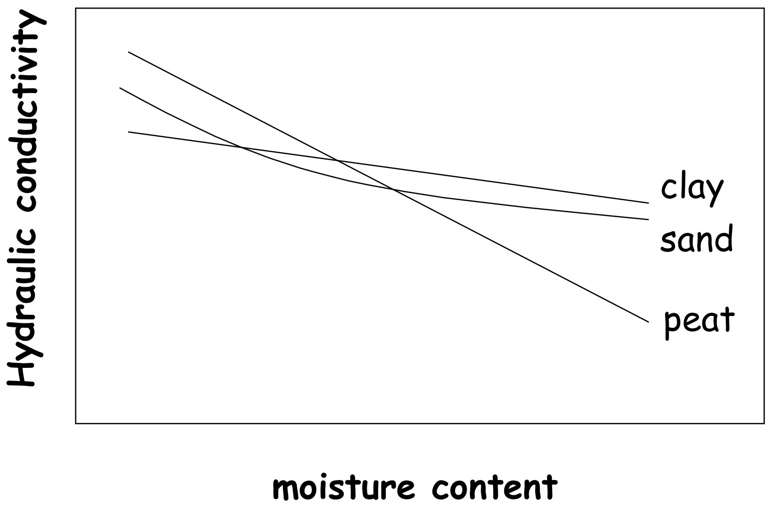

Figure 2.3. The relationship between moisture content and hydraulic conductivity in clay, sand and peat.

A significant proportion of the water within a substrate may be seen as unavailable to the plant, which is something to be remembered when considering any measurement based on water content. The hydraulic conductivity of a variety of horticultural substrates is extremely low and only water that is in close contact with the root may be readily available to the plant.

A significant amount of water remains tightly bound in ultra-micropores, typically less than 0.20mm in diameter, with surface tensions in excess of –15 bars (-1.5MPa). Generally plants cannot extract water from substrates with water potentials greater than –1.5Mpa. Consequently, the available water (AW) to a plant can be seen as the difference between the field or container capacity and the unavailable water.

For containerised growing, the size of the container also has significant effects on the amount of available water (Fig. 2.4) and the length of time that the plant can survive between irrigating. It is important for some pore space to remain unsaturated in order for the substrate to remain partially aerated. Low porosity substrates, which are easily saturated by excessive irrigation, will create an anaerobic environment (a low oxygen environment), which most plants cannot tolerate for any significant period of time. Increasing the porosity of a substrate will decrease the chance of water logging. However, as porosity increases so does the possibility of nutrients leaching out of the substrate and into surface and ground waters.

Most of this understanding may appear intuitive, however it is fair to say that in practice, the physical properties of substrates used in horticulture, such as conductivity and capacity are as much a function of substrate preparation as the innate property of the constituent media.

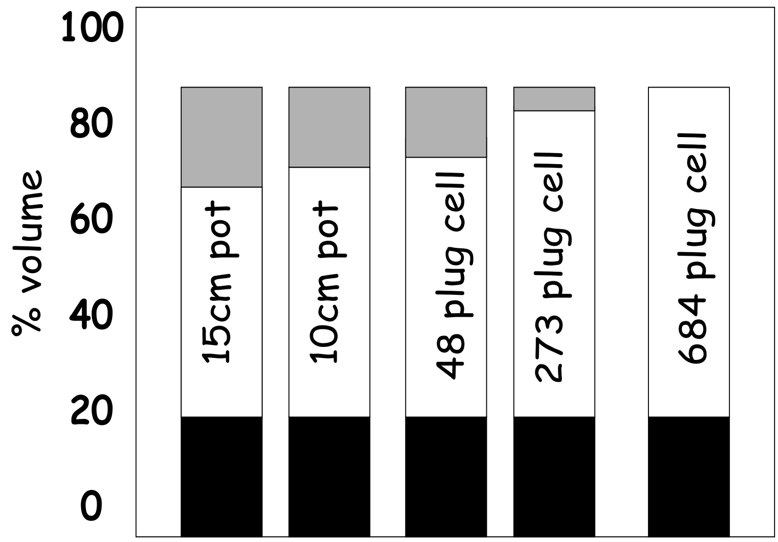

Figure 2.4. The relative volume percentages of available water (white); unavailable water (black) and pore space (grey) in typical containers.

Conclusions

Most commercial businesses have a good handle on the substrates they employ. The plant's requirements, rather than any direct consideration of using the substrate as a management tool to control runoff and leaching have driven their composition and design. Manipulating the substrate may however, offer one clear way in which to reduce these factors, minimising water loss, nutrient leaching and runoff into groundwater.

One clear issue for the industry is the need to re-consider the most suitable measurement of substrate water status. To date, very few commercial methods of monitoring soil water content use a measurement of substrate water potential. A potential area of technological development will be the production of such instrumentation, which is affordable and robust in a range of commercial production environments.

Future Research Priorities

Several priorities, including the need to develop peat free alternatives define the development of this particular sector of the industry. The following may offer some further significant and valuable contributions:

1. The potential to consider new methods for monitoring soil water potential, via an affordable and robust method.

2. Continued objective assessment of using substrates to manipulate plant nutrient and water uptake properties in a more directed manner to control plant performance.

FURTHER READING

Holmes S, Lightfoot-Brown S, Bragg N and Deen J (2001) Peat alternatives for commercial plant production in the UK: a grower guide. Horticultural Development Council.

Tuzel IH, Tuzel Y, Gul A, Altunlu H and Eltez RZ (2001) Effect of different irrigation schedules, substrates and substrate volumes on fruit quality and yield of greeenhouse tomato. *Acta Horticulturae:* **48**: 285-292.

PC 151 Tomatoes: water uptake by NFT and rockwool grown crops. See summary in Appendix 1.

HNS 107a Container HNS: Improving water management within the growing media. Further details available from the members section of the HDC website (www.hdc.org.uk).

GLOSSARY OF TERMS

Hydraulic conductivity	A measure of water movement through a substrate
Water Potential	A measure of how easily a substance will release or take up water
Water holding capacity	The ability of a substrate to hold/contain water

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3. MEASURING WATER IN SUBSTRATES

SUMMARY

This chapter gives a brief outline of the technologies available to measure the water content of soils and artificial substrates such as Rockwool™; their advantages, limitations and suitability of use in the horticultural sector. The chapter concludes with a brief consideration of what irrigation monitoring and control systems are and a list of further sources of information on commercially available sensors.

Methods of Measuring Substrate Water Status

Several methods exist for the measurement of water content in a variety of soil-based or artificial growing media. Current methods rely on one of the following types of technology/measurement:

Measurement of Evapotranspiration (the water lost by plants)

The basis of the measurement relies on calculating the amount of water lost from a growing media directly (via **evaporation**) or via its uptake and then loss from plants growing in the media (**evapotranspiration**). The loss of water from plants can be calculated using a mathematical equation that takes into account all environmental variables such as humidity, temperature, wind-speed etc. This equation is called the Penman-Monteith equation, after the two scientists who first formulated the expression. The equation was originally devised to describe water loss from a uniform area of vegetation (e.g. a field of wheat). However, it is still possible to apply the equation to very different kinds of plants, growing in a variety of situations including, glasshouses, fields, orchards, nurseries and polytunnels. To estimate the water loss from plants using this method, it is necessary to make a whole range of environmental measurements, including sunlight intensity, wet and dry-bulb temperature, wind speed etc. This is usually achieved by mounting commercially available weather stations close to the site of commercial production (e.g. centre of the glasshouse, orchard or field). In practice, it is also necessary to adapt the equation to consider the particular evaporative properties of the plant you are growing. Reference information for the evapotranspiration characteristics for specific crops is however, widely available (see further information).

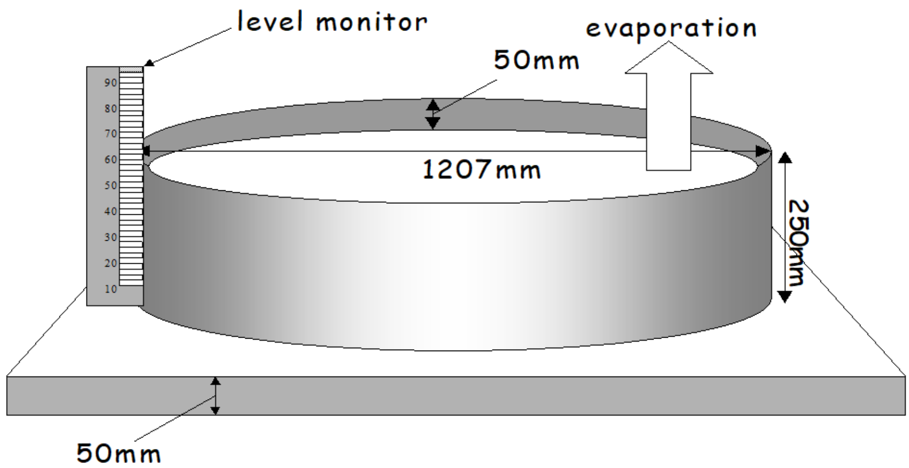

Figure 3.1. Diagram of a pan evaporator

As well as calculating water loss via the above equation – it is also possible to measure water loss directly, by measuring the amount of water lost from a reference area close to the growing crop. A commonly used reference surface is the **Class A evaporation pan** (Fig. 3.1), a 250cm^2 circular plastic or metallic pan connected to an electronic or mechanical monitor to record water loss via evaporation. The evaporation rate from the pan and an adjacent crop are both driven by the same environmental variables. Any differences between the rates will be due to the specific nature of the crop being grown. Again, information is widely available for specific crops to allow the grower to correct for this difference.

Other devices such as a **Piche evaporimeter** (Fig. 3.2) can also be used to make a direct measurement of evaporation. This evaporimeter consists of a cylindrical tube of glass filled with water, with one end closed and the other end covered with a disc of porous paper held in place by a brass spring clip. When held vertically, the amount of water evaporated from the paper surface of an $11cm^2$ can be read on a scale on the glass tube.

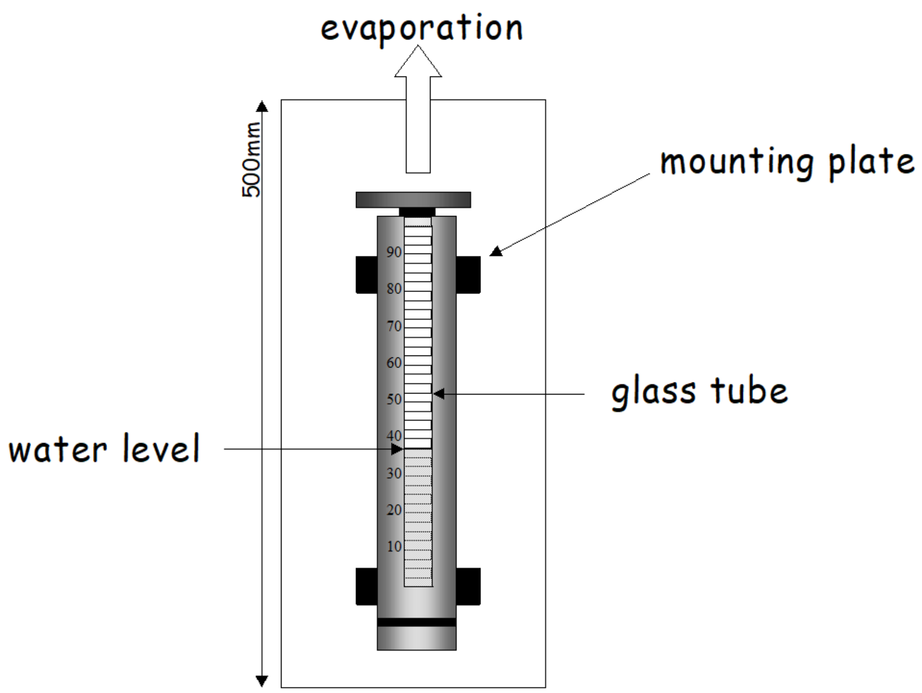

Figure 3.2. Diagram of a Piche evaporimeter

Pros, cons and costs

Measurement or estimation of evapotranspiration still remains one of the most widely used methods by which to monitor water loss and schedule irrigation. Measuring evapotranspiration ranges from the highly complex and expensive (e.g. purchase of a weather station, series of evaporimeters, computer-assisted irrigation scheduling and the necessary irrigation delivery system), through to a a single evaporation pan or evaporimeter, to decide the period of irrigation applied manually. The major limitation to methods based on evapotranspiration is the assumption that measurement of evaporation from a class A pan or evoporimeter is the same as evapotranspiration of the crop of interest. A large database of crop specific factors does however, minimise these risks (see above) and allow the calculation of evapotranspiration to take account of the evaporative characteristics of a particular crop.

Large scale, fully automated systems are commercially available and are usually commissioned to suit specific requirements of the commercial grower. Further sources of information for such services can be found on the Commercial Horticultural Trade Association's (CHTAS) website or via the trade search function of the Horticultural Trade Association's website (see further information for addresses).

As such, measurement of evapotranspiration is probably the most widely applicable method of assessing crop water use, being routinely used in the production of field crops, soft fruit, glasshouse crops and ornamental nursery stock.

Measuring substrate tension

The ability of any substrate to 'pull water in' can be measured in terms of a tension, potential or negative pressure. Commercially available **tensiometers** measure this tension directly and are buried into the substrate close to the plants under cultivation in the field or in pots.

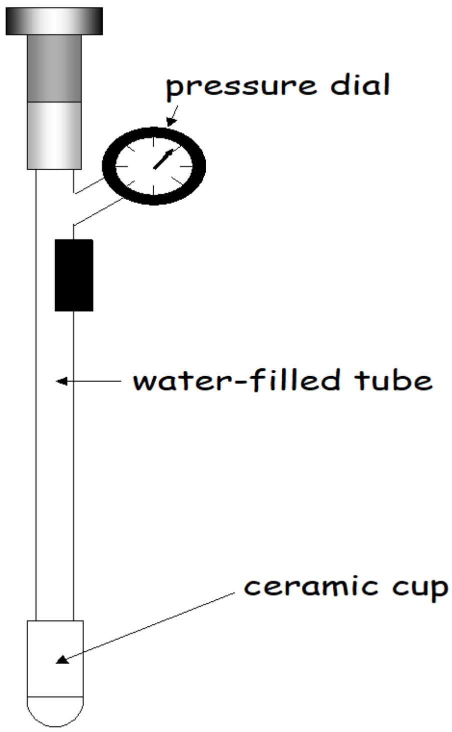

Figure 3.3. Diagram of a tensiometer.

A tensiometer consists of a column of water within a sealed glass tube. A porous pot seals one end of the tube. When the cup is buried in the soil water will move out via the pot into the soil. Sealing the column of water prevents the water simply flowing out via the porous cup (Fig 3.3). As a result, a tension within the column of water is generated and this tension is measured by a pressure sensor in the water column to provide a pressure readout. A typical tensiometer set up would consist of two tensiometers. One located in the upper root zone, monitors the active root area and is used to determine when irrigation is needed. A second tensiometer, installed near the bottom of the root zone, is used to adjust the irrigation amount or system run-time in order to ensure that sufficient water is being applied, and to avoid over-irrigation and loss of water due to drainage beyond the root zone.

<u>Pros, cons and costs</u>

The major disadvantage of tensiometers as a means to measure substrate water content is their inability to operate in moderately dry soil. As soil dries, the connection between soil water and the water column within the tensiometer can become disconnected, allowing air into the water column. Once air bubbles are within the column, measurements are not valid. The main advantage of tensiometers is their ability to give a direct readout of substrate water potential (Chapter 2). As discussed in chapter 2, water potential is the variable 'measured' by a plant as opposed to the actual water content of the soil. As such any irrigation decision based on this technology will be well coupled to the actual water status of the plant. Their relatively simple construction, makes commercially available tensiometers relatively inexpensive (less than £100), considering their portability and are available from a wide range of commercial suppliers in the UK (for a list of potential suppliers see Further Information).

Tensiometric measurements can be easily made in field soils and containers. Some difficulties in small pots and artificial media may occur.

Dielectric Devices

A range of devices are commercially available which use electromagnetic radiation (radio waves) between 30-1000MHz to detect the substrate water content. Such Devices emit electromagnetic radiation into the water (the dielectric) within the substrate and compares the signal emitted with that re-detected to quantify the amount of water within a substrate. The relative dielectric constant of a soil varies with soil water content. Various methods exist to quantify the amount of water via this method, with **TDR** (Time domain reflectometry) and **capacitance probes** forming the two major types of device currently available. Figure 4 illustrates the typical appearance of a soil moisture probe used to measure the relative dielectric constant of a substrate.

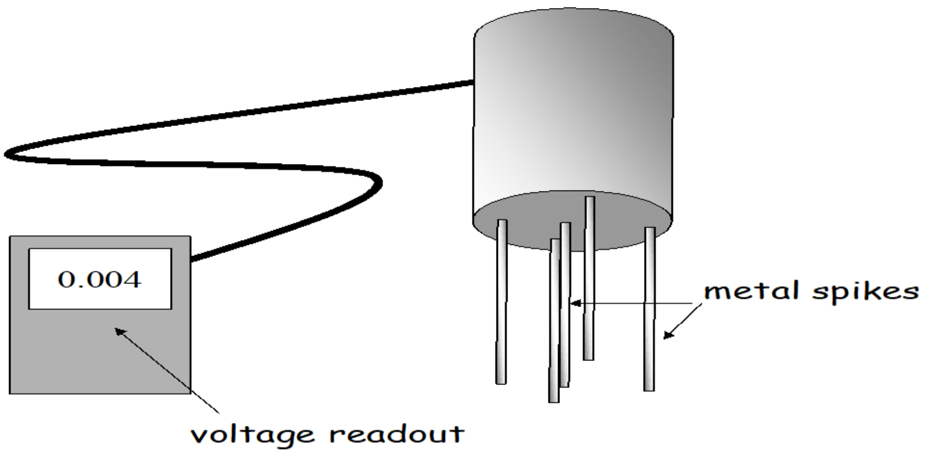

Figure 3.4. Diagram of a typical soil moisture probe to measure the relative soil dielectric constant

Pros, cons and costs

The advantages of such probes include the relatively large amount of soil tested and their portability and subsequent opportunity for frequent measurements. Some commercially available probes can actually co-measure soil water availability and soil water salinity. The main disadvantage of this technology is the cost of the probes themselves, with the simplest of probes costing a few hundred pounds.

Measurements with commercially available probes can be made in field soils, containers and artificial substrates. Accessories and certain probes will allow measurements to be made in deep soil and some probes can be buried to provide continuous measurement at a particular depth. Again, the consideration of the relationship between estimated water content and actual water status may cast doubt on any technology which measures water content as opposed to water potential.

Neutron Probes

The science behind neutron probes requires some explanation. A molecule of water consists of one atom of oxygen and two atoms of hydrogen (hence H_2O). Atomic particles such as neutrons slow down when they encounter a body of similar mass, such as a hydrogen atom within a water molecule. The energy from the neutron is transferred to the hydrogen atom and the re-bounding neutron travels much slower with lower energy (Fig. 5). It is this basic principle which has been adapted to estimate the density of hydrogen nuclei in soil. As hydrogen nuclei in soils are exclusively part of water molecules, the number of slow neutrons detected close to a source of high-energy neutrons, is proportional to the amount of water in the soil.

In practice, neutron probes are used for field grown crops and are composed of a radioactive neutron source and a detector which are simply lowered into the ground via access tubes, which remain permanent, to allow repeated measurements over several weeks or months.

Pros, cons and costs

The main advantages of neutron probes include the ability to sample relatively large volumes of soil and their portability. The use of radioactive material as the high-energy neutron source remains the main disadvantage and has led to the decline in the use of this technology. Commercial probes are still available and are relatively inexpensive and neutron probes are often used for field and tree crops.

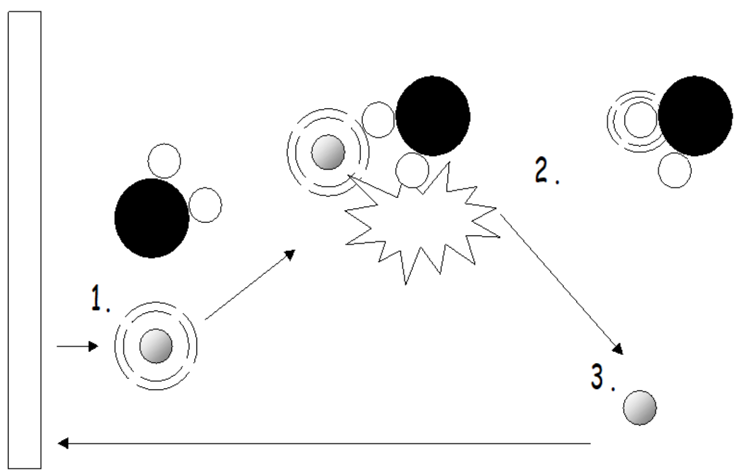

Figure 3.5. The principle behind the neutron probe. High-energy neutrons are emitted from the probe (1.) and collide with the hydrogen nuclei of water molecules (2.). The loss of energy slows the speed of the neutron and lowers its energy level, which is re-detected by the probe (3.).

Irrigation Monitoring and Control

Any of the above methods of measuring water loss from the substrate, can be integrated into an irrigation control system. Monitoring and control systems can differ according to whether they constitute an open or closed loop system. In open loop systems a measurement of soil water content would result in a period of irrigation to re-charge to a set-point. The main disadvantage of this system is the inability to quantify any errors that may exist between what you calculate you need to return to a set-point and what is actually achieved. In such cases errors can build up without detection. In a closed loop system, measurement of substrate water content before and after irrigation would be made, compared to the irrigation system modulated to take into account the difference between predicted and actual substrate water contents.

Whether closed or open, the degree of complexity of systems can range considerably. A simple open loop system may consist of no more than using hand held soil moisture measuring equipment and subsequent human decision on how much water to apply. The other extreme, would be an automated, software-enabled control system, with automatic gain control software and the ability to build in weather forecasting into the decision-making control software.

Conclusions

Although some larger businesses will be familiar with some, if not all of the above technologies, the cost of many monitoring devices have, in the past made their use prohibitive. However, several companies now manufacture, low cost apparatus which will allow growers to make good measurement of the water content of their substrates and use this information to determine plant water use and make irrigation scheduling decisions. Current research will eventually allow fully automated irrigation systems to be made available which use one or more of the above soil measurement techniques.

Future Research Priorities

Future priorities within this area, lie with the development of robust, low cost monitoring devices of substrate water potential. Ideally the development of affordable, accurate combination probes to determine water potential, content and electrical conductivity will bring significant added value to the industry.

FURTHER INFORMATION

DeSilva FF, Wallach R, Polak A (1998). Measuring water content of soil substitutes with time-domain reflectometry (TDR). *Journal of the American Society of Horticultural Research* **123**: 734-737.

PC 142 Tomatoes: comparison of methods for determining irrigation frequency with measured crop water use. See summary in Appendix 1.

Shaddick C. Irrigation monitoring is a must. *The Grower*, July 1998, p.20.

'Root zone ready'. The *Grower* 13 July 2000, p 37.

Lilburne C. (2001). Measured moisture. *Horticulture Week*, July 19th, 21 - 24.

Soil monitoring equipment. *Grower*, 9 March 2000 p.18.

Discussion on the use of digital tensiometers to control irrigation of containerised stock can be found at:
http://www.geocities.com/CollegePark/Union/1888/Paper98Summary.htm

For detailed information on dielectric and tensiometric based sensors available on the market see:
http://www.microirrigationforum.com/new/sensors/index.html

A useful range of guides on estimating evapotranspiration are to be found at the United Nations Food and Agriculture Organisations (FAO) Website:
http://www.fao.org/documents/

A range of companies selling all types of sensors can be found at the Horticultural Trade Association's (HTA) and the Commercial Horticultural Trade Associations (CHTA) Websites:
www.the-hta.org.uk
www.ukexnet.co.uk/hort/cha/index.htm

A detailed discussion of methods of measuring soil water content can be found in:

Rundel, P. and Jarrel, W.M. (1989). Water in the Environment. In*: Plant Physiological Ecology: field methods and instrumentation.* Chapman & Hall, 1989, pp.29-40.

GLOSSARY OF TERMS

Evapotranspiration	The loss of water held within a plant via evaporation
Class A evaporation pan	A standardised piece of equipment to quantify evaporation
Piche evoporimeter	Commercially-available meter to measure evaporation
Tensiometer	A meter which measures the tension exerted by soil water on a sealed column of water
TDR	Time domain reflectometry – A method used to calculate soil water content using radio-waves

* *

4. HOW DOES THE PLANT TAKE UP AND USE WATER?

SUMMARY

This chapter outlines how water moves from the substrate and into the plant via the root system and discusses the factors which regulate this uptake (including rooting environment, plant spacing, water deficit and microbiological activity,) and how this understanding may be exploited commercially.

Roots development and the growth environment

The roots of a plant form the main system by which plants take up both water and the nutrients. The actual form of the root system will be both a function of the specific characteristics of that plant and the environment in which it is growing. The environment can have a dramatic effect on root form and growth. For example, there is a very clear relationship between the total amount of sunlight received by a plant and root length (Fig. 4.1).

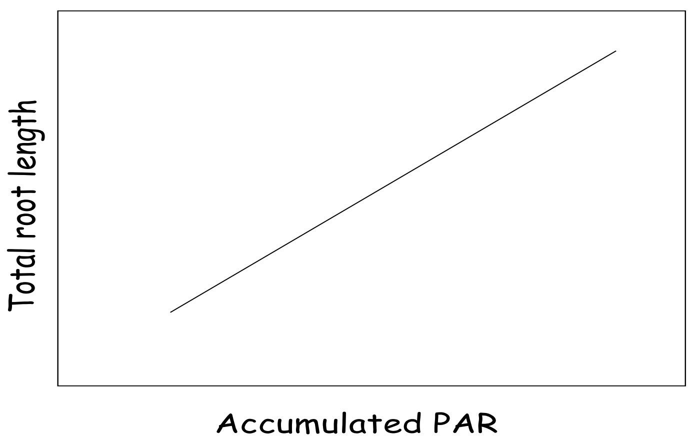

Figure 4.1 The general relationship between the total amount of sunlight intercepted by a plant (accumulated PAR) and root length

Similarly, roots growing in drying soil often exhibit significantly decreased rates of growth. Interestingly, however, root growth appears far less sensitive to reduced water availability, relative to the shoots (Fig. 4.2). This is the main reason why plants of horticultural interest, often exhibit an increased root to shoot ratio when soil water contents fall.

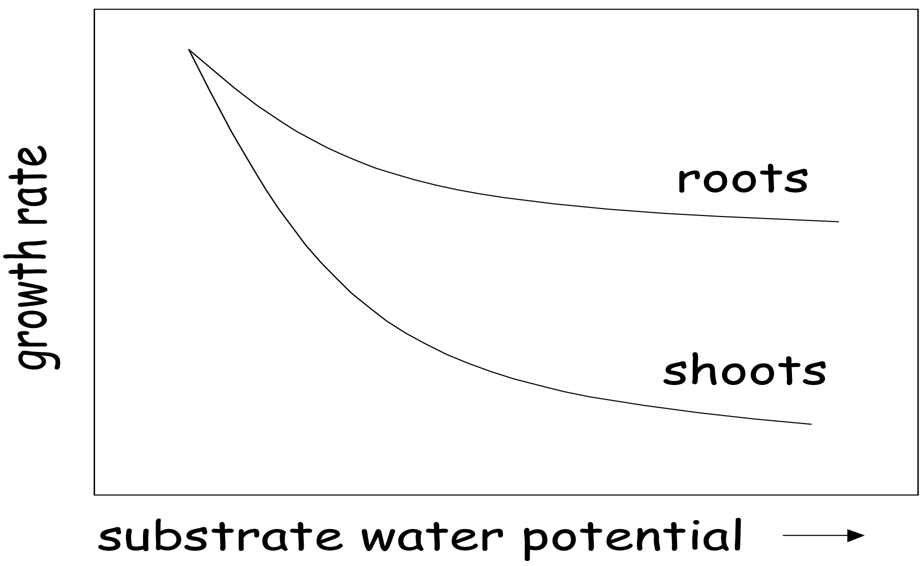

Figure 4.2. The typical response of shoot and root growth to increasing substrate water potential as the substrate dries.

Soil compaction will restrict where the roots can penetrate the soil and the final shape of the root system. As the strength of the soil increase (i.e. it becomes more compacted) the rate of root growth will decline (and shoot growth can also be substantially restricted).

The spacing of plants can have a significant effect on root morphology (Fig. 4.3). Competition for soil nutrients and water will drive changes in the branching and overall morphology of root systems in such a way as to maximise nutrient and water uptake. In commercial production the spacing and form of containerisation will impact significantly on how best to apply fertiliser and irrigation to such root systems.

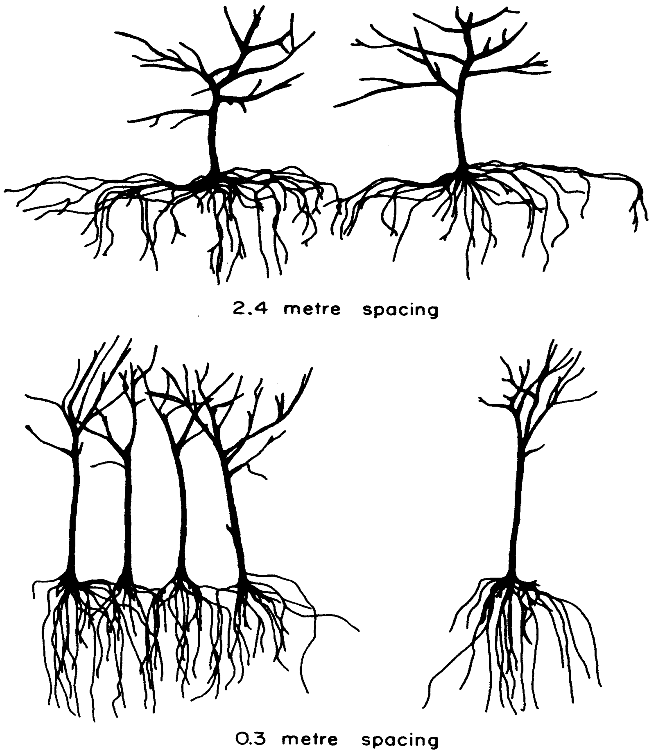

Figure 4.3. The effect of plant spacing on apple tree root development. The lower figures compares two trees grown at 0.3m spacing with one grown at 2.4M spacing. This drawing is courtesy of Dr. Chris Atkinson, HRI East Malling, Kent, UK.

No environmental influence will act alone, the interplay of all factors, some synergistic and some antagonistic will interact to influence the overall rate of root growth.

Many of these issues are clearly understood by the industry. Some, less so. The ability to impose a stress on the plant in order to change the root to shoot ratio, is not a widely-used tool. Future applied research may develop a better understanding of how controlled water deficit could be employed to manipulate overall plant shape. This may be particularly relevant in the production of ornamental crops such as trees, shrubs and pot plants. Work currently underway (Chapter 4) is developing the ability to use controlled deficit irrigation methodologies to change plant shape, increase visual quality and provide hardier, more drought tolerant hardy ornamentals.

'Real' root systems

A root system is much more than a collection of roots. A whole range of interactions between the root and various soil fungi, bacteria and other micro-organisms form a complex relationship. Roots release a wide range of organic and inorganic compounds into the soil which can then be subsequently used by soil micro-organisms which live close to the root. Micro-organisms will also act to change the availability of nutrients in the region close to the root. Several potential substances which are released by roots may have some potentially useful functions to the plant, including conversion of unusable nutrients to usable forms, protection against physical stresses, defensive responses to pathogens and inhibition of competitive plant growth. Little exploitation of such understanding is currently underway in horticultural production, making this a clear priority for future applied research.

One highly sophisticated example of such an association are mycorrhizae. Mycorrhizae are specialised groups of soil fungi form a series of complex interactions with the root to the point where parts of the fungal body penetrates into the cells of the root. Rather than being a parasitic relationship, the association increases the uptake of nutrients and water by the plant, while the fungus receives organic carbon compounds from the plant. Such associations are common in a whole range of ericaceous horticultural crops, including ornamental heathers, Rhododendrons and Azaleas.

Microbial activity is essential for plant functioning – but not only in those species which have an obligate requirement for such associations. Plants growing in sterile media may often show reduced performance, without the existence of complementary soil micro-organisms. Again, little information is currently available to quantify the extent to which this may be an issue for horticultural crops and as such may form a future research priority.

Pathways of water movement

At a finer scale, understanding the pathways of water and nutrient movement within the root may offer the potential for commercial manipulation. Water and dissolved nutrients enter the root at its surface and must then move across it, before reaching the water conducting vessels, which permit rapid transport of water and nutrients to the rest of the plant (Fig. 4.4). These vessels are termed **xylem vessels**. The passage of water through the root is thought to occur along a combination of two pathways. In the first, water enter cells near the surface of the root and then move from cell to cell. This is called the **symplastic** pathway of water movement. Alternatively, water can move *between* the cells. This is the **apoplastic** pathway. It is generally understood that all flow is ultimately symplastic because of the existence of various barriers within the root, which prevents a purely apoplastic flow of water. In this way, all dissolved substances in water entering the root will go through a living cell. Recent evidence has begun to suggest however, that so-called apoplastic bypasses may develop and allow water and anything else within it, to pass directly from the soil into the xylem stream of the plant. This may have particular relevance for certain horticultural species, but little information is currently available on what species may possess this apoplastic bypass. An apoplastic bypass may assist the movement of substances from the soil into the plant. This may be beneficial in terms of nutrient uptake and the possibility of introducing plant growth regulators via the roots. Future research will need to assess the significance of apoplastic bypasses in horticultural crops, including protected crops such as tomatoes and cucumber, particularly since the degree to which bypasses form would appear to be prevalent in hydro and areoponic systems.

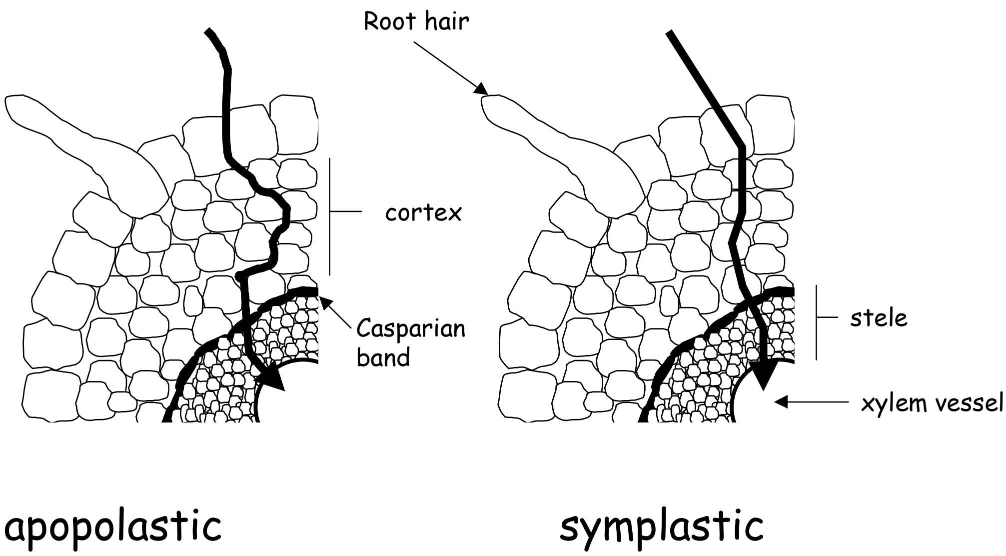

Figure 4.4. A cross-section of a typical root showing the symplastic and apoplastic pathways of water movement into the root

The driving forces for water uptake

The driving force for the uptake of water is a water potential gradient between the soil and the root. The water potential of the soil is primarily determined by how much water is held within the soil, how well bound to the soil it is and what substances are dissolved within the soil to generate what is known as an 'osmotic potential'. The water potential of the root is generated by the loss of water from the leaves via transpiration. This sets up a water potential gradient throughout the plant. The cohesive property of water means that as water is lost from the leaf, a tension (or potential) is generated within the xylem vessels throughout the whole plant. This tension, generated by evapotranspiration drives water movement through the plant into the leaf and water uptake from the soil into the root.

Water will move down a water potential gradient. Consequently, under optimal conditions, the root will have a lower water potential than the soil to generate a flow of water from the soil to the root. However, when substrate water content declines, or the concentration of dissolved salts in the soil is high, the soil water potential can be so low that water cannot be extracted. Soil water potential may even be lower than that of the root. In such circumstances water does not flow from soil to root and may well flow from root to soil, dehydrating the plant. Plant roots are well-adapted to this phenomenon and minimise flow of water out of the root by waterproofing older parts of the root.

It is this basic biology which regulates the rate of water uptake by plants. Practical implications are clear. During the night, when transpiration rate is very low, movement of water from soil to root will be driven by the difference in water potential between soil and root. However, the root water potential will only consist of the potential generated by the dissolved substances in the root cells. During the day this potential is significantly enhanced by the water potential gradient generated by transpiration. The amount of water uptake is therefore drastically reduced during darkness. Irrigation regimes should therefore bear in mind the efficiency of water uptake and the potential detrimental effect of water logging when prolonged night watering is conducted.

However, the slow uptake of water during the night, in the absence of any significant transpirational loss can be sufficient to fully hydrate a plant to the point at which the plant obtains the most favourable water relations. Recent applied research at Southampton University by Dr. Gail Taylor, has demonstrated distinct benefits to the industry using this understanding. If salad leaves such as lettuce are harvested at the end of the night, when the leaf tissue is full hydrated after a night of re-charging with water, their shelf life is significantly improved.

Resistances to water transport

Several resistances exist in the pathway of water movement from soil to root. One major resistance will be at the interface between the soil and the root surface. Poor packing of soil around the root as a function of planting or the physical structure of the soil can have a profound effect on water uptake and plant water status as discussed earlier (Chapter 2).. This was demonstrated clearly in experiments in which plants were rooted in sand within a plastic bag. As the plant transpired it was possible to measure a steadily increasing water deficit within the leaves. By applying physical pressure to the plastic bag, by squeezing it, the plants' water status improved (Fig. 4.5). Although this was a very simple experiment, it clearly demonstrated the significance of soil structure and packing on plant water status and the limitation to water uptake that can be imposed by a root soil interface resistance.

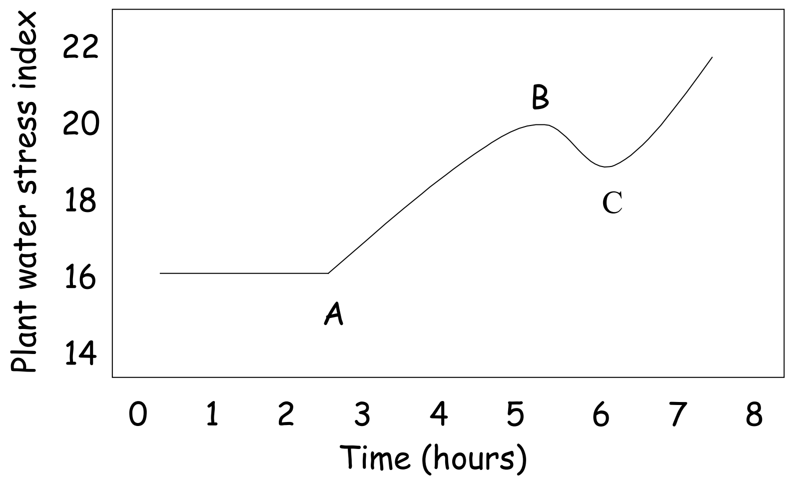

Figure 4.5. The effect of changing soil packing around roots on plant leaf water status. Adapted from Faiz and Weatherly (1982). At point A water deficit began to develop and at time B the plastic bag was squeezed. An immediate fall in stress followed reaching a minimum at C after which the stress increased again.

Roots and the sensing of water deficit

Roots are the primary plant organ which sense soil water deficit. It is now well understood that as a plant experiences water deficit, the root to shoot ratio will increase. This has been interpreted as an adaptive response which maximises resource input to the root system to maintain water uptake, while limiting leaf expansion and thus transpirational water loss. Work over the last twenty years has established that roots sense drying soil and communicate this information to the shoot via chemical signals within the water conducting xylem. Recent work has demonstrated that the concentration of one of these signals, abscisic acid, within the roots of plants, shows a strict correlation with the soil water content, such that decreased soil water contents were associated with increased concentrations of abscisic acid in the root. This chemical signal reduces water loss from the leaves via its effect on the stomatal pores on the surface of the leaf. It would also appear to be responsible for limiting the rate of leaf area production. The significant horticultural application of this signalling mechanism is discussed in detail chapter 5.

Water and nutrient supply

As well as the lack of water to the plant, water deficit will also interact with nutrient supply. Some very recent work has shown that nitrate availability has a very significant effect on root hydraulic conductivity (a measure of how easy water travels through roots). Nitrogen is a major component of proteins. Many proteins are carriers, which can be used to transport or 'pump' molecules from one place to another at a cellular level. Aquaporins are a group of carriers which actually transport water across cell membranes and may assist in the speed with which water moves through plant cells. This recent evidence suggests that reduced nitrate supply may limit the production of aquaporins and consequently the level of hydraulic conductivity. In an analogous manner, other recent work has shown that the concentration of nutrients such a potassium within the water-conducting xylem vessels can have a big effect on longitudinal hydraulic conductivity of these vessels. The significance of these observations to the industry is clear. Future applied research will need to determine if it is possible to use fertilisers to actually enhance water uptake by roots and deliver increases in plant quality and performance.

Conclusions

Understanding plant water uptake has numerous implications for the horticultural industry. The clear dependence of the root system on the environment, both in terms of pot sizes and the nature of the rooting media appear relatively intuitive, while the significant effect of accumulated sunlight on root growth may be less so. Many environmental variables will change the root to shoot ratio. This information can be used to alleviate root stress or to manipulate the plant into a desirable form for physical appearance or optimum nutrient and water uptake.

The necessity for microbial activity is well known in certain sectors, however in other sectors a clear understanding of the role for such organisms is not clear. The functioning of 'real' root systems and the influence of root exudates on microbial activity remains an area of great interest scientifically which may have significant impact on horticultural production. Manipulation of such activity may enhance plant growth and yield by promotion of more favourable nutrient and water relation.

Understanding how water and nutrients enter the plant will help to enhance water and nutrient and water use efficiency. The ability of different growing media to increase the 'leakiness' of some roots may have profound effects on what leaves the roots and what can be introduced to the plant via a non-selective root system.

Future Research Priorities

1. Using controlled water deficits to control plant quality and yield.
2. Assessing the significance of apoplastic bypasses in horticultural crops.
3. Increased understanding of soil microbial activity in non-ericaceous horticultural crops.
4. Use of fertiliser to enhance water uptake and use efficiency.
5. Exploitation of plant root-to-shoot signalling mechanisms.

FURTHER READING

FV 220: Application of beneficial micro - organisms to seeds using priming techniques. Available from the members section of the HDC website (www.hdc.org.uk)

HH1320SPC The effects of root environment on the production of protected crops (Horticulture Research International). Available from DEFRA:
http://www.defra.gov.uk/research/Projects/Reports/PDF/HH1320spc.pdf

HH1321SPC Physiological responses of protected crops to root-induced stress (Horticulture Research International). Available from DEFRA.
http://www.defra.gov.uk/research/Projects/Reports/PDF/HH1321spc.pdf

PC 54 Tomatoes: use of potassium nitrate and chloride and calcium nitrate and chloride to elevate root zone conductivities and their effect on yield and quality. Available from the members section of the HDC website (www.hdc.org.uk)

Faiz SMA and Weatherly PE. 1982. Root contraction in transpiring plants. *New Phytologist* **92**: 333-343.

GLOSSARY OF TERMS

Xylem vessels	The water conducting vessels within a plant
Symplastic	Relating to things which are cellular
Apoplastic	Relating to things which are associated with the space between cells

* *

5. CAN WE REDUCE WATER INPUTS AND GET ANY BENEFITS?

SUMMARY
This chapter discusses how plants regulate their water loss and how this understanding may be exploited by the horticultural industry to use water more efficiently and gain some potential benefits.

What regulates plant water loss?

The rate of water loss from a plant is governed by the environment (temperature, relative humidity, wind speed, solar radiation etc.), leaf area and leaf conductance (the ability to transfer water to the atmosphere). The primary regulator of leaf conductance is exerted via the stomata (Fig.5.1), the small, microscopic pores found on the leaf surface which permit water loss and allow carbon dioxide to enter the leaf.

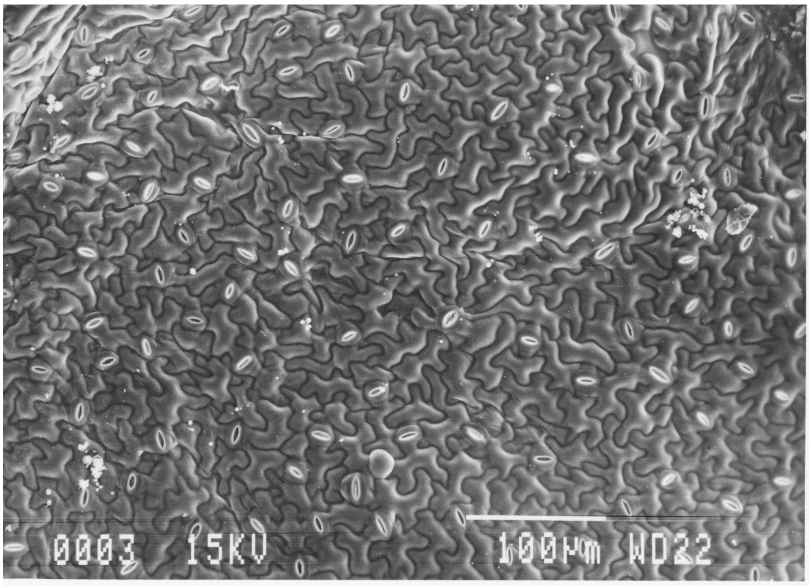

Figure 5.1. Stomatal pores on the lower surface of a cucumber leaf.

The size of the stomatal aperture is governed by two specialised cells known as guard cells. These cells regulate the size of the aperture by changing shape in response to the amount of water within them. The stomatal aperture is reduced by guard cells losing water and increased by guard cells taking in water. Stomatal opening and closing is tightly regulated.

New ways of thinking

Traditionally, scientists thought stomatal aperture declined in line with plant water status, to conserve water loss as availability declined. In a similar manner the growth rate of plants was thought to slow. Water within the cell generates the physical pressure (turgor) required for growth. Consequently as water availability declines it would seem reasonable to argue that growth would slow as turgor falls. However, an increasing amount of evidence now demonstrates that stomatal closure and reduced growth rates are exhibited in plants growing in drying soil, in the absence of any change in plant water status. Several pieces of scientific work have demonstrated this phenomenon. In particular, a split-pot experiment demonstrated quite simply how the link between roots in contact with drying soil and any change in plant water status could be de-coupled to examine what regulates growth and stomatal aperture in plants growing in drying soil. Apple trees were established with their root systems split between two containers in such a way as to be able to water the two halves separately (Figure 5.2). By watering one half of the root system and allowing the other half of the root system to dry, it was possible to maintain the water status of the plant while allowing a significant part of the root system to be in contact with drying soil. Even though the water status of the plants was maintained, leaf growth rate was reduced and stomatal conductance declined. Re-watering of the dry roots or their removal, removed the inhibition of leaf growth and stomatal re-opened, demonstrating some form of positive signal must be present in the drying roots and be transported to the shoots.

Figure 5.2. The artificial splitting of a root system between two pots. Photograph courtesy of Dr. Brian Loveys, CSIRO Plant Industry, Australia.

Current work aims to identify what these signals are and how they regulate growth and stomatal aperture. It is well established that the plant growth regulator abscisic acid (ABA) is responsible for stomatal closure. ABA is produced in the roots in response to reduced soil water status and transported to the shoots where it acts on the stomatal guard cells to induce water loss and cause stomatal closure. Evidence is also beginning to suggest that this same chemical regulator may control the rate of leaf expansion.

Using the plants' chemical signalling response

By reducing the amount of water given to a plant, the roots will begin to dry the soil as they extract the available water. Under such circumstances, chemical signals such as ABA are produced by the drying roots and transported to the leaves where they close the stomatal pores and reduce transpirational water loss. The same signal may also limit leaf expansion as discussed previously. If this signalling system is well developed then the plant will maintain its water status by closing its stomata, before any significant change in plant water status.

Figure 5.3. The Cotinus plant on the left has received 150% of its total water requirement. The right hand plant has received 50% of its total water requirement. Photographs curtsey of Dr. Ross Cameron, HRI East Malling, Kent, UK.

Deficit irrigation in hardy ornamentals

A currently ongoing Hortlink project (see HNS 97 – Appendix A) focusing on water use efficiency in hardy ornamental nursery stock has begun to successfully demonstrate how a variety of deficit irrigation methods may be used to control water loss and control vegetative vigour.

Regulated deficit irrigation has been shown to have a significant effect on the height of the hardy ornamentals *Cotinus* and *Forsythia* and have a significant influence on the overall shape of these plants (Fig. 5.3).

Deficit irrigation in other horticultural crops

Manipulating the plants own chemical signalling system to regulate water loss and the rates of leaf production and growth is an increasing area of commercial interest in horticulture.

The partial root-zone drying (PRD) technique is the premier and unrivaled example of how we can use a fundamental understanding of how plants function in relation to water availability, to deliver significant horticultural benefits. The PRD technique was developed by Dr. Brian Loveys at the CSIRO Waite Institute in Adelaide, Australia from original experiments jointly at Lancaster University and HRI Wellesbourne in the UK. The technique is based on experiments described earlier, in which the root systems of apple were established in two separate pots and irrigated independently. This system made it possible to allow one half of the root system to dry the soil while the other half continued to receive irrigation. In this way the plants water status was maintained via a supply of water to one half of the root system, yet chemical signals emanating from the drying roots were produced and transported to the shoots. By alternating the side that was irrigated or allowed to dry, the entire root system was maintained in a healthy condition. Under these circumstances the chemical signals were demonstrated to limit transpirational water loss via their effect on the stomata and limit leaf production and expansion rates. This technique was developed as an academic tool to illustrate that such chemical signals existed and that stomata closure and limitations in growth could occur without any change in plant water status.

The primary interest in this technique comes from its ability to reduce excessive vegetative vigour, control the amount of water transpired by plants and significantly reduce the amount of irrigation water used in production. Commercial viticulture in Southern Australia were quick to recognise the potential of this technique to reduce the expensive and unsustainable use of irrigation water and reduce the labour costs associated with pruning. By installing irrigation systems in vineyards capable of irrigating the two halves of a root system independently researchers in Australia have demonstrated that PRD can significantly reduce vegetative vigour. Manual removal of lateral side-shoots is expensive but essential in order to ensure the developing bunches are exposed to the sun.

By operating PRD, vigour is reduced and a favourable bunch exposure index is achieved. More remarkably however, the subsequent quality of the wines produced from grapes irrigated in this way, is significantly superior than that produced with twice as much water. The reasons for this still remain to be fully understood. In part, PRD would appear to generate a suitable canopy architecture for the correct exposure of developing bunches to the sun and other evidence would suggest that sugars fixed by photosynthesis are diverted towards the fruit and away from excessive vegetative vigour. The value of this work to the Southern Australian wine industry, in terms of reduced labour costs, lower irrigation bills, the lessened environmental impact and significant increases in wine quality is measured in tens of millions of Australian dollars.

PRD is now being trialed in several different horticultural crops in Australia at a commercial scale and a European project led by Lancaster University in the UK is now tasked with trialing PRD in variety of European crops including raspberries and tomatoes. In a recent trial with tomatoes grown in soil, research has demonstrated that although PRD marginally reduces whole plant yield, the technique can be used to control fruit size, increase fruit quality and produce a desirable change in customer preference for PRD versus control tomatoes, in terms of smell, taste and flavour.

CONCLUSIONS

Using PRD as a case study clearly demonstrates the potential to change plant performance via the manipulation of naturally occurring plant control mechanisms, with significant benefits. Although deficit irrigation methods are well established, a better understanding of how plants respond to water deficit is leading to new ways of thinking of how to impose such deficits. Future research will lead to the production of protocols for such techniques as PRD in a variety of horticultural crops grown in the UK.

Future research priorities

1. Continued development of deficit irrigation techniques in a range of UK horticultural crops.
2. Development of rockwool-based deficit irrigation systems.
3. Development of PRD as commercial system for UK horticulture.

FURTHER INFORMATION

Further information on the HNS97 HDC funded project can be found on the members section of the HDC website (www.hdc.org.uk). A summary of the project is also found in Appendix 1.

HNS 38 Water use under different hardy nursery stock container systems. See Appendix 1 for summary.

PC 166 Protected ornamentals: the efficiency of water use in different production systems. See Appendix 1 for summary.

Marsal J, Rapoport H; Manrique T and Girona, J (2000). Pear fruit growth under regulated deficit irrigation in container-grown trees. *Scientia Horticulturae* **85**: 243-259.

Cameron R. (1999). Less is more. *Horticulture Week*, May 20th, 20 - 23.

Gress A. (2001). Drought control. *The Grower,* 2001, Apr. 12th, 16 - 17.

A scientific evaluation of PRD on hardy nursery stock, tomato crops and grape production is provided in the following papers:

Loveys BR, Dry PR, Stoll M and McCarthy MG (2000) Using plant physiology to improve the water use efficiency of horticultural crops. *Acta Horticulturae* **53**: 187-197.

Davies WJ, Wilkinson S and Loveys BR (2002) Stomatal control by chemical signalling and the exploitation of this mechanism to increase water use efficiency in agriculture. *New Phytologist. In Press.*

Davies WJ, Bacon MA, Thompson DS, Sobeih W and Rodriguez L. (2000). Regulation of leaf and fruit growth in plants growing in drying soil: exploitation of the plants' chemical signalling system and hydraulic architecture to increase the efficiency of water use in agriculture. *Journal of Experimental Botany* **51**: 1617-1626

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6. CAN WE USE THE PLANT TO MONITOR WATER USE?

SUMMARY

This chapter outlines the potential for using the crop to measure plant water status and use in order to apply irrigation water effectively, specifically via the use of Infra-red thermography.

Understanding the regulation of plant water loss

In recent years, interest has grown in monitoring plant water status rather than that of the soil in order to schedule, save and optimise the use of irrigation water.

How is water loss regulated from a crop? Two distinct viewpoints can be identified. A plant physiologist would argue that the stomata are the primary site for the regulation of water loss from the crop. However, a more physically-based, meteorological view would suggest that this effect is minimal and that the primary driving forces for transpiration are those factors of the physical environment such as temperature, solar radiation, relative humidity and wind speed.

In horticulture, the degree to which a plant's transpirational water loss can be 'controlled' to any significant effect by stomatal conductance and the plant *per se*, as opposed to the environment, will depend on the growth environment and type of plant. Horticultural crops with small leaves, grown in unprotected environments, in relatively small areas that possess a fairly non-uniform or 'rough' canopy, are typically well-coupled to the environment. The water loss from such crops, which include hardy ornamentals and orchard crops, is significantly affected by the degree of stomatal conductance and its associated driving forces. However, large leafed crops, grown over large areas, exposed to low wind speeds and possessing a relatively uniform canopy structure, will exhibit evaporative water loss more closely correlated with the solar energy for evaporation at any one time, rather than any modulation in stomatal aperture. Typical crops, within this category would include glasshouse crops and field crops such as potatoes.

The control of transpiration is the integral of both environmental and plant control. In particular species and under particular growth conditions, one may predominate. While environmental drivers such as radiation, humidity, windspeed, and temperature combine to impose a driving force for water loss, the plant has evolved many mechanisms to regulate this loss. As well as stomatal regulation, plants can modulate leaf area and number under the control of plant growth regulators and possess structural features such as hairs and waxy cuticles to minimise water loss.

Estimating canopy water loss

Quantification and estimation of evaporation from a crop can be done in a number of ways. The evapotranspiration for a particular crop (ET_c) can be calculated as a product of a reference measurement of evapotranspiration (ET_o) and a crop co-efficient (k) which takes into account the overall evaporative characteristics of a particular crop canopy as discussed in chapter 2. The reference evapotranspiration can be calculated by using weather data or measured directly by techniques such as Pan evaporation (Chapter 2). The characteristic of the crops evaporative behaviour (k) will change over the season as the crop develops, consequently ET_o and k combine over a growing season to produce a predictive ET_c (Figure 6.1). Calculation of ET_o using weather data is done using the Penmon-Monteith equation which describes evapotranspirative water loss from a crop canopy. This equation is now incorporated into all major irrigation scheduling systems used in the UK.

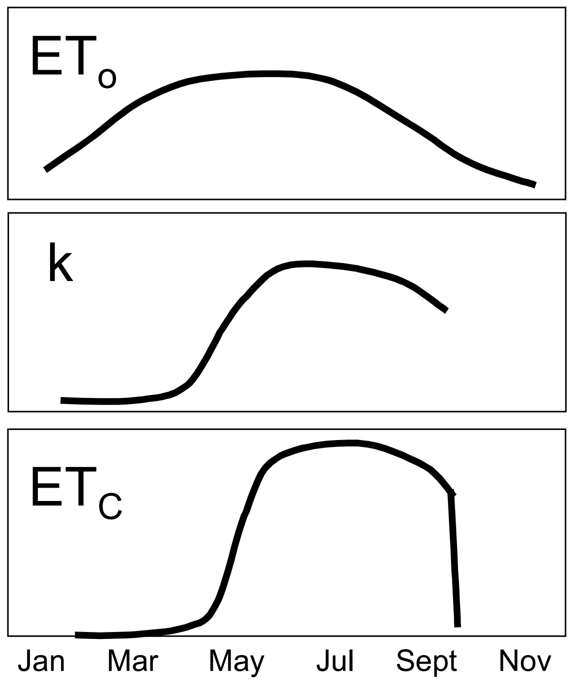

Figure 6.1. Diagram to illustrate how the absolute rate of evaporation and change in the crop coefficient of evaporation combine to produce a predictive rate of water loss for a crop over a growing season.

Irrigation scheduling protocols have traditionally used evaporation models such as the Penmon-Montieth model or systems based on soil water measurement as discussed earlier. In contrast to this and other way of assessing plant water use described in earlier chapters it may also be possible to use the plant as a tool to monitor and schedule irrigation.

Infra-red thermometry and thermography

The use of infra-red sensors to remotely measure plant water status is gaining significant agricultural interest. A measurement of leaf or canopy temperature in its simplest form will give a measure of the degree to which the stomata are opened or closed. Stomatal water loss results in evaporative cooling. As the stomata close, the temperature of the leaf will increase if all other environmental factors remain the some. Consequently, leaf or canopy temperature may give a measure of how open the stomata are and the rate of evapotranspiration from the crop.

A measure of leaf temperature can be achieved with an infrared thermometer or camera as the amount of infrared radiation emitted by an object is directly related to its temperature. Basic infrared thermometers cost a few hundred pounds, but only give basic spot measurements of temperature by pointing the gun-like thermometer at a plant canopy. A far more robust technology is offered by infra-red digital cameras which cost several thousand pounds, but provide very high resolution information on the variability in leaf surface temperature (Fig. 6.2).

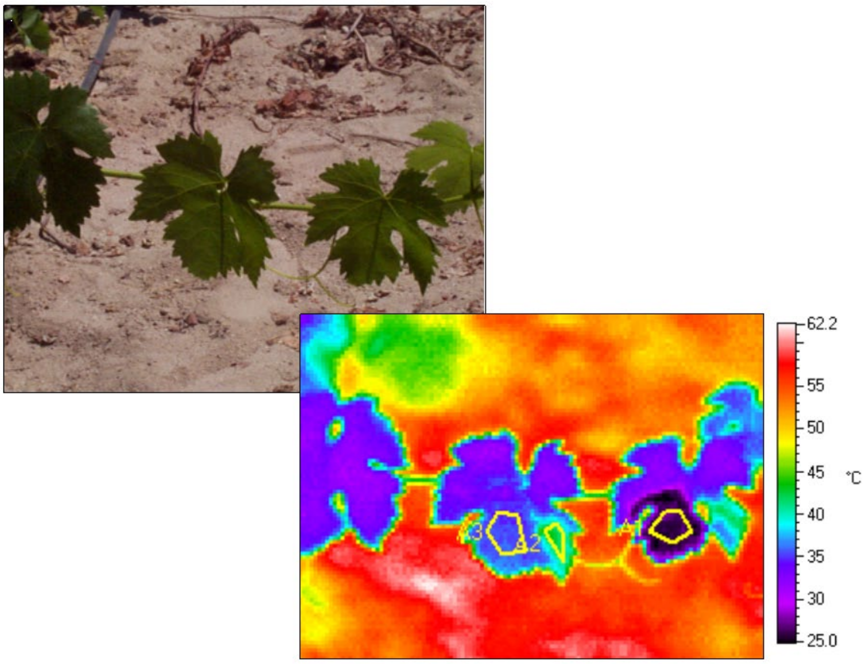

Figure 6.2. Visible and infra-red image of grape-vine leaves.

The ability of the leaf to maintain a leaf temperature below that of ambient air temperature. can be used to generate a measure of plant water stress, using the Idso water stress index, which relates the deviation in leaf temperature, relative to ambient, from a non-water stressed base line (Fig.6.3). In practice, measured crop temperature would be assessed against a previously determined non-stressed crop temperature to calculate a crop water stress index or CWSI. Although this index is useful, it is not directly related to any particular plant characteristic such as stomatal conductance or evapotranspiration and it is very sensitive to environmental fluctuations in radiation and wind speed. It is also difficult to gain a 'non-stressed' index for a particular crop.

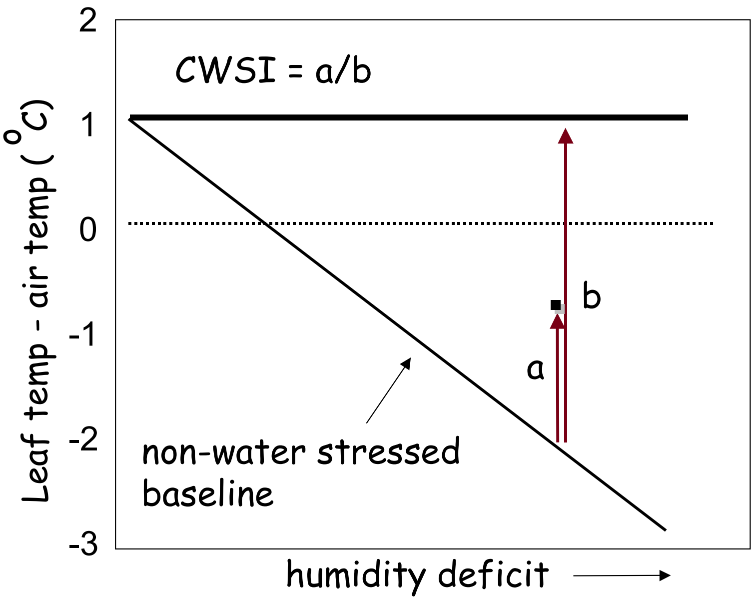

Figure 6.3. A diagrammatic explanation of how a crop water stress index can be calculated using a reference base line.

The main limitation to the technique is the bias in measurements, which include measurement of soil temperature in view when making the measurement. One such way to normalise infrared temperature measurements is to make reference measurements against a standard wet and dry surface. In this way its possible to generate a new type of stress index analogous to Idso's index, where the stress index:

$$(SI) = (T_{leaf} - T_{wet})/(T_{dry} - T_{wet})$$

where T_{leaf} is the temperature of the leaf, and T_{wet} and T_{dry} is the temperature of the wet and dry reference surfaces, respectively.

Other ways of measuring plant water status

IR thermography offers the potential to measure crop water status remotely over a large area. However, it is possible to measure plant water status in other ways, which are briefly assessed below. The main disadvantage of these techniques is the fact measurements are made on individual plants or parts of plants, as opposed to plant canopies.

Pressure Chamber

Using a pressure bomb it is possible to determine the water potential of a plant, using a pressurised leaf chamber to measure water status. Leaves are excised, sealed in the chamber and pressure applied until sap appears at the cut surface where the leaf was removed from the plant. The pressure required to achieve this point is directly related to the water potential on the crop. A single chamber is expensive and each measurement can take several minutes.

Turgor Pressure Sensor

A miniature displacement sensor attached to a leaf can be used to measure reductions in leaf thickness, and thus turgor pressure. However, this technique relies on the assumption that turgor pressures change in response to reduced water availability. This is not always the case. Similar sensors can be attached to measure changes in the thickness of woody stems. For further details of other potential monitoring devices using the plants' own responses see the further reading section at the end of this chapter.

CONCLUSIONS

In the future it may well be possible to use IR imaging to estimate crop water use and develop sophisticated irrigation monitoring and control systems using this monitoring technology. The current cost of IR cameras will prohibit its rapid uptake and wide-use in horticulture, in all but the largest commercial producers. The potential to hire the services of an IR camera and operator from a UK research institution may however, allow growers to commission a fixed term study using such equipment to verify the robustness of other irrigation monitoring and control equipment.

The use of IR imaging in UK horticulture will also require further work to demonstrate its suitability of use in our climate and in protected environments such as glasshouse. Current work underway in the UK focuses on its use in the commercial production of raspberries and potatoes.

Future research priorities

1. Continued development of IR imaging methodology for the UK climate and horticultural crops in field and protected environments.

2. Development of new techniques using plant water status as a monitoring component of irrigation systems.

FURTHER READING

Leonardi C, Guichard S and Bertin N. (2000) High vapour pressure deficit influences growth, transpiration and quality of tomato fruits. *Scientia Horticulturae* **84**: 285-296.

Jones H (1999). Use of thermography for quantitative studies of spatial and temporal variation of stomatal conductance over leaf surfaces. *Plant, Cell and Environment* **22**: 1043-1055.

FV 140 Improving irrigation scheduling using infra-red thermometry. See Appendix 1 for summary.

Langton A.. The "Speaking Plant". *The Grower*, Feb. 2001, pp.18 - 19.

An excellent review of plant-based measuring technologies is given in the paper: Water Conservation: Irrigation Scheduling Techniques, Resource Management Branch, Ministry of Agriculture and Food, CANADA. Order no. 577.100-1 March 1997.

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PART 2

Current and future applied research and development

A cross sector perspective

Introduction

This section considers internationally and nationally funded applied horticultural research with the aim of establishing its value to the industry and a future action plan for applied research in the area of efficient horticultural water use. In doing so, strong emphasis is placed on research focused on using a better understanding of a plant's physiology for commercial benefit. This emphasis, is recognised by the European Union's current fifth framework programme as a key requirement in delivering sustainable and efficient water use across the European Union.

International work

The UN IPTRID Database

The most comprehensive coverage of scientific research and development is provided by the United Nations Food and Agriculture Organisation's International Programme for Technology and Research in Irrigation and Drainage (IPTRID) database of current global activity, hosted by Cenmagref in France: http://iptrid.montpellier.cemagref.fr/). The database holds details of all activities relating to the sustainable development of irrigation systems and strategies in developing countries. The database is a useful demonstration of how the majority of international research which is geared towards optimising irrigation water via methodologies do not incorporate an understanding of plant physiology. Most studies have been conduced to consider optimal amounts of irrigation water and differing methods of applying water to a variety of crops.

A large amount of international research on efficient use of water in agriculture and horticulture is concerned with the development and uptake of established methodologies, as opposed to the development of novel technologies. As such, relatively few lessons can be learnt by our own domestic industry.

Commercially driven horticultural research overseas

After considering the vast amount of agronomic development in less developed countries, discussed above, analysis of research and development in highly developed economies, with prosperous horticultural industries offers some opportunities for adding value to the UK industry. In the specific area of water use, the United States, Australia and several Mediterranean Countries provide the most significant contributions to international activity on the efficient use of water in horticulture. However, in all but a few isolated but highly significant examples (discussed in Part I), the majority of work has excluded a sound appreciation of the plant's innate physiology in the design of irrigation technologies; in terms of both characterising plant responses or using such responses to develop new techniques. The majority of very worthwhile work again focuses on the optimisiation of water and nutrient inputs and the use of different types of irrigation delivery systems to minimise nutrient and water without any significant yield penalties. Major crop specific advances have been made in this way and irrigation protocols for many important horticultural crops established. The pressure to develop such protocols has to an overwhelming extent, been motivated by dwindling high quality water resources in hot dry countries with increasing urban populations, with particular emphasis on sustaining production for export. As such, research has been conducted on a range of non-domestic produce, including citrus, grapes and field crops such as aubergines, peppers and tomatoes, with little focus on increased water use efficiency in horticultural crops relevant to UK. As such, the UK industry, in considering and responding to pressure to increase its efficiency of water use, will be in a strong position to make a significant international contribution to applied research into efficient irrigation practices for commercial horticulture, in temperate, densely populated regions of the world.

It would be wrong however to discount the advances made in Mediterranean horticulture. While many of the crops are not currently grown in the UK, climate change models now reliably predict an increase in mean UK temperatures and distinct changes in rainfall patterns over the next 50-100 years. As the impact of climate change is felt, there will be increasing pressure on growers in the UK to move to precision irrigation techniques, including drip and trickle irrigation. Countries such as the United States, Australia and Israel have several years of experience of using such systems and the domestic industry may be well placed to begin considering how such experiences can be transferred into UK commercial horticulture.

Nationally funded applied research

The majority of applied, near-market research funded within the UK is supported by the Horticultural Development Council (HDC) and DEFRA

(Department for the Environment, Food and Rural Affairs). Table 1 lists projects funded by HDC over the last 10 years. DEFRA have sponsored two research projects of direct relevance, independently from the HDC on the efficiency of water use in horticulture (HH1320SPC and HH1321SPC). Full copies of the final report for both projects, which consider manipulation of the root environment to enhance water uptake and fruit quality in glasshouse tomato crops, can be found at:

http://www.defra.gov.uk/research/Projects/Reports/PDF/HH1320spc.pdf

http://www.defra.gov.uk/research/Projects/Reports/PDF/HH1320spc.pdf

A summary of the DEFRA report on independent water audits for container grown nursery producers is also provided at the end of Appendix 1.

The prominence and wider application of work on tomato

The largest body of work has considered the irrigation needs of tomato crops growing in rockwool or NFT (PC 23; PC 82; PC 83; PC 142 and PC 151). To a greater or lesser extent, this set of work has focused on the relationship between growth media and water/nutrient relations; different measurements of plant water use; irrigation scheduling strategies and yield responses to irrigation. One clear priority for the industry as a whole, should be to ensure that findings from work within this sector is transferred, where relevant, to as broader section of the industry as possible.

Summarising this work several common themes of importance to many sectors arise, including:

1. Water and crop quality.
2. Water and nutrient uptake.
3. Measuring plant water use.
4. Manipulating roots and growth media.
5. Defining the relationship between irrigation frequency and yields.
6. Determining the relationship between irrigation and nutrient efficiency.

Many of these issues concern a wide cross-section of the horticultural industry. Thematic analysis, presentation and dissemination of this work, which is, in part, a function of this document, will ensure maximum return from applied research to as wider community of commercial growers as possible.

Table 1. HDC FUNDED RESEARCH ON WATER USE

Reference	Topic	Title	Aim
PC23a (1991)	Tomatoes: Growth media	Growth media management for main crop tomatoes	▪ Production of tomatoes using recycled nutrient solution in rockwool ▪ Low nitrogen in feed formulation ▪ Comparison of fertiliser usage in rockwool and NFT ▪ Monitor treatments with respect to yield
PC 23 c (1991/2)	Tomatoes	Irrigation Requirements of the tomato crop	▪ To optimise irrigation frequency and volume of water ▪ To study the benefits (if any) of watering at night ▪ To determine yield and fruit quality
PC 23 b (1991)	Cucumbers	Recirculation of run-off solution from hydroponic systems	▪ To evaluate the effect of recirculating nutrient solution on rockwool and foam grown crops and compare to two substrates using run to waste system
PC23 (1991)	Tomatoes	Evaluation of recirculation systems	▪ An evaluation of recirculation of nutrient solution on crop performance, in terms of growth, yield and fruit quality
HNS 38a (1993/4)	Nursery stock (containers)	Improving irrigation efficiency for nursery stock in containers	▪ To test the feasibility of developing a simple method to determine the amount of irrigation required by container plants ▪ Possible methods included a bucket evaporator and an electrical sensor known as the evapo-sensor

HNS 38 (1993/5)	Nursery stock (containers)	Water use under different hardy nursery stock container systems	▪ Investigation of the potential of improving water efficiency of gravel systems by infilling with sand ▪ Comparison of performance against standard gravel and drained bed systems. ▪ Assessment of the potential of the rapitest meter to monitor water status of growing media and as a tool for crop water management
FV 39/39a (1991/4)	Irrigation	Timing of irrigation during vegetable crop establishment	▪ Aim to produce a mathematical modelling approach for predicting the optimum time to supply water to the crop
FV 46 a (1993/6)	Carrot Storage Roots	Effect or irrigation, development and variety on mechanical stress and tissue strength in carrot storage roots	▪ To establish relationships between carrot root water status and root fracture properties ▪ To devise methods of reducing damage in commercial practice. ▪ Examination of changes in water status to quantify the build up of mechanical stress within storage roots in relation to water supply ▪ Measurement of the susceptibility of root tissue to fracture
PC 82 (1992/3)	Tomatoes	Irrigation regimes for a long season rockwool crop	▪ To determine effects, if any, of time of application of extra volumes of feed solution on development, yield and fruit quality ▪ To determine impact of substrate and choice of growing system in plant performance ▪ Monitor amount of feed solution running to waste under different irrigation regimes.

PC 83 (1992/5)	Tomatoes	Irrigation systems for NFT	▪ Comparison between rockwool and NFT growing systems ▪ Optimise NFT system
PC 83a (1995/6)	Tomatoes	Commercial evaluation of yield response to plant position in NFT channels	▪ To determine whether differences in yield of up to 10% between the top and bottom of the NFT channels would be found in commercial situations ▪ The experiment aimed to determine if earlier findings at Stockbridge House in 1995 would be the same in commercial nurseries
HNS 88 (1997/8	Slow Sand Filtration	Monitoring the commercial development of slow sand filtration	▪ Monitoring of the progress of the SSF systems for pathogen removal under fully commercial conditions at two pioneering HNS nurseries ▪ Use of sensitive microbiological techniques (MAFF research programme) for testing pathogens.
HNS 88a (1998/00)	Slow Sand Filtration	Development of a low cost test procedure for assessing the efficacy of slow sand filtration on individual nurseries	The development of a low cost system for sand-based filtration which to:- ▪ Identify pathogenic fungi in nursery supplies ▪ Measure the filter maturation period ▪ Compare sands, performance and cost ▪ Test flow rates ▪ Familiarise staff with the operation of SSF
HNS 97	Efficiency of water use in HONS	Improving the control and efficiency of water use in container-grown hardy ornamental nursery stock	▪ Development of scientific rationale in HONS irrigation strategies ▪ Evaluation of new equipment to measure plant water use ▪ Irrigation to enhance quality

PC 119 (1996/7)	Glasshouse Irrigation	A review of R&D and evaluation of current techniques for irrigating edible crops grown in hydroponic systems	▪ The provision of a list of key areas where growers could improve upon irrigation practice ▪ To identify further R&D in order to make further improvements
FV/SF138 (1994)	Soft Fruit	Review of the use of fertigation and potential for its application	▪ A report concentrating on the potential benefits of fertigation to the strawberry crop
FV 140 (1994/6)	Irrigation scheduling	Improving irrigation scheduling using infra-red thermometry	▪ To identify limitations in operating performance of leaf and canopy UK temperature sensing techniques ▪ To develop an improved method for normalising leaf temperatures ▪ To develop a simple reference surface for use with hand held IRTs ▪ To modify procedures for using IRTs to improve operating performance in the UK ▪ To compare IRT with other irrigation scheduling methods and evaluate the benefits initially for field vegetables.
PC 142 (1998)	Tomatoes	Comparison of methods determining irrigation frequency with measured crop water use	▪ Measure and record water use of crop grown in recirculated NFT system and in rockwool run-to-waste ▪ To compare recorded rates of water usage with model simulations ▪ To identify differences in water use for tomato crops grown in NFT and rockwool run-to waste ▪ To assist in extrapolating NFT water use models to other hydroponic systems

PC 151 (1999)	Tomatoes	Water uptake by NFT and rockwool grown crops	▪ Identify differences in water use for tomato crops grown in NFT and rockwool run-to-waste systems ▪ To measure and record water use of crop grown in re-circulated NFT and in run-to-waste rockwool to validate the Silsoe irrigation model ▪ To identify crop growth and yield differences
PC 166 (2000)	Protected Ornamentals	The Efficiency of Water Use in different production systems	▪ To enable growers to compare different irrigation systems that reduce water and fertiliser wastage, meet customer accreditation demands and legislation. ▪ To provide costings information to compare systems for irrigation and run off treatment ▪ To identify targets for future R&D work
FV 195 (1998)	Carrots	The control of common scab with irrigation	▪ To determine if there is a crop growth stage particularly associated with disease infection ▪ To determine the soil moisture conditions associated with infection ▪ To develop a commercial irrigation schedule for disease control

Research for the Future

This section, aims to develop potential priorities for the future, from current understanding of the issues presented in Part I and the closing discussions between growers and researchers at the two-day meeting held on this subject in May 2001. These priories (Table 2), are accompanied by a potential action plan of delivery to assist those setting applied and thematic research priorities with the industry over the coming years. Priorities are not presented in any priority order.

Table 2. Potential priorities and key actions for applied horticultural research to enhance water use efficiency

PRIORITY	**KEY ACTIONS PROPOSED**
Improved transfer of findings between sectors	▪ Regular transfer activities, including meetings, workshops, cross-sector publications via in house HDC programmes, sponsorship of thematic programmes at industry meetings and exhibitions or outsourcing to training organisations (e.g. HortiTIPS, PSI, Hortitech)
Full use of extensive body of understanding within the scientific literature and research	▪ Collaboration between industry, HDC and University plant science departments with expertise in horticultural plant science (e.g. Nottingham, Reading or Lancaster) to conduct desk-studies of scientific literature ▪ Use of Biotechnology and Biological Sciences Modular Training for Industry Programme to develop a training programme in association with a University ▪ EU 5th framework accompanying measure focused on horticultural water use
Increased use of remote sensing techniques for all sector	▪ Funding of a demonstration project on IR thermograhpy by HDC and/or DEFRA ▪ Development of a Teaching Company Scheme with a commercial supplier of imaging equipment
Development of plant-based monitoring systems	▪ UK assessment of technologies commercially available
Development of deficit irrigation methods (including PRD)	▪ Full-scale commercial field trials of irrigated crops ▪ Development of rockwool-based technology via applied research ▪ Small Business Research Initiative bid to BBSRC/DEFRA by SME consortium ▪ Wider dissemination of work within the HONS sector via above activities ▪ UK commercial evaluation

Development of substrate monitoring equipment based on analysis of soil water potential not content **Development of combined monitoring equipment for electrical conductivity, soil water content and potential**	▪ Organise meeting between market leaders for research equipment in this area and growers to purse technology development ▪ TCS scheme funded by HDC and/or DEFRA with Delta-T to stimulate development
Regularly updated information on the regulatory issues surrounding water use	▪ Development of a HDC-hosted website in conjunction with the Environment Agency
Increased understanding of how substrate properties can be manipulated to enhance water uptake.	▪ Scientific assessment of root hydraulic properties of different crops (particular those grown via rockwool and NFT systems) in different substrates, using single root–pressure probe technologies (available at Universities of Bangor, Birmingham and Lancaster)
Exploitation of PRD in UK horticulture	▪ Joint research projects between Australia and UK (via Leverhulme International Research programme)
Evaluation of the significance of apoplastic bypasses in horticultural production	▪ Technology transfer from European lab activity via EU sponsored symposium ▪ Scientific screen on relevant horticultural crops ▪ Development of diagnostic test to establish existence and development of bypasses ▪ Demonstration of results that are relevant to horticultural production
Developed use of fertilisers to enhance water uptake	▪ Novel research on the role of nutrition and aquaporin expression ▪ Analysis on the effects of nutrient sources and levels on root hydraulic conductivity in horticulturally –relevant crops

Development of rockwool based deficit irrigation technologies **Assessment of the role of substrate microbiological activity in water uptake in non-ericaceous species**	▪ Applied research on horticultural crops in protected environments ▪ Transfer of understanding from the BBSRC programme 'Biological Interactions in the Root Environment' via symposia for horticulture ▪ Technological development, potentially in partnership with suppliers including Grodania A/S
Transfer of experience from USA, Israel and/or Australia	▪ Joint symposia eg. HDC and RHDC (Royal Horticultural Development Council) in Australia

From priorities to profits

Many of the key actions suggested will require research and technology transfer activities to be undertaken on behalf of funding agencies such as the HDC and DEFRA. Here (Table 3) we give an indicative list of potential future collaborators to assist in providing deliverables to the industry related to the efficient use of water:

Table 3. Potential future collaborators

Organisation	Key Strengths
Universities	
Cranfield (Institute for Water and the Environment)	Water use efficiency of crops; Advanced irrigation technologies; precision irrigation
Dundee (Dept. of Biological Sciences)	Plant water relations; IR imaging
Imperial College at Wye	Environmental Change; food production and land use
Lancaster (Dept. Of Biological Sciences)	Plant water relations; novel irrigation techniques; root-to-shoot signalling; IR-imaging
Newcastle (Dept. of Agricultural and Environmental Sciences)	Soil science; management of irrigation systems
Nottingham (Division of Plant Sciences)	Plant responses to water stress
Reading (School of Plant Sciences)	Environmental Physiology of crops; effects of climate warming
Southampton (School of Biological Sciences)	Water relations of salad leaves
Sussex (Plant Stress Unit)	Responses of plants to drought
Research Institutes	
Horticulture Research International	Horticultural crop production; plant water relations; root-to-shoot signalling
Stockbridge Technology Centre	Glasshouse crop production; irrigation technologies in artificial media
Private Organisations	
ADAS Horticulture	Deficit irrigation technology; water and yield quality

APPENDIX 1

SUMMARIES OF HDC FUNDED RESEARCH ON HORTICULTRUAL WATER USE

and

Summary of Independent Water Audits for Container grown Nursery Stock Producers
(Briercliffe; Hewson & Brough)

PC 23a
Growth Media Management for Main Crop Tomatoes

Relevance of work: This report aims to investigate the potential for the production of tomatoes in rockwool using recycled nutrient solution. Recycling of nutrient solutions in NFT and rockwool systems greatly reduces fertiliser use and run- off to the ground. The effects of using low nitrogen trial feed formulations are also highlighted.

Situation: A comparison is made between fertiliser usage in conventional rockwool systems and those using rockwool in recirculated systems.

Findings:
1. Each of the treatments only had a small effect on the total yield of the graded fruit.
2. A low-nitrogen regime was considered to be as good as a regime using conventional feed. Slab conductivity of the rockwool requires careful monitoring.
3. Magnesium deficiency may occur in rockwool treatments during late April.
4. Plant losses equated to 5% and were more severe in rockwool systems using re-circulated nutrient than run-to waste system.
5. Fruit size and quality was unaffected by any of the treatments.
6. Fruit sugars were higher in fruits taken from low nitrogen feed regime and were preferred by consumers.
7. Low nitrogen feed regime produces a slight increase in yield compared to using a \`solufeed\` nutrient regime.

PC 23b
Cucumbers: Recirculation of run-off solution from hydroponic systems

Relevance of Work: The ability to reduce run-off in hydroponic systems which may contain pollutants is of value, whilst also reducing the amount of nutrients and water purchased for growing the crop.

The Situation: The research sought to evaluate the effects of recirculating the nutrient solution on rockwool and foam-grown crops and compare these two substrates with standard run-to waste systems. Cucumber variety Rubella was used for the trials, with CO2 maintained at 1000vpm from Jan-April and reduced to 350vpm from then onwards.

Findings:
1. The foam substrate required frequent irrigation with small volumes of water;
2. There was some reduction the numbers of plants lost as a result of stem disease when either the foam slabs or re-circulated water was used.
3. There was a trend towards higher production for re-circulated treatments than run-to waste and a significant difference in yield between April and June.
4. No significant differences were found in the average fruit weight between rockwool and foam grown fruit or fruit from the run-to waste and re-circulation systems.
5. There were no overall differences in fruit length between the systems.
6. Plants grown on foam produced an equal amount of class 1 fruit to those grown on rockwool.
7. There was more grade A fruit (250-400g) in July and less grade C fruit (500 – 650g) from run-to-waste systems.
8. There were no positive conclusions with respect to fruit shelf life.
9. Foam slabs may need sterilisation prior to use.

PC23C
Irrigation Requirements of the Tomato Crop

Relevance of Work: Irrigation of glasshouse crops may be calculated on the amount of solar radiation falling on the crop canopy. The introduction of rockwool systems has resulted in new watering strategies to compensate for reduced root volume and water holding capacity of the substrate.

Situation: The research aimed to optimise the frequency and volume of water applied, study the benefits or otherwise of watering at night and determine the yield and fruit quality. A reduction in the amount of run-off water would lead to savings in both water and nutrient supplied. Based on estimates produced at ADAS (Wye), reducing run-off by 10% would reduce the nitrate loss form 700 to 450kg.ha. By manipulating the irrigation frequency, timing of application and the volume of water applied the effects on the crop were monitored.

Findings:
1. The time taken to first anthesis , the number of fruit set and number of marketable fruit were unaffected by irrigation regimes or their sub treatments.
2. The highest yield was recorded from the double row with night waterings.
3. The trend strongly suggested that low volume applications of about 50 mls combined with no watering during the night had an adverse effect on fruit quality in the early season.
4. Monetary returns were not significantly different to the end of the season.

PC 23d
Tomatoes: Evaluation of recirculation systems

Relevance of work: All Dutch salad crops must be grown in a closed system using recirculation of nutrient solution for example. Various growing methods are used such as the `V` system whereby tomatoes are grown as a double row of plants contained in a single row of rockwool. Alternate plants may then be layered alternately to either side.

It is possible that growers in the UK may also have to find ways of recirculating nutrient solution. This research has bearing on the matter as a comparison is made between crops grown using a recirculating system and a system that is allowed to run to waste.

Situation: omatoes of the variety Liberto, Spectra and Blizzard were used in both run to waste and recirculation treatments.

Findings:
1. Use of recirculation did not reduce the total yield or percentage of class 1 fruit and there was no significant difference between the two systems, hence there was no significant difference in monetary value.
2. Recirculation may have some association with slightly higher levels of fruit defects such as increased flecking or russetting.
3. Constant monitoring is essential to ensure the delivery of the optimum nutrient solution.
4. Fruit size was similar in both systems, although some larger fruit was obtained from the V systems using recirculation systems.

PC 33a
Alstroemeria: The effects of irrigation regime in the flower production cycle

Relevance of Work: Growers aim to produce flower cultivars with all year round production capabilities. Alstroemeria is in the top ten most important flowers to be marketed, but is subject to peaks and troughs in production. This study concerned the relationship between the supply of water to the plant and flower production.

Situation: The project aimed to provide growers with a crop watering system, which maximised the marketable yield of Alstromeria by timing water usage to stages in plant growth. The impact of dormancy (the sharp reduction of reproductive shoots) would also be investigated as well as improvements in irrigation management and its influence over the control of dormancy and flowering. Cultivars Eleanor and Carmen were used for the trials and irrigation water maintained in a pre-determined range (based on data provided by evaporimeter readings).

Findings:

1. No significant differences were found in total numbers of marketable Eleanor stems over a two-year period between non-regulated plants and those on a regulated irrigation regime.
2. Marketable stems of regulated beds were slightly depressed but gave rise to significantly more early first grade stems in the second year.
3. Dormancy may be broken with the application of water.
4. Irrigation regimes need to be tailored to suit broad cultivar types.
5. Carmen grown in regulated beds were too dry in the first season, which showed that the lack of water had disturbed the physiology of the plant.
6. Cultivar Eleanor showed redistribution in production with peaks occurring to coincide with higher marketable prices. Overall increases were estimated to be an additional GBP3.40 per meter in return.

PC 35b
The effect of irrigation and trimming on fruit quality

Relevance of Work: This work aims to determine the effect of irrigation and root zone warming on the fruit of the sweet pepper. The work is relevant in that it seeks to find the optimum solution for irrigating the crop, which will also minimise the effects of blossom end rot, which presently lowers the marketable value of the crop.

Situation: A two-year project comprising four irrigation regimes used sweet peppers varieties Cubico, Lambada and Mazurka for the trials. Treatment one comprised day and night standard irrigation with additional irrigation from 1100-1400hrs and the use of a perlite reservoir. This was compared to treatment 2, which differed in that rockwool was used as the reservoir.

Findings:

1. Variety Cubico produced the highest yield, with Mazurka producing the best quality and yield in year.
2. The perlite reservoir was the most beneficial in use, particularly when combined with night watering regimes.
3. Where extra leaves were allowed to remain on the side-shoots of the plants then appearance of rot declined. Flecking was also reduced but the incidence of fine new cracking was slightly higher.
4. Calcium levels were the highest in fruit grown by the perlite reservoir treatment.
5. Fruit from the standard day irrigation treatment had the poorest shelf life.
6. The use of a reservoir improved fruit quality in months May and June but the same treatment led to a reduction in quality towards the end of the season.
7. The combination of extra watering plus the use of a reservoir increased fruit cracking and showed a marked decline in terms of fruit product shelf life.
8. Four waterings of 100ml per plant spaced throughout the night appeared successful, but averaged over the season, the irrigation systems did not have any significant effect on the percentage of class 1 fruit.

HNS 38a
Improving Irrigation Efficiency for Nursery Stock in Containers

Relevance of Work: The research aimed to test the feasibility of developing a simple means for growers to decide on the amount of water required by container plants.

Situation : Overhead sprinkler irrigation may be low on capital cost in the first instance but is wasteful with regards to over-watering which also runs at a cost. Water use varies between pants and plant species and between different days of the year. Water requirements change according to the season, with a decrease in demand at certain times of the year. If the irrigation system is set to water the plants according to their needs for the most dry periods and not adjusted accordingly as the weeks pass, then up to 250% more water could be applied than is necessary.

Water used by plants can be measured according to (1) meteorological requirements using the Penman estimate (2) using evaporimeters to measure evaporation for a free water surface, (3) using an electrical evaporation sensor device.

Findings:

1. The electrical evaporation sensor was the most consistent and accounted for 86% of the variation in measured plant water use.
2. The method used to check irrigation requirements varies on a daily basis as the amount to be delivered will depend on the size and spacing of plants.
3. Plants that are spaced widely use less water per unit area than those standing 'pot thick'. However, overhead irrigation is inefficient when containers are spaced out. Drip irrigation is the preferred method for large plants.
4. A simple black plastic bucket part-filled with water can be weighed and weighed again at intervals to determine the evaporation rate. This method works well on rain-free days but may be erratic during wet weather.
5. Plants of the same size and species should be kept together to minimise wastage.
6. The electrical evaporation sensor invented at East Malling and developed for the control of fog propagation systems.
7. Correlation for estimating evapotranspiration. though further refinement is still required.

HNS 38
Water Use Under Different Hardy Nursery Stock Container Systems

Relevance of Work: The two-year project between 1993/4 and 1994/5 (updated in 2000 with report entitled Independent Water Audits for Container Grown Nursery Stock Producers) investigated the potential for improving water efficiency if gravel systems by infilling with 25-50mm of sand. Performance was compared to standard gravel and drained sand bed systems. The Rapitest Meter for monitoring the water status of the growing media was also studied for its suitability as a crop research tool.

Situation: A large proportion of the industry uses gravel or Mypex standing for container plants together with an overhead irrigation system, with surplus water running to waste. Drained sand beds have a good record of efficient water use although the capital investment can be high. Overhead systems of irrigation may use up top 70% more water than drained sand beds. The research sought to compare the water usage between the systems employed and the methods, by which water could be monitored, based on the water status within the growing media.

Eighteen small (6m x 1.5m) beds were used for the trials which were exposed to external weather and subject to different treatments as follows: 25mm gravel over Mypex using overhead irrigation; 75mm sand & drain, over polythene and with seephose irrigation; 75 mm sand & drain over polythene and using overhead irrigation; 25mm gravel over Mypex and 25mm sand, using overhead irrigation; 25mm gravel over Mypex and 50m sand, using overhead irrigation; 25 mm sand over Mypex with overhead irrigation

Hydrangea, Genista hispanica, Lavendula hidcote, Cytisus kewensis were used for the trials in the first year with a single species of Hydrangea and Lavendula `Hidcote` used for the second year.The 75mm drained sand bed system was the most efficient in water use especially when irrigating with a low-level seephose. Savings of 70% were found in the dry season when compared to gravel systems.

Findings:

1. Sand infills should be used in conjunction with a non-permeable polythene lining, not Mypex, to avoid water being_drawn out of the bed during dry weather.
2. The Rapid test meter was accurate in monitoring the differences in water status of the growing media both between systems and different plant species.
3. Once calibrated, the Rapid test provided a means of identifying a set point for when to commence watering.
4. There was a noticeable variation in the requirements of individual species, highlighting the problem of mixed cropping within the bed. *Hydrangea* for instance had higher water requirements than *Cytisus* with *Genista* and *Lavendula* having a low requirement for water.
5. Plant quality was similar for all the bed systems in operation, with improved root development in Lanvendual plants sited on sand.
6. The addition of 25mm of sand to a 25mm bed of gravel improved the efficiency of water use. A 50mm addition of sand would be preferred.

FV 39/39a
Timing of Irrigation During Vegetable Crop Establishment

Relevance of work: Crop uniformity is essential in order to maximise the amount of marketable product. The grower seeks to maximise the number of seeds that germinate whilst reducing the variability between emerging crops. In addition, crop management problems that occur from second flushes of the old crop appearing in newly planted crops are to be avoided. For optimum efficiency and profitability, a uniform crop, which can be harvested at the right stage of growth, is desirable.

The time from sowing to the initiation of root growth differs between seeds, and is dependent upon the availability of soil moisture. The grower needs to be able to predict the optimum point at which the growth of the radical can be initiated within the crop in order to produce a crop at a uniform stage of growth.

Situation: The rate of germination is associated with temperature and degree-days (^{0}C)-using records of maximum and minimum temperatures can be used as a tool to help the grower predict the germination period. The concept of the degree-day is simple in that it refers to the amount of time that the air temperature is below a base temperature. The base temperature for the purposes of the report has been taken as 2 degrees Celsius. Information on degree days for localities within the UK can be purchased from the Met Office but are best determined by recording temperatures shown on external maximum and minimum thermometer on a daily basis.

Findings:

Three main categories of crop could be determined: *fast growers* - whereby half the crop germinates in less than 40 degree days; *medium growers* - germination between 40-80 degree days and *slow growers*- germination in excess of 80 degree days. Fast germinators include: lettuce, radish, calabrese and certain brassicas; medium germinators include: cabbage, onions, carrots, leeks and slower growing brassicas; slow germinators include: parsnips, red beet.

FV46a
Effect on Irrigation, Development and Variety on Mechanical Stress and Tissue Strength in Carrot Storage Roots

Relevance of work: Root fractures in carrots cause a loss of marketable product. Reducing the incidence of root fractures would give rise to an increase in product quality and improve earnings. Turgor pressure (the condition in a plant cell when the cell vacuole is swollen with water and pushes the cell protoplasm against the cell wall thereby promoting rigidity in plants) and growth are both factors that are taken into account.

Situation: Splitting of carrots can take place during periods of growth or may be due to mechanical damage. The research aimed to establish the relationship between carrot root water relations and root fracture properties in order to revise methods and reduce damage in commercial practice. Changes in water status and quality mechanisms were examined, as was the stress in roots in relation to the supply of water.

Findings:
1. The strength of carrot root tissue increases with time especially at the end of the season.
2. Carrot strength varies little between varieties and is not affected by irrigation treatments.
3. Tissue strength was greater for later sown carrots.
4. The effects of irrigation on splitting in the ground are probably due to differences in the rate of growth.
5. Effective scheduling of irrigation to achieve most rapid growth when roots are at their strongest may be practically employed; Growth should be allowed to diminish prior to harvest.
6. Splitting may be associated with the strength of the carrot cell walls and the ease with which the skin of the carrot becomes `notched'.
7. Greater proportions of carrots split during growth following the application of a substantial amount of irrigation water in the early stage of development, followed by moderate applications to the end of the growth period.
8. Rapid growth may be stimulated by the availability of water, rather than an increase in `root turgor` as greater turgor is found in the split-resistant varieties whilst varieties susceptible to splitting such as Tamino possessed low turgor.
9. Splitting was more common in carrots larger than 80g.

PC82
Tomatoes: Irrigation regimes for a long season rockwool crop

Relevance of the work: This research investigated whether extra irrigation applied in the morning or at different times during the 24 hour period had any bearing on yield and if so to determine if the increase was due to the timing of the application of to the volume of water applied.

Situation: Tomato plants (c.v. Calypso) were cultivated using Grodan and Cultilene rockwool as well as Cultilene glasswool. Crops were grown as both double rows and in a `V` system using each type of substrate. Carbon dioxide levels were maintained at 1000 vpm. Plants were watered using a `standard irrigation` regime was taken to be 150ml of water applied to each plant. A variety of other treatments involved watering at different times of the day.

Findings:

1. Reduced root volume doesn't result in reduced yield.
2. The standard regime produced a final yield of 48.93 kgm^{-2}provided plants have sufficient nutrients in the applied water.
3. The night watering regime produced a yield of 50.5kgm^{-2} which is not significantly higher than the standard regime.
4. Grodan rockwool resulted in marginally higher yield in April and July.
5. Cultilene crops had a higher percentage of run off and may require smaller, more frequent, volumes of water to be applied.
6. The treatments had no particular effect on the time taken for fruit to develop to first anthesis.
7. There was no appreciable change in the number of fruit set, marketable value or fruit softness.
8. Lower levels of Gold Spot were obtained in the watering by night treatment.

PC 83 and 83a
Tomatoes: irrigation systems for NFT

Relevance of work: To compare rockwool and NFT growing systems for tomatoes and consider ways of optimising NFT systems.

Situation: This 3-year trial established in 1993 studied the crop growth and productivity of tomatoes grown using nutrient film technique (NFT). The aim was to optimise yield. In years 1,2, &3 NFT treatments were compared to standard rockwool run-to-waste systems. Years 1&2 were also compared to rockwool recirculation systems. Treatments were designed to concentrate on modifying the NFT solution to improve the root environment and maximise yields. Both oxygenation and magnetisation treatments were also separately employed. In one treatment, Oxygen was added to the NFT solution to raise the dissolved oxygen content of the solution by 100%. In another treatment, a polar magnet was installed in a line of the feed solution to produce a magnetising effect.

Findings:

1. Although there was no significant variation in monetary return in year1, on average, the monetary return on NFT was significantly higher than that of rockwool.
2. All NFT treatments, with the exception of the magnetic treatment, performed better than the rockwool.
3. Flow rates of 3 l/min, 5 l/min and 3 l/min combined with increased oxygenation all produced higher rates of yield than rockwool treatments.
4. Total marketable yield was excellent from all systems with no distinct differences between average total yields of NFT and rockwool treatments.
5. Best performance in terms of yield was obtained from the 3-l/min treatment, although this was only slightly greater than the 5l/min-control treatment.
6. A decrease in yield was apparent the further the distance away from the NFT inlet.
7. Fruit quality was higher in NFT system than rockwool at the start of the season, but low in all treatments during the hot weather at the height of the summer.
8. Fruit composition pH, sugar content and percentage of dry matter varied little between treatments, with fruit from the magnetic treatment declared best for overall flavour whilst possessing the lowest levels of fine net and radial cracking of the fruit.
9. Increasing flow rate in NFT channel from 5 l/min to 10 l/min had a beneficial effect of fruit yield.
10. Drip irrigation works well but plants at the top of the channel may suffer from water stress during hot weather.
11. Magnetic treatment produced higher yields at the start of the season, lower yields at the end of the season, but a high level of blossom end rot was evident, with similar nutrient values of the fruit to other treatments.
12. The increase in oxygen levels did not have any significant overall effect.
13. Findings from PC 23a suggested that potential yield benefits may be gained by adding extra inlet valves, increasing the flow rate and increasing the oxygenation of the nutrient solution.

HNS 88a
Development of low-cost test procedures for assessing the efficiency of Slow Sand Filtration on individual nurseries

Relevance of Work: The ability to make financial savings on the amount of water discharged from the premises as well as on the cost of water purchased for irrigation purposes is of importance to the Grower. If water used for irrigation could be recycled and plant quality maintained then further savings might be possible. Obstacles to overcome include reducing the infections of *Phytophthora, Fusarium* and *Phythium*, which, once present in recycled irrigation water, may contaminated plants with resultant financial losses.

Situation: Using slow sand filtration (SSF), whereby water is passed through a sand column of specified characteristics, can clean water that has been contaminated by plant pathogens.

The benefits of SSF are the relatively low installation cost, the flexibility to the grower in terms of size and design and the fact that the system is \`environmentally friendly\`, having no chemical or high-energy requirements. A significant part of the SSF method relies on biological processes, which can break down if the rate of flow of the filtration water is too fast.

The objectives of the research project were to: 1. identify pathogenic fungi present in existing nursery supplies. 2. Measure when the biological filter has become sufficient \`mature\` to provide an effective barrier to the pathogens; 3. Compare sands for performance and cost effectiveness. 4. Test flow rates in order to gauge the size that would be required by a full scale filter. 5. Disseminate the information on the concept and operation of SSF.

Sand selected for SSF has to be physically graded to provide information on the effective size (ES_{10}). The ES10 is a sieve mesh diameter through which 10% by weight of the sand will pass. The UC value indicates the uniformity of the sand. The lower the UC value, the more uniform the sand is (ES_{60} divided by ES_{10}). Information on the grade of sand should be sought from the sales representative, prior to purchase. Where sieve analysis data is not available a good indicator for selecting sand is to accept no more than 10% by weight of sand less than 0.2mm in diameter and no more than 10% by weight greater than 1.00mm diameter.

Findings:

1. Sands with an ES_{10} value of 0.2-0.33 were effective at removing pathogens in SSF.
2. Suitable sand types were lime-free sharp sands.
3. SSF performance was improved as sand with lower UC value was utilised.
4. Sands from a range of sources worked will at water flow rates of 0.2mh-1.
5. Low flow rates must be maintained for full efficiency.
6. Small-scale pilot filters constructed using 330 litre water butts worked well in all three commercial nursery sites assessed in the trial. Refer to report HNS88a for construction details.
7. Regular testing of the water supply is required if SSF system is introduced .
8. The efficiency of SSF activity against plant pathogens was not affected when water had a pH value in the range of 6.6-8.8 or and electrical conductivity in the range of 0.09-1.*22uS*.

HNS 88
Monitoring the Commercial Development of Slow Sand Filtration (SSF)

Relevance of Work: Slow sand filtration has been used since the early eighteenth century for the purification of water. SSF provides a means of reducing the amount of water required to be abstracted and used for irrigation purposes, as irrigation water can be recycled. The method of filtering used water through sand relies on the ability of the sand to build up a flora of bacteria which removes plant pathogens prior to the irrigation water being reused. Research conducted at Geisenheim, Boskoop and Wageningen in Holland as well as that conducted at HRI Efford shows that SSF successfully removes pathogens Phytophthora and Pythium. MAFF Projects HH1708SHN and HH1733SHN identify SSF as a very promising method in terms of efficiency, flexibility, sustainability and cost.

Situation: Raw water from nursery beds, the glasshouse roof and surrounding areas is passed through a sand column at a slow flow rate ($0.1\text{-}0.2mh^{-1}$) and allowed to run to waste until a biofilm layer has been established over the surfaces of the grains of sand. This is a layer of biologically active organisms such as bacteria, which aid the removal of plant pathogens. This `priming period` is a necessity and the biofilm layer must be allowed to become `mature` in order for the effective removal of plant pathogens to take place.

Two hardy nursery stock nurseries installed SSF to clean recycled water and progress was monitored with respect to the removal of plant pathogens using SSF under fully commercial conditions.

Findings:

1. The `priming period' for the establishment of the biofilm layer may take several weeks.
2. The volume of output is determined by the filter size. Every $1m^2$ of filter surface area will produce $1\text{-}3m^3$ of water (220-660gallons) per day, depending on the size of the sand grains used for the filter.
3. SSF runs continually.
4. The size of the SSF unit needs to be able to produce at least the maximum daily needs required by the site over 24 hours, and should be aimed at the amount required during the driest weather.
5. Water storage is required as the filter is too slow to apply water directly to the irrigation system.
6. Best practice includes collecting the rainwater in a reservoir, which feeds the SSF unit. The SSF unit then feeds the treated water to a clean water storage holding tank or reservoir (which must be of sufficient size to provide for the needs of the irrigation system plus provide sufficient water during the three day period that the filter is maintained.
7. Spores of plant pathogens will pass through the SSF column unless it has been fully primed and the biofilm layer allowed to mature.

8. Priming of fresh new sand took approximately 20 days.
9. SSF was 100% effective in removing phytopthora and Pythium pathogens once the sand was primed, and remained effective even when water temperatures were at 6C .
10. The SSF took 24 hours to re-prime after a maintenance clean-up period and 12 days after a 4-month winter shutdown period.
11. Frequent clean-ups are necessary due to clogging of the surface of the sand layer with silt, detritus, algae etc. A pre-filtration system could alleviate this problem.
12. Significant costs savings were reported which justified the expense of installation.

HNS 97
MAFF Horticulture LINK project HL0132LHN
Improving the control and efficiency of water use in container-grown hardy ornamental nursery stock (HONS)

Relevance of Work: To determine a scientific rationale for nursery stock watering strategies by matching irrigation more closely to the plant's actual requirement, thereby minimising waste. The project will determine guidelines to optimise irrigation management using both existing infrastructures (usually overhead irrigation in the nursery environment), and by implementing new techniques. Precision application of water (drippers) may also allow greater control over plant growth speed and form, reducing pruning frequency and improving plant aesthetics without a requirement for artificial plant growth regulators. This is because it is possible to manipulate the plant's own chemical signalling system.

Situation: A four-year project a) evaluating existing and new instruments for monitoring and controlling water use in the nursery environment, and b) investigating new irrigation techniques to improve plant quality using an experimental approach (RDI and PRD). Three model species were chosen: *Forsythia x intermedia* "Lynwood", *Hydrangea macrophylla* "Bluewave" and *Cotinus coggyria* "Royal Purple".

Findings:

1. Water consumption varied by up to 100% between different nurseries during set periods, indicating that large savings in water use are feasible.
2. Plant quality was similar between plants watered to set times and those watered on the basis of evapo-transpirational demand (ET), even though the latter gave rise to a 30-40 % reduction in water use over the season.
3. Atmospheric "evaposensors" provide a low cost approach to predicting water use, but predicted and actual water use was better matched when more expensive container-located sensors that measure soil moisture were used.
4. Experimental approaches detected that it was feasible to reduce water consumption by 50% of well-watered controls without inducing plant injury (RDI, PRD).
5. 50% ET RDI plants maintained a compact growth habit and required only minimal pruning if this technique was practised throughout the growing season (*C. coggyria*).
6. *F. x intermedia* plants grown under RDI had greater tolerance for later drought episodes, despite an intervening period of generous watering.
7. PRD was equally as good as RDI at regulating shoot vigour but has the advantage that it eliminates any risk of plant injury due to water deficit (lesions, early abscission) and maintains leaf size in *F. x intermedia* and *H. macrophylla*.

PC119
Glasshouse irrigation: a review of R&D and evaluation of current techniques for irrigating crops grown in hydroponic systems

Relevance of Work: The research identified key areas where growers could improve irrigation practice based on current knowledge and where further development was required. Improving crop growth. yield and quality whilst reducing waste in terms of water and nutrients is of importance.

Situation: A review was conducted of the irrigation of edible crops (tomatoes, cucumbers and peppers) that were grown in hydroponics.

Findings: I

Irrigation practice could be improved by employing the following factors:

1. Calculating the irrigation volume on an area basis (per m^2 rather than per plant).
2. Measuring applied volume by using correctly calibrated litre counters (not length of time that irrigation is run). Calibration should be checked, by measuring actual volumes applied and making comparisons with computer set points.
3. Early identification of problems in the irrigation equipment should be sought by checking for variations in dripper output.
4. Ensure the equipment has the capacity to supply sufficient water during weather extremes. Estimates suggest 1 litre per m^2 per hour for a rockwool-grown crop.
5. Measure light transmission in the glasshouse and calibrate solarimeters.
6. Continue to invest in more accurate equipment and dripper systems.
7. Position drainage slits carefully.
8. Aim to balance water supply with demand particularly in dull weather. Transpiration sensors could be one method, which will help in this respect.
9. Pay attention to the design of the delivery system and accuracy of the drippers. Supply lines arranged on the 'Tichelmann' system (which provides an equal delivery of water through all supply lines) together with CNL drippers, may improve delivery (EU funded Management & Control for Quality in Greenhouses MACQU project Air3-CT93-1603 refers).
10. Estimates of evapotranspiration can be provides using the Penman- Monteith equation. This is an equation that allows the energy used in transpiration to be calculated from environmental variables within the plant.

11. Potential transpiration can be measured rather than predicted using Jones-Rothwell evaporimeters.
12. An increase in the concentration of CO_2 in peppers for 300 to 1200 vpm reduces evapotranspiration by 15-20% but such enrichment was found to be negligible in tomato and cucumber crops.
13. There is no evidence that using more substrate in hydroponics increases yield (15 cm slabs now being commonplace).
14. Growers need to know the mineral content of the borehole supply in use as high levels of iron can block nozzles and requires treatment before use.
15. Glasshouse water can contain increased levels of Pythium and have a different composition from mains supplies especially in hard water areas.
16. More research is required on how water is taken up by both NFT crops and those grown in rockwool and why systems vary made to the bottom of the wrapper so that drainage is not impeded (and slab conductivity is not allowed to rise as a result).

FV/SF138
Review of the Use of Fertigation and the Potential for its application

Relevance of Work: This review concentrates mainly on the strawberry crop, the primary soft fruit crop in the UK with regard to monetary value and production, although some of the results may have applications to all soft and cane fruits. The review focuses on the nutritional requirements of the crop and fertigation.

Situation: The majority of strawberry crops are grown outdoors, with only a few strawberries grown in raised beds. A high proportion of the strawberry root system was found to occur in the top 15cm of soil (Dana, 1981) Adequate soil moisture is required to allow for the flow of nitrate, calcium, magnesium and the diffusion of iron and phosphates to the roots. Previous work by May & Pritts, (1990) show that optimal growth occurs at a pH of 6 as problems with aluminium and manganese toxicity may occur as the pH becomes low, due to the increased acidity.

Strawberries are inefficient at taking up nitrate. The selection of an appropriate source of nitrate would help to prevent further leaching to groundwater. Nitrate is essential for early growth and flowering but excess must be avoided as it is implicated in possible yield reduction, delayed ripening, excessive vegetative growth and increased susceptibility to moulds.

Phosphorous is required for the promotion of vigorous, well-branched root systems with deficient plants exhibiting reduced growth, lower yields and poor quality fruit. Phosphorous is most available between pH 5.5 and 7 as insoluble precipitates may be formed with aluminium and iron at a lower pH (less than 5) or with calcium at a higher pH. Excessive uptake of phosphorous may result in the reduced uptake of zinc, iron and copper and other micronutrients.

Potassium is required during stages of rapid growth and ensuring leaf and fruit development. More potassium may be contained in the fruit than any other element. Overall, the nutrient requirements of strawberries may vary according to the variety grown.

Findings:

1. Nitrogen may be applied in any soluble form such as ammonium nitrate, calcium nitrate, potassium nitrate, urea, monammonium phosphate, and diammonium phosphate or ammonium sulphate.
2. Recommended rates of 80kg of nitrogen per ha and below have been recommended (ADAS) with a reduction of 20kg nitrogen/ha less required for June bearing crops.
3. Everbearing varieties such as CVs. \`Ostara\` or \`Rapella\` may require higher levels of nutrient during the pre-field planting stage.
4. Best responses have been achieved using base dressings or base plus fertigation of between 40-80 kg nitrogen per ha.
5. Trials in the United States reported an increase up to 17% in fruit weight with fertigation than with pre-planting applications of nutrient.

6. Trials in Italy show the benefits of fertigation continued into the late Autumn.
7. The application of a base dressing followed by fertigation with nitrate only was a method preferred by Groninger and Soorsma in the Netherlands.
8. The use of drip irrigation to apply phosphorus fertiliser may allow for more direct application of phosphorus into the rootzone (taking soil properties, source of phosphorus and amount of water applied into account).
9. Irrigation water that contains higher concentrations of calcium, magnesium, phosphoric acid or urea phosphate are effective in preventing phosphate salt precipitation in trickle irrigation schemes.
10. Alternative sources of phosphorus include potassium phosphate, monoammoniun phosphate, and diammonium phosphate and ammonium polyphosphate. Glyserophosphate in conjunction with phosphoric acid may also be used.
11. In raspberry and blackcurrant crops similar results were found. Fertigation was more beneficial in terms of nitrogen than with broadcast fertiliser alone.
12. Nitrate concentration in leaves should not exceed 2.8% on sites subject to freeze injury, with suggestions of using half the application of nitrogen as a base dressing and the other as fertigation over a 90 day period by the Dutch.
13. Acidifying fertilisers can acidify the volume of soil below the emitters with prolonged use.
14. The more acidic fertilisers such as ammonium sulphate are not recommended for use on low pH soils or sandy soils.
15. Urea may cause acidification at a greater depth due to its mobility.
16. Reduced pH is associated with an increase in aluminium with losses of calcium, manganese and potassium from the upper layers of the soil.
17. The 'cation exchange' complex of the soil may be altered with the consequent removal of calcium ions. This may result in reductions of soil permeability due to the use of ammonium and potassium fertiliser together with low-calcium water.

FV140
Improving irrigation scheduling using Infra- red Thermometry

Relevance of Work: Techniques such as infrared thermometry (IRT) may be used to optimise the use of water in crops. Commercially available instruments such as the 'Scheduler" may be used to monitor stress in crops. Improvements in precision together with new techniques are always being sought. Research was conducted to develop alternative cost-effective scheduling in irrigating vegetable crops grown in the field. IRT techniques detect plant water stress and may indicate local variation over a given area. When data is entered into other irrigation scheduling packages (such as IRRIGUIDE provided by ADAS) estimates of the amount of water required may be determined.

Situation: Research was conducted over three years at Wellesbourne and at a commercial holding on runner beans, French beans and potatoes. Crops were given a range of irrigation treatments and measurements of soil moisture status and environmental conditions were compared to data from IRT. Hitherto, techniques for detecting plant stress have included: 1. measuring soil moisture using a 'neutron probe'. 2. Time – domain reflectrometry instruments (an electronic approach to soil moisture and salt content of the soil using 2 to 3 metal probes inserted in the soil). 3. Electronic devices such as EnviroSCAN ®. 4. calculating the soil moisture deficit (IRRIGUIDE).

IRT measurements were taken with the Barnes model (PRT10) Agema (Thermopoint 20-50) AGA Thermopoint and a further device supplied by Protimeter Ltd.

Findings:
1. A rise in temperature in the crop can be detected by using IRT.
2. Changes in canopy temperature could be detected within 24 hours of irrigation being ceased in certain crops.
3. A new, more sensitive, crop stress index has been developed which aims to provide the grower with more precise control of irrigation of horticultural crops. This compares IRT crop temperature with reference temperatures from wet and dry surfaces.
4. Theoretical approaches from directly estimating the underlying measure of stress in the plant (as detected by IRT) are being analysed, subject to appropriate instrumentation being available.
5. New IRT equipment needs to be designed to cater for newly developed techniques.
6. IRT sensors that measure the temperature of significant areas of the crop canopy (rather than single leaves) would be beneficial in applying the technique to other field vegetable.
7. Growers, given minimal instruction can also use Porometers (which measure conductance of water vapour through the stomata).
8. Alternative measures such as using sensors to determine stem and pod thickness may be useful to identify crop water stress in certain circumstances.

9. The new stress index performed as well as the 'Scheduler' (which produced most accurate data on fine days).
10. The precision of IRT stress indexes can be refined by using additional environmental variable but is likely to be confined to research rather than offer a practical solution.
11. Theta probes (a capacitive device used to determine soil moisture levels) were convenient to use and offer a viable alternative to the neutron probe for the continuous monitoring of soil moisture.
12. The EnviroSCAN system had useful software but was not evaluated during the trial.
13. Time Domain Reflectrometry instruments provided good results and are alternatives to the neutron probe.

PC 142 and 151
Tomatoes: Comparison of Methods of determining Irrigation Frequency with Measured Crop Water Use

Relevance of work: Improvements in irrigation control can help to maximise productivity by improving crop growth, yield and fruit quality whilst minimising on nutrient and water inputs.

Situation: A previous HDC Project (PC119) suggested that water uptake of rockwool grown tomato crops is significantly greater than those grown in NFT. Data from the Silsoe Research Institute suggests otherwise. The purpose of the work was to determine whether there is a consistent difference in water uptake by crops grown in NFT and in a rockwool substrate.

The main objectives of the two projects (PC 142 and PC151) were: 1. To measure and record water use of a long season tomato crop grown in recirculated NFT system and in a rockwool run-to-waste system; 2. To compare rates of water usage using simulated models based on (1) solar radiation (2) solar radiation and vapour pressure deficit (3) the Silsoe Research Institute (SRI) model based on the Penman-Monteith equation; 3. To identify differences in water use for tomatoes grown in NFT and rockwool run-to waste systems

The tomato variety *Espero* was planted in modern Venlo glasshouses at HRI Stockbridge House with four double rows of NFT alternating with four double rows of rockwool. Crop water was measured between August and October.

Findings:

1. There were no differences in water usage between rockwool and NFT systems of any significance, which supports the work conducted by Hamer 1998.
2. It was recognised that there were large potentials for inaccurately measuring water flow and drainage volumes of rockwool run-to-waste systems.
3. The SOLAR model considerably overestimated crop water during periods of high radiation, which was greater in the mornings than in the afternoons. Insufficient water was supplied during dull periods and none at night, when there remained a requirement.
4. The Solar and Vapour Pressure Deficit models underestimated water use by 30% both for the morning and afternoon periods. The inaccuracy of the model was reduced to 10% at the end of the season and was the most accurate predictor of water requirements at night from September onwards.
5. Overall growth habits of both crops were similar but the rockwool grown crops were more vigorous until late into the season.
6. Water use in NFT crops was similar to rockwool grown crops.

PC 166
Protected Ornamentals: The efficiency of water use in different production systems

Relevance of Work: Growers in the UK need to produce a marketable crop of good quality to meet imposed specifications whilst also complying with legislation. Inputs such as heating, lighting, water, fertilisers etc. all produce a cost which has to be borne by the grower. Comparisons need to be provided between the costs and benefits of various irriagation systems to enable the grower to make cost-saving alterations, implement new systems and reduce water and nutrient costs of growing the crop.

This work is highly relevant in providing details of the losses due to irrigation for each of the different growing systems, together with the set up and running costs.

Situation: The trials were conducted in two stages as follows: Stage 1. An assessment made of the variation in efficiency between the production systems. Twenty production systems were used for the trials within seventeen nurseries in the UK. The objective of stage one was to establish the degree of variation of water loss between the different growing systems. Systems included: 'Ebb & Flow', overhead gantry, hand watering, capillary, drip/trickle; Overhead spraylines and trough track.

Stage 2. The quantity of water used and lost when growing a crop of Poinsettias (var. *Sonara*) was determined throughout the season, in respect of four selected production systems. The quantity of water taken up by the plants was calculated. The 'Air Filled Porosity' and particle size tests were conducted on different growing media and water samples were analysed for nutrient content.

Findings of stage one:

1. Capillary systems lost between 54 and 89% of water supplied.
2. Drip systems lost 11-47% of water supplied.
3. Trough track lost 87% of water supplied.
4. Overhead spraylines lost 55% of supplied water.
5. Hand-watering varied between 8-78% in terms of lost water.
6. The value of fertiliser wastage was estimated to be £450 for every 10,000 plants grown in one capillary system.
7. Growers need to be aware of which substrate is selected as a growth medium as a more 'open' medium promotes leaching.
8. The use of compost moisture measuring equipment may save up to 30% of water as it is applied in response to plant requirements, rather than in response to timing device.
9. Recirculating systems have higher initial investment costs but little water is 'lost' from the system.
10. To eliminated run-off, recirculated closed production systems have to be employed.
11. When starting from scratch, recirculating systems should be designed first and the glasshouse built around it.

12. Re-circulated water should be free of sodium, chloride and sulphates and have a low alkaline level.
13. Recycling systems can reduce water by 30% over standard capillary matting or overhead systems.
14. Compost may be enhanced with additives such as perlite, coir etc. to produce amore open but moisture retentive substrate.
15. Water sterilisation is necessary to reduce pathogens in recirculated systems.
16. The cost of implementing recycled systems can be off-set by up to 30% in labour costs in the production phase. Crops should be kept to maximum density prior to spacing to optimise usage of CO2, water and light.
17. Good equipment such as pots and substrate should be used.
18. Capillary matting can retain high levels of Nitrogen, which accumulates as leachate water evaporates. This may be a factor, which contributes to plant scorching as a result of the high conductivity levels of the residue.
19. Growers may benefit from new capillary matting which reduces water loss and distributes water well whilst being cheap to use.
20. The cost of the 'Ebb & Flow' System is estimated to be £33/m^2 but the volume of water and fertiliser applied is not critical as unused solution is recirculated to other plants.
21. In 'Ebb & Flow' run-to waste systems, potential losses of water and fertiliser are between 40-120 litres per plant per season.
22. Trickle drip systems into individual pots were very efficient with losses down to 20ml per plant at each irrigation, compared to 54 ml in the capillary system.
23. Trough track systems lost 1.5 litres of water for each plant at each irrigation, but could be made to be efficient if the water was recycled.
24. Spraylines were inefficient, losing 159 ml of water per plant.
25. Growers should check the quality of water prior to irrigating as it might already be high in Nitrogen before additional nutrient is also applied.
26. Growers should be aware that run off water contains as many, if not more, nutrients than the feed applied to the crop often exceeding 11.3 mg/l of N set by the EC Directive in many instances. This exposes the grower to the risk of litigation, should the run-off enter watercourses.

Findings of stage 2:

1. Highest water uptake was in the Ebb & Flow recirculating system, with10l taken up by each plant in the season.
2. There were no real losses for nurseries using the recirculation system.
3. Labour costs for handwatering were up to £4680 p.a., which should be, contrasted against the purchase costs of a machine.
4. Greatest savings in fetiliser costs are obtained by improving application efficiency.
5. Watering regimes should be matched to substrate types; those containing 20-30% of particles less than 2mm in size, with low Air Filled Porosity, need less water.
6. Mains water varies in content on a regional basis and may contain substances at levels which may cause growth restriction in plants or problems with precipitation. Details regarding the content of mains water should be frequently requested from the local water supply company.

Ebb & Flow Systems 1. Have a high initial implementation cost but require less labour and will produce pay-backs in the long term. 2. Ensure the tank is low before emptying. 3. Irrigation water applied to flood benches is absorbed within the first 5 minutes. Efficiency improves if small quantities are applied thereafter.

Capillary Systems. 1.Good quality matting is required on a level surface. 2. Matting should have polythene or other film underneath. 3. Matting can be overlayed with perforated polythene to increase the lifespan and reduce moss growth. 4. Water should be applied to matting evenly and on a 'little and often' basis.

Drip Systems. 1. This system is efficient in the larger pot sizes but not suitable for small pots, trays and packs. 2. Drippers need to be maintained regularly. 3. The dry environment help to avoid disease

Hand watering. 1. Inefficient and labour-intensive and highly variable. 2. Shut off valves should be used on the lance. 3. Polythene sheets should be placed between the base of the plant and the bench.

Spraylines. 1. Overhead sprinklers lost 55-79% of applied water. 2. This system is only 50p m^2 cheaper to install than the capillary system. 3. Inaccurate, wasteful and provides an excellent environment for the promotion of disease. 4. Attention should be paid to nozzle design. 5. Nozzles at row-ends should have an angle of 180^0. 6. Apply water during dull periods to avoid high evaporation.

Gantry. 1. More targeted, uniform application of water. 2. Shut off nozzles in sections without packs to be watered. 3. Apply water in dull periods.

Other Systems. Consider other systems such as the 'Bottom Up' from Australia, which can be fairly expensive compared to other capillary systems but saves on water.

FV 195
Carrots: The Control of Common Scab with Irrigation

Relevance of Work: Common scab is caused by the organism *Streptomyces scabies* that is found in most arable soils that are not too wet. Previous research at ADAS Gleadthorpe in the 1980s and more recently in Denmark suggested that the micro-organism could be influenced by irrigation. Experiments were designed to investigate the effect of irrigation and the timing of application and whether an improved irrigation strategy could be beneficial in controlling common scab in the carrot crop.

Situation: Following a wet season when the incidence of disease is low, irrigation schedules were proposed as follows:. Irrigate to maintain soil moisture deficit below 15mm until 8 weeks after emergence then maintain soil moisture deficit below 30mm between weeks 8 and 12 of the crop and continue to irrigate to maintain soil moisture deficit below 40mm until harvesting.

Findings: The schedule was intensive and subject to certain logistical problems such as the integration of the irrigation schedule with pest control applications, for which leaching must be minimised. Recommendations included applying 10mm of water whenever the soil moisture deficit reached 15mm during weeks 8-10 of growth, increasing the application to 25mm to maintain the soil moisture deficit below 40mm. Although excess irrigation may continue to reduce the incidence of scab it was recognised that other pests and diseases could potentially flourish under the regime.

DEFRA REPORT
Independent Water Audits for Container Grown Nursery Stock Producers
Tim Briercliffe, A Hewson, and W Brough: ADAS Horticulture for Horticulture and Potatoes Division MAFF

Relevance of work: Growers using mains water supplies face rising water costs whilst those abstracting water either from surface or ground sources will have to meet more stringent legislation in the future regarding abstraction licences. Growers are subject to increasing pressures in terms of protocols to be adhered to and responsibility with respect to the environment.

The audits aimed to provide growers of hardy nursery stock with an independent assessment of their existing water use strategy and provide details for further improvement. 44% of the audited nurseries had reservoirs but in excess of 50 % relied on mains water with a very high proportion of smaller nurseries (10000m^2) almost totally reliant on mains water.

Situation: Fifty nurseries across England were provided with a free (MAFF funded) water audit. Nurseries were visited and assessed by ADAS consultants throughout the summer. The results of the audit were presented to the growers concerned, together with practical recommendations to ensure legal compliance whilst aiming to reduce costs and enhance water efficiency. Most nurseries relied on mains water with a few using collected rainwater off glasshouse roofs. Abstracting groundwater or riverwater is cheaper than mains supply but the application process is becoming more rigorous. A final score between 9-12 marks out of 20 for the majority of growers highlighted the fact that there was room for significant improvement in water use efficiency as well as the opportunity to make financial savings.

Findings:

1. Many nurseries did not have access to space to expand their water storage capacity should they desire to recycle their water. Space could only be found at the expense of production areas.
2. Overhead sprinkler irrigation (which is often inefficient and may impact on plant quality) was commonplace.
3. Nurseries could make use of roof water and surface water (which must be treated to remove pathogens prior to use) and save run-off water from polytunnels.
4. Water used for irrigation should be sent to the laboratory for analysis periodically. Mains water can be high in bicarbonates and can leave limescale deposits on foliage when applied through overhead irrigation systems, as well as having an adverse effect particularly with ericaceous plants. Using an acid dosing unit can offset the effects.
5. Nutrient levels in run-off water should be analysed periodically in order to prevent having to pay potential fines.
6. Understanding of environmental and other related legislation requires improvement by the majority of growers.
7. Disinfection of recycled water can be employed using such processes as chlorination, slow sand filtration, ultra violet light, ozone applied to the water, combined ozone and ultraviolet and reedbeds.
8. Nurseries with above ground tanks store should store at least 40% of their maximum daily demand of water.
9. Nurseries with reservoirs should store an amount equivalent to one week of maximum demand and aim to have the reservoir lined with a high quality butyl or clay lining.
10. Outdoor storage tanks should be covered, preferably with a solid cover; to prevent pests, diseases, weeds and algal blooms.
11. Most nurseries make decisions of when to water based on grower experience, with individuals having their own assumptions on the needs of different plants. Less than 2% of the audited nurseries used tensiometers to check moisture levels in substrates, mainly due to the lack of training on the use of such equipment.
12. Grouping plants according to their water requirement e.g. siting similar varieties and sizes together as they have similar water demands could enhance efficiency in water usage.
13. Problems with high weed levels, moss and liverwort development and associated diseases were found to be present as a consequence of uneven, poor watering regimes.
14. Half of the growers used growing media that contained a 'wetter' or polymer, which aimed to reduce water loss.
15. Growers could benefit by checking the air filled porosity and particle size of the growing media used. Those with a higher AFP rating may require a more frequent watering regime.
16. The maintenance of records regarding the labour input in terms of staff time devoted to irrigation could highlight areas where improvements could be made.

NOTES