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2003 SCIENTIFIC MEETING

"CEs AND THE BELOW-GROUND ENVIRONMENT"

Volume 14

Contents

L.D. Incoll (editor)

UK CONTROLLED ENVIRONMENT USERS' GROUP

2003 SCIENTIFIC MEETING

"CEs AND THE BELOW-GROUND ENVIRONMENT: ALL IN THE DARK"

The scientific part of the annual meeting consisted of five invited contributions. Summaries of these, supplied by the speakers, follow.

SUMMARIES OF PAPERS

W.J. Davies (Department of Biological Sciences, Lancaster Environment Centre, University of Lancaster, Lancaster LA1 4YQ, UK. E-mail: w.j.davies@lancaster.ac.uk) **The below-ground environment in the field and controlled environments**

[Manuscript not supplied]

N.C. Bragg (Bulrush Horticulture Ltd, Newferry Road, Bellaghy, Magherafelt BT45 8ND, Co. Derry, Northern Ireland. E-mail: qd59@dial.pipex.com) **Growing media for container use- a review**

Introduction

The development of substrate in the UK for the use in containerised plant production can easily be traced through the period from the late Victorian to the present day. Most of the development has been driven by the locality of the grower to the market place and hence the density of the materials that could be selected and used.

Between the end of the Victorian period and the 1930s substrates were dominated by 'home-brewed' mixes. These were very much concoctions of the individual rather than researched mixes. As will be seen below, it was really only with the development of John Innes (JI) mixes in the 1930s that uniformity in substrates for containerised plants was introduced and developed. Various materials have been dominant in the development of such substrates and are reviewed below.

Peat

Peat is the generic terms applied to a wide range of accumulated organic debris, which has undergone partial anaerobic decomposition. In most peats it is possible to find clear signs of their botanical origins (Godwin, 1981).

Peats were traditionally used in the UK and Ireland (as in many other countries even today) as animal bedding material and today the use of such materials for bedding is still widely practised in the Baltic States. Peat has also always been cut/harvested and dried locally and used as domestic fuel. During the 20th century the use of peats as a fuel source to generate electricity increased markedly world-wide in those countries with large reserves, e.g. Sweden, Finland, Russia and Eire.

Country	Horticultural use / 10^6 m^3
Ireland	0.5
Germany	4.3
Sweden	1
Finland	1.5
UK	3
The Netherlands	3.4

The use of peat in the garden can be easily traced back into the 19th century when the material was used both as a walling material in the form of the dried block cut material, or as a soil conditioner, particularly where it was desired to acidify the soil for ericaceous specimens, which became very popular in Victorian times (Johnson, 1890). However at the time of writing his dictionary much of the beneficial properties of sphagnum-type mosses were recognised as materials for preserving and packaging plant tubers and the use of 'heathland' soils was regarded as more of the type of 'bog soil' for conditioning.

John Innes mixes

In the UK the first key reference to the use of sphagnum moss in seed and potting composts was in the work of Lawrence and Newell (1939). This was work undertaken at the original John Innes Horticultural Institute at Roehampton, London. The aim was to develop a pasteurised media for the germination and growth of all seedlings obtained from the breeding program. Prior to this weak seedlings were often overcome by soil-borne fungal pathogens and hence the full results of the breeding lines could not be assessed. This work led to the now internationally famous John Innes (JI) mixes, which had different strengths of fertilisers for the varying stages of growth of the plants. In the original mixes the 'peat' was, or could be, substituted for by leaf mould and then the base fertiliser would be adjusted to meet the specific additions.

Once the JI mixes were established in the UK, they quickly were adopted by many of the ornamental growers, as the reduction in soil-borne pathogenic problems was immense. The on-nursery use of such mixes was quite acceptable whilst the customer came to the nursery to fetch the products but as the trend increased with regard to nurseries only wholesaling plants to retailers, there then was increasingly the need to reduce the fresh density of the substrate.

UC mixes

In the United States in the 1950s University extension units such as that at University of California, Davis, were developing mixes based purely on 'peat' and 'sharp' sand in differing proportions. This led to the production of the manual 'The UC system for producing healthy container-grown plants' (Baker, 1957). Whilst the UC work led to a whole series of mixes from 100% peat to 100% sand, two mixes appeared to be universally adopted by many growers. These were the 50/50 peat /sand mix for propagation and the 75/25 mix for all potting on mixes, fertilisers being adjusted to specific requirements.

Other US mixes

It is often forgotten that at a similar time, other university extension units were adopting slightly different approaches to the new substrate mixes (Bunt, 1988). Cornell University for example developed a whole series of 'Peat-lite' mixes based on the use of sphagnum peats and Perlite ™ and/or vermiculite. Penn State University extension service developed all-peat mixes at a similar time.

UK Developments

In the UK the then Glasshouse Crops Research Institute (GCRI) where many of the original John Innes staff had transferred, adopted the use of and development of the UC mixes for UK growers. Similarly this occurred in Holland. The use of such mixes for many container operations was therefore to be prevalent for the next 20 years.

At a similar period in the 1960s 'soil blocks' for the growth of both vegetable crops and also cut flowers was gradually replaced by the use of very black and degraded sedge peats, which were also found to be able to be 'blocked'. The advantage was again a weight consideration and also the fact that availability and consistency of the 'black' peats was far easier than obtaining consistent soils/loams. Prior to this period the cutting and propagules had been raised in beds or troughs, which had then necessitated lifting them with the associated root disturbance and damage prior to planting out. The advantage of the 'newer' systems was the ease of handling and the lack of root disturbance and hence the lesser chance for soil-borne diseases to enter the damaged tissue (Large, 1972).

By the 1970s the demands in the UK and elsewhere for high-grade sphagnum peats had increased beyond the ability of the traditional harvesting and screening operations and new mechanical harvesting techniques had been introduced (Robinson and Lamb, 1975). For many purposes of container growth, the quality of the peats in terms of the particle size and the associated Air-Filled Porosity became an issue (Bragg and Chambers, 1988). The result was development work on the use of barks for inclusion in mixes to improve the physical characteristics of mixes (Scott, 1983).

From the late 1980s the screening and presentation of peat-based products to the professional grower market improved and many of the supply companies offered either refined graded peats with or without the addition of supplements such as bark, clay, Perlite ™ and/or vermiculite. The mixes were targeted at specific crops and growing conditions e.g. there might be an ebb/flood bench mix for *Poinsettia* which was a specific grading, such as 2-15 mm screening, with a specific wetting agent to ensure that the particles easily re-wet after considerable drying back on the benches.

Environmental auditing and the future of container mixes

More recently within Europe there have been strong conservation efforts to have wetland habitats conserved as part of the biodiversity action plan for the planet. Various 'peatland' conservation campaigns have been started by environmental groups and this has led to audits of the wide scale use of 'peats' both in the hobby, landscaping and grower markets, (Pryce 1992: Bragg, 1991).

In the UK there are now well stated peat extraction conditions which the UK Growing Media Association (GMA) members all adhere to within working areas. However the opening up of the Baltic States and Russia to European markets has led to large areas of bog land becoming available for peat extraction and hence peats from younger sphagnum deposits are now being blended with the declining stocks of UK materials.

Additionally to satisfy the retailers (e.g. M&S, B&Q) concerns about the use of wholly peat mixes, gradual replacement in mixes by alternatives including composted products is occurring, albeit at a rate which is slower than that desired by environmental action groups (Anon, 2003). The present UK Government has a set of aspirational targets for peat replacement in container mixes. The horticultural industry has agreed to work towards the targets, 40% replacement by 2005, currently estimated at 37% of all substrates, and 90% by 2010. Whilst it is seen as possible to meet the first target, the latter is seen as both unrealistic and damaging to the industry and is currently being further discussed and revised by Government departments in discussions with retailers, users and suppliers.

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I.C. Dodd (Department of Biological Sciences, Lancaster Environment Centre, University of Lancaster, Lancaster LA1 4YQ, UK. E-mail: I.Dodd@lancaster.ac.uk) **Root-zone temperature: fundamental effects and control in CE systems**

In keeping with the theme of this meeting, "CEs and the below-ground environment: all in the dark", root-zone temperature (RZT) is seldom reported in scientific experiments, even though an immersion thermometer costs less than £20 sterling at the local hardware store. Air temperature is almost universally reported, and since RZT is well coupled to air temperature, RZT will be within ± 5°C of air temperature in most environments. Although RZT is usually dependent on air temperature, physiological experiments show profound effects of varying RZT at the one air temperature (Fig. 1).

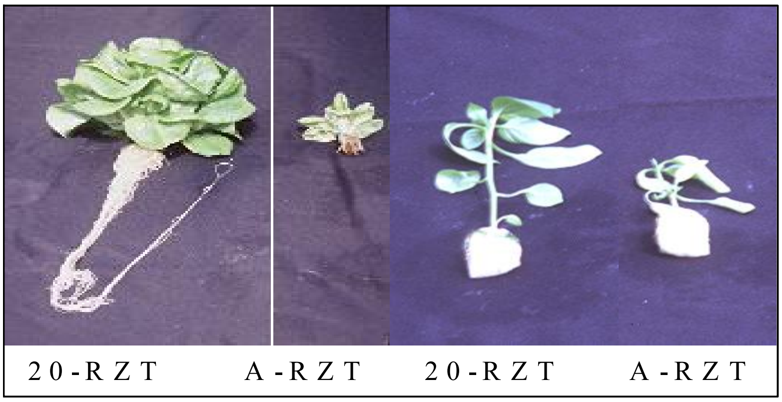

Fig. 1: Lettuce and pepper plants grown at a constant 20°C RZT or ambient (A) RZT (30-40°C) in Singapore. Plants are supported in aeroponic troughs by polyurethane cubes. Reproduced, with permission, from Dodd *et al.* (2001).

This paper considers:
- Mechanisms of plant response to RZT.
- How RZT can be influenced in controlled (and uncontrolled) environments.
- Opportunities offered by RZT control.
- Whether the differences in RZT commonly observed in UK greenhouse environments influence plant growth and yield.

The relationship between almost any plant physiological variable e.g. biomass, leaf area, and RZT shows a local maximum (Fig. 2). RZT can influence nutrient uptake, water uptake and also root phytohormone production, and all of these can influence plant carbon gain. Growth of plants at multiple RZTs can define an optimum temperature for production, and allow correlations to be established between physiological mechanisms and growth. Measuring the coincidence of physiological variables in reciprocal RZT transfer experiments can also help examine the mechanisms of growth inhibition of plants grown at sub-or supra-optimal RZT.

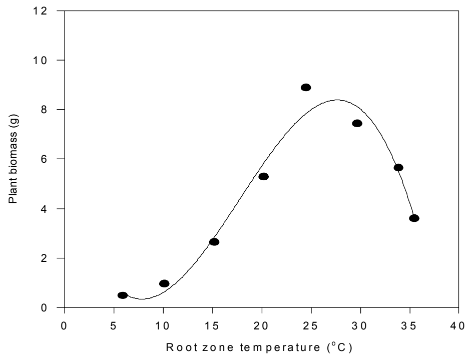

Fig. 2: Dependence of prairie grass biomass on RZT. Re-drawn from De Lucia *et al.* (1992).

Although plants in most commercial production systems receive a luxury nutrient supply, high (or low) RZT can decrease tissue nutrient concentrations due to impaired root nutrient uptake. Shoot nutrient concentrations can be compared against critical nutrient levels to determine whether any particular nutrient is likely to limit growth. In plants grown at high RZT, non-stomatal inhibition of photosynthesis was correlated with decreased leaf nitrogen concentrations (He *et al.*, 2001).

In short-term (several days) measurements root hydraulic conductivity (Lp_r) increases linearly with root temperature (Markhart *et al.*, 1979). However, high RZT for long periods of time (several weeks) can greatly decrease Lp_r (Dodd *et al.,* 2000) and leaf water potential (De Lucia *et al.*, 1992). Reciprocal temperature transfer experiments showed that stomatal inhibition of lettuce photosynthesis was correlated with decreased leaf relative water content (He *et al.*, 2001).

High RZT (>35°C) increased cucumber leaf ABA concentrations 5-7 fold compared to plants maintained at a RZT of 25°C (Du and Tachibana, 1995), which is likely to induce stomatal closure. High RZT also decreased shoot cytokinin concentrations (Tachibana *et al.,* 1997), which may directly limit leaf expansion. Generally, the effects of RZT on plant hormone status and its consequences have been poorly studied.

These physiological considerations are important in soil-less horticultural production under controlled environments, especially in the tropics, where production of temperate crops is frequently limited by high RZT. Root-zone cooling of aeroponically grown plants has allowed commercial production of temperate vegetables (such as the lettuce in Fig. 1) previously thought impossible in Singapore (see http://www.aerogreen.com.sg). In contrast, soil warming has been used to stimulate yield of temperate vegetables grown in spring and autumn at high latitudes (Gosselin and Trudel, 1985); and to aid establishment of tropical fruit tree seedlings (e.g. papaya) in the sub-tropics (Pomper *et al.*, 2003).

RZT of soil-grown plants depends on a number of factors such as pot size and colour, soil type and moisture content, and whether pots are mulched. Measurements made in naturally and artificially lit compost-grown plants in the Lancaster Environment Centre showed that RZT varied within 3°C of air temperature, and that commonly available commercial composts varied by 3°C in their RZT. Are such differences likely to significantly influence plant growth? Various coloured plastic mulches were used to impose a range of RZTs on field grown tomatoes in the USA, and an optimal RZT could be defined to within 1°C (Diaz-Perez and Batal, 2002). Also cucumber yield has been stimulated by soil warming which raised the seasonally averaged RZT by only 2°C (Gosselin and Trudel, 1985). Under certain circumstances, it seems likely that manipulating RZT will influence UK greenhouse production.

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R. Harrison-Murray (Horticulture Research International, East Malling, West Malling, ME19 6BJ, UK) **Water: from basic principles to instrumentation**

A generous oversupply of water is easily arranged and, as long as drainage arrangements prevent waterlogging of any part of the root zone, will generally ensure that growth is not limited by water availability. More problematic is to achieve a controlled and reproducible restriction on water supply to the plant. The need for experimental techniques to impose controlled water deficit is of increasing importance as water for irrigation becomes a more scarce resource and climate change makes rainfall less reliable. Appropriate environmental control techniques are required whether the research focus is physiological, biochemical, molecular or breeding.

Control can be aimed at one of three different components of the soil-plant-atmosphere continuum. We can either seek to control the soil water status, the plant water status, or the rate of water supply (i.e. control at the interface between environment and plant).

Controlling soil water status

The most frequently used measures of soil water status are:

Gravimetric water content, θ_g
Volumetric water content, θ_v
Water potential, ψ
Matric potential, ψ_m
Suction or tension, $(= - \psi_m)$

$$\psi = \psi_m + \psi_s$$

(with additional terms for gravitational potential, ψ_g, and air pressure potential, ψ_a, when relevant).

Only ψ is a direct measure of the availability of water to the plant but, since ψ_s is usually small and/or constant, ψ_m measured with a tensiometer is often an acceptable surrogate. Beyond the range of a tensiometer, direct measurement is only possible by thermocouple psychrometry, which is technically quite difficult and very sensitive to errors from temperature gradients. Indirect methods depend on equilibration of the matric potential in a block of a standard porous material with that of the surrounding soil. The water content of the block is then used to estimate the soil matric potential. For example in simple gypsum blocks the water content is estimated from the electrical conductivity between two embedded electrodes. In the

Equitensiometer (Delta-T Devices, Cambridge) it is the dielectric constant. The time required for the blocks to come to equilibrium limits the speed of response.

For any particular soil, or other porous medium, ψ_m can be related to water content by the water release curve. The water release curve therefore allows ψ_m to be estimated from water content or *vice versa*. One problem is that some soils show considerable hysteresis (i.e. the curve for rewetting is not the same as for drying). However, the method has the attraction of technical simplicity for plants growing in pots or other containers. For example, the soil can be adjusted to a desired water content (equivalent to the target ψ_m) at the start of the experiment and the plant in its pot can then be watered to a constant weight to maintain this condition. However, it is important to recognise that if the desired water content is substantially below field capacity then its hydraulic conductivity will be low and the applied water will not distribute itself uniformly. The treatment is therefore less clearly defined and reproducible than at first it seems.

There are also methods that aim to control ψ or ψ_m directly. For values up to about 5 kPa, plants may be placed at a specific height above a water table in a sand bed or similar arrangement. This can be effective where transpiration is close to zero but otherwise low unsaturated hydraulic conductance of the sand results in ψ around the roots dropping well below the intended value. A recent version of this approach emerged from the development of systems for growing plants under microgravity in space (Steinberg and Henninger, 1997). However, even with multiple porous tubes buried in the growing medium of young soybean seedlings, ψ declined sharply with distance from the nearest tube unless the pressure in the tubes was kept above -2 kPa. This approach is more likely to be satisfactory when transpiration rates are extremely low, such as in leafless hardwood cuttings taken in winter from dormant deciduous plants (Harrison-Murray and Howard, 1992).

A widely used approach is to adjust ψ by reducing ψ_s instead of ψ_m since this can be achieved simply by adding solutes. However, even with large molecules such as the high molecular mass polyethylene glycols (PEG), uptake of the solute can occur, leading to osmotic adjustment, toxicity or other effects not related to water relations. Furthermore, plants are unlikely to respond to ψ_s in exactly the same way as ψ_m. To overcome this drawback, the osmoticum is sometimes used indirectly, to influence ψ_m in soil that is separated from the osmoticum by a semipermeable membrane (e.g. Rossi *et al.* 1993). The problems of this approach include the need to use add fungicides to protect the membrane from microbiological attack, incomplete exclusion of the solute and toxic contaminants. Also, except for roots in contact with the membrane, these systems inevitably suffer from reduction of ψ_m around the roots as low water content of the growing medium leads to low hydraulic conductance.

Controlling plant water status

If the intention is to impose a known water deficit on the shoot, then it follows from what has been said about hydraulic conductance that the dynamics of the soil-plant-atmosphere continuum are crucial. They are also difficult to control. In many cases, researchers have simply withheld water and monitored the changing soil and plant water status until a threshold is reached at which the plant is rewatered. This is crude and difficult to reproduce but effective.

Continuous restriction of water supply can result in a more stable and reproducible treatment. For example, in the 'Snow and Tingey' system, the supply of water is regulated by altering the hydraulic conductance of the porous column supplying water to the growing medium. Using a CE cabinet to create a reproducible transpiration demand, this system can achieve a relatively stable reduction in leaf water potential compared with well-watered controls (Wookey *et al.*, 1991).

Leafy cuttings, during the period between excision and the appearance of the first roots, represent a special case. The capacity for water uptake through the cut base is so restricted, especially once significant blockage of xylem has occurred, that plant water status is controlled mainly by transpiration demand. As a consequence, a controlled environment system, which created gradients of wetting and irradiance perpendicular to each other, proved valuable in understanding the physiology of responses of cuttings to their environment (Harrison-Murray, 1998).

Exploiting the pneumatic component of soil water potential

Air pressure is normally at atmospheric pressure throughout the soil-plant-atmosphere continuum. If *part of the system* is in a pressure chamber then ψ increases in that part compared to the parts outside the chamber.

$$\psi = \psi_m + \psi_s + \psi_a$$

where ψ_a is the pneumatic potential

By pressurising the root system, the water supply to the shoots can be increased so that shoot water potential can be maintained at a high value even when the soil has been allowed to dry out substantially (i.e. to low ψ_m). This approach has provided important evidence in favour of the involvement of root-sourced chemical signals in the responses of stomata and leaf growth to drought (e.g. Gollan *et al.,* 1986).

Regulating supply relative to evapotranspiration

If there is no limitation on water supply, then the rate of crop water use depends on a combination of environmental variables (wind speed, irradiance, etc.) that is often referred to a 'evaporative demand' or more precisely as 'potential evapotranspiration' (ET_p). Under natural conditions, demand often exceeds supply so that plants have to be able to reduce their water loss to survive. Irrigation can remove that restraint but there are increasing pressures to restrict irrigation. Therefore, application of a fixed percentage of ET_p is increasingly attractive as a means of imposing *controlled* water deficit, especially on plants growing in pots and protected from rainfall. Combined with a consistent transpiration demand in a CE cabinet, it could also be used to impose a *reproducible* plant water deficit. Since water is never withheld completely, the water deficit develops gradually, in a way that simulates natural drought. This approach has been used successfully for a DEFRA-sponsored Horticulture LINK project on irrigation of woody ornamentals (Harrison-Murray, 2003).

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J.H. Macduff (Institute of Grassland and Environmental Research, Aberystwyth, SY23 3EB, UK). **Plant nutrient control in controlled environments.**

This paper outlines the principles of plant nutrient control in CE, the different categories of control, alternative solution culture–based systems and design issues relevant to the development of controlled plant nutrition facilities.

Reasons for nutrient control

Research in plant nutrition covers a wide range of topics ranging from optimising crop yield and nutrient use efficiency, assessing nutrient effects on human health, developing phytoremediatory technologies to investigating the functional roles of nutrients in ecosystems. Whether they are essential to plants, merely beneficial or phytotoxic, nutrients are primarily acquired by plant root systems from the aqueous phase of the soil, mainly via diffusion and mass flow, although transfer mediated by rhizosphere micro-organisms is significant for certain nutrients. Nutrient availability in the soil solution is determined by many factors including dissolution from the solid phase and release from exchange complexes, mineralisation and environmental factors including temperature and soil water status which also affect rates of nutrient uptake by the plants and subsequent translocation to the shoots.

Control of the nutrient status in the root zone has been extensively reviewed (e.g. Hewitt, 1966; Ingestad, 1982; Asher & Edwards, 1983; Wild *et al*., 1987; Jarvis, 1989) and is commonly undertaken where simplification of soil and environmental heterogeneity is required for studying specific components, variables and metabolic pathways determining nutrient acquisition by plants. It is also necessary where the objective is to define nutrient supply to the root *per* se or to measure nutrient uptake without destructively harvesting the plant. Spatial and temporal uniformity of nutritional and environmental conditions within the root zone is generally easier to achieve in solution culture than soil or solid media systems. Solution culture offers advantages in terms of minimising the width of the nutrient concentration gradient at the root surface, ease of access to root tissue, measurement of nutrient uptake and maintenance of sterile culture. However it does not simulate field conditions.

There are two main conceptual approaches to the control of plant nutrient status in the root zone. The first aims to define the composition of the solution surrounding the roots and the second to define the rate of addition/supply of nutrients to the root zone. The first approach enables kinetic analysis of nutrient uptake, based on the axiom that 'rate is a function of state', by defining and in some cases controlling nutrient concentrations at or near to the sites of transport into the root system (e.g. Wild *et al*., 1987). In the second approach nutrient 'doses' or 'addition rates' are controlled, and may be programmed relative to desired plant growth rates, as in the 'relative addition rate approach (Ingestad, 1982), enabling plant attributes to be studied under defined sub-optimal nutrient supply rates.

Experimental approaches

Experimental systems for culturing plants hydroponically in controlled nutrient solutions can be classified as (1) static/stirred, (2) flowing to waste and (3) flowing re-circulated. Static/stirred culture systems range from beakers to large tanks and in all cases they require vigorous aeration. Where the initial nutrient composition is known plant uptake can be determined by depletion over a given time interval. These systems are suitable for 'dosing/addition rate' approaches to nutrient control. However, regular replenishment of nutrients will be required if the aim is to maintain near constant concentrations in the root zone. In 'Flowing to waste systems' nutrient solution of known composition passes (either pumped or by gravity) through the chamber containing the root system and then to waste; hence it is more amenable to kinetic than dosing studies of nutrient uptake. Flow rate may be controlled and plant uptake may be measured by depletion. A significant drawback may arise from the costs of supplying water and nutrients and of their disposal in the waste solution. However, the risk of disease is relatively low compared with re-circulating systems and these systems are widely used in commercial hydroponics. In 'flowing re-circulated systems' the spent nutrient solution is re-circulated after flowing past the root system. Although the initial nutrient composition may be known this will be depleted by uptake over time unless further nutrients are added. Hence some form of nutrient or conductivity monitoring is usually included to which nutrient re-supply is linked. Where constant nutrient concentrations are maintained by regular nutrient additions, plant uptake may be calculated from the amounts of nutrients added (e.g. Wild *et al*., 1987). Depending on their sophistication, re-circulating systems are equally suitable for kinetic and dosing studies of nutrient uptake.

Design Issues

Scientific objectives, scale (including provision for replication), location, materials, desired level of nutrient and environmental control, system flexibility, operational efficiency and cost must all be taken into consideration in the design of a new controlled plant nutrition system. Most of these facets are heavily circumscribed by the scientific objectives which may entail nutritional control at the single root, split root system, single plant, plant canopy or mini-ecosystem levels, over time scales ranging from minutes to months. With respect to the type of nutrient control system, decisions must be made between (1) flow to waste/re-circulating systems (2) compositional/dosing approaches and (3) manual/automatic control of nutrient monitoring and dosing/additions. The options for automatic monitoring/analysis of nutrient solutions range from the measurement of electrical conductivity of nutrient solutions at one extreme, to independent measurement of one or more major macro-elements, and of all macro and micro nutrients at the other extreme. Monitoring and control of pH is also advisable particularly where pH dependence of nutrient uptake is an issue or where analytical systems (i.e. nitrate specific ion selective electrodes) are known to be pH sensitive.

Control of root zone/solution temperature and adequate aeration are prerequisites because of the sensitivity of nutrient uptake to below ground environmental factors. Control of microbial contamination (e.g. by UV sterilisation) in the root zone may also be desirable. With respect to the aerial environment, light, temperature humidity and gas composition all affect nutrient uptake.

Nutrient analysis and addition

Selection of appropriate nutrient analytical systems is vital where nutrient monitoring is to be performed on-line (i.e. automatically) and linked to nutrient replenishment or dosing. Besides the choice between manual and on-line analysis the following factors need to be considered: (1) desired levels of precision, accuracy, drift, interference and calibration protocols, (2) duration of the analytical cycle, (3) adoption of common or separate analytical pathways for replicate plant culture units, (4) operational time scale (minutes to months), (5) linkage to nutrient replenishment/dosing, (6) capital and recurrent costs, (7) staffing and (8) reliability/maintenance issues.

Whether manual or automatic the frequency of nutrient additions (ranging from continuous to daily) usually depends on the deviations tolerated from the 'set–point' concentrations where the aim is to maintain constant compositions. Automatic addition systems were commonly based on electro-mechanical control equipment linked to auto-titrators in the past, but personal computer and industrial process controller based systems have largely superseded these enabling programmable nutrient addition (e.g. relative to desired plant growth rate). The choice of salts for re-supplying specific nutrients and their solubility in stock/pumping solutions must be factored into the design of addition systems, particularly where nutrients are to be controlled independently. For example, if NO_3^- and K^+ are to be independently monitored and re-supplied, then $Ca\ (NO_3)_2$ and K_2SO_4 are appropriate salts for supplying these ions, but not KNO_3. Nutrients which are not specifically monitored (i.e. commonly all micro-nutrients and some macro-nutrients) may be re-supplied at fixed rates, or where a more sophisticated 'demand-based' regime is desired, in fixed ratios to the re-supply of a monitored nutrient (i.e. N or K). Where a specific nutrient is monitored and re-supplied to maintain constant concentrations in re-circulating nutrient solutions, net uptake of the nutrient may be calculated from the quantities of nutrients delivered to the system to maintain steady state.

Operational efficiency and flexibility

Measures for promoting efficiency and minimising 'down-time' include (1) simplification of control systems, (2) attention to detail in system design and operation, including hygiene, (3) high thresholds for 'fatal breakdown', (4) preventative maintenance and 'in house' repair, (5) permanent staffing and (6) facilities for batch production of experimental plants. The ability to meet changing scientific priorities and objectives is enhanced by paying attention to (1) choice of materials (i.e. using chemically inert plastics), (2) modularity and portability of plant culture and nutrient control units, (3) ease of modifications/upgrading and (4) simplicity of design.

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