13

GROWING PLANTS IN
SOILLESS CULTURE:
OPERATIONAL CONCLUSIONS

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13.1 Evolution of Soilless Production Systems
13.2 Development and Change of Soilless Production Systems
13.3 Management of Soilless Production Systems
References

13.1 EVOLUTION OF SOILLESS PRODUCTION SYSTEMS

The previous chapters present various specific facets of soilless plant production, representing the state of the art and include some perspectives on the direction in which the field is moving. In some cases, gaps in knowledge were pointed out and required future research was suggested. Generally the chapters focus on particular facets of a system whose full complexity was beyond the scope of each specific chapter. In some cases lack of appreciation of the complexity imposed by the interaction of all the factors may lead to problems and failures for practitioners. The aim of this final chapter is to integrate various concepts from throughout the book and from other sources, to provide practitioners with practical operational tools, allowing them to optimize crop production. The focus is to develop a better understanding of the intricate processes taking place within the system along the root zone–plant–atmosphere continuum, as affected by the interactions among the growing substrate, the liquid and gaseous phases.
Chapter 13 Growing Plants in Soilless Culture

held in its matrix, and its nutritional status. Aerial conditions, although exerting major effects on plant performance, are beyond the scope of this chapter.

One concept that was discussed in Chap. 8 was the historical perspective on nutritional limitations to plant growth. The work by Mitcherlish suggested that plant productivity is limited by the nutritional factor that is limiting. This concept has been verified and is appropriate if all factors except one are non-limiting. As such this concept is also true in a broader sense when considering all factors that impact soilless crop production. However, when multiple factors are limiting, we must anticipate interacting effects which are more complex than simply suggesting causality of suboptimal production to the most-limiting factor. This is particularly important in practice because it is extremely rare that all production factors are simultaneously optimized.

A further consideration regarding this issue is the fact that the root zone is a dynamic microenvironment where many of the factors are in continual change. Many factors can change second-to-second or minute-by-minute, while some change over the course of days or weeks. Management of such dynamic systems requires constant attention, and the advent of computer technology coupled with sensor technology provides a situation where we can anticipate significant changes in the field as control technology improves.

13.1.1 MAJOR LIMITATION OF SOILLESS- VS. SOIL-GROWING PLANTS

In the first chapter, we described the historical reasons for the advent of soilless cultivation and its further expansion to the level it has reached to date, and we briefly suggested reason why its share in global food and plant production will continue to grow in the foreseeable future. It is particularly important to note the speed with which soilless production has changed over the past 50 years. Anyone considering soilless crop production should be aware that the field as a whole is dynamic, with horticultural practices changing continuously. One consequence of this is that in various chapters, methods and technologies are presented as being in widespread use or commonly accepted. Within this rapidly changing field, such methods may be quickly replaced by alternate methods as scientific understanding and economic feasibility change. Perhaps the most dramatic change is currently occurring in relation to management of recirculation systems for various soilless production systems.

Various reasons persist for the continued growth of soilless production as part of agriculture. Some of these reasons can be inferred from the chapters dealing with the physical and chemical characteristics of substrates, emphasizing their superiority over soil cultivation, ease of control of water, oxygen and nutrient availabilities and the resulting improved crop performance. Another advantage is the relative freedom from soil-borne pathogens and improved possibility of disinfestation of the medium among growing cycles. However, growing crops out-of-soil also imposes some limitations which test the grower’s skill to avoid losing the potential benefits offered by the advantages. The extent of these limitations and how to practically deal with them is discussed in this chapter.
13.1.2 THE EFFECTS OF RESTRICTED ROOT VOLUME ON CROP PERFORMANCE AND MANAGEMENT

One of the biggest contrasts between soil-less and soil-based production is the spatial confinement of the roots into a specific, well-defined root zone. The smaller the root zone, the more intensive the production system needs to be to manage this volume.

Sonneveld (1981) reported that the volume of medium available to a tomato (*Lycopersicon esculentum*, L.) plant grown in a soil bed in a greenhouse is approximately 200 L, while the corresponding volumes for production in substrates are typically an order of magnitude smaller. He calculated that the volume of water (and hence nutrients) in the root zone at any given moment to a tomato plant would be an order of magnitude greater in soil than in soilless production. Thus in soilless production involving such substrates as peat and stone wool, irrigation needs to be carried out much more frequently than in soil-based production if the nutrient and water storage aspects were the same. In fact, with Nutrient Film Technique (NFT) systems, where the water volume may well be an order of magnitude smaller than substrate-based soilless production, application of water needs to be continuous so as to avoid nutrient deficiencies and water stress.

Numerous experiments and simulation studies demonstrated that a continuous growth process of the root system is essential to ensure efficient water and nutrients uptake from soil (Williams and Yanai, 1996; Nye and Tinker, 1977; Sadanal et al., 2005). Root growth is especially important in the case of low mobility nutrients such as P, Mn, Zn and more so when their concentrations in the root-zone solution are low since in this case ion diffusion towards the depletion zone is minimal. Plants growing in soil typically exhibit fine root growth so as to gain access to water and nutrients from less-explored regions of the root zone. In fact, active, vital growth by such plants depends on continued formation of new roots (Williams and Yanai, 1996; Nye and Tinker, 1977; Sadanal et al., 2005). In frequently flushed soilless root zones, the near-absence of clear depletion zones somewhat diminishes the need by the plant for such active ‘foraging’. However, since the process of root growth is, by nature, a persistent one (Bengough et al., 2006), root systems of container-grown plants are usually very dense. Optimization of soilless production systems means that irrigation and fertilization must be carried out with precise timing and location, and that such systems suffer from minimal tolerance for error.

Under normal horticultural conditions of sufficient supply of water and nutrients, substrate volume has little or no effect on root/shoot ratio (NeSmith et al., 1992). Therefore, to satisfy the canopy needs for water and nutrients, root density must increase with decreasing substrate volume (Keever et al., 1985; Boland et al., 2000). The increased root density involves greater oxygen and nutrient consumption per unit volume of root zone, resulting in intense root-to-root competition for oxygen and nutrients, leading to more rapid declines in the concentration of dissolve oxygen (DO) and available nutrients. At the same time, the reduced DO levels can negatively affect root function, increase their susceptibility to diseases and eventually cause their death. Lack of sufficient DO may also inhibit ammonium oxidation, leading to pH decrease, accumulation of toxic levels of ammonium in the liquid phase and even to toxic...
levels of ammonia in the gaseous phase of the root zone. This phenomenon may be aggravated by the consumption of oxygen by micro-organisms that decompose organic matter. Even in inorganic media, the decomposition of dead roots and root exudates contributes to oxygen consumption. The continued mineralization of organic matter may also be accompanied by compaction of the medium, resulting in decreased oxygen diffusion rate (ODR), leading to slow flow rate of gaseous oxygen into the medium gaseous phase. Frequent solution replenishment with DO-saturated water can minimize the severity of these problems. Another method to prevent low and decreasing ODR is through the choice of medium’s components.

13.1.3 THE EFFECTS OF RESTRICTED ROOT VOLUME ON PLANT NUTRITION

Two effects of restricted root volume on plant nutrition are that: (1) it can physically restrict root growth, so that volume, length and surface area of the roots are reduced and (2) limited reservoir size within the root zone and small buffer capacity of inert media may lead to restricted nutrient supply. It is not possible to raise the nutrient supply without limit by elevating their concentration, as this involves a potentially detrimental increase in osmotic potential, which interferes with water uptake (Sonneveld, 1981). A partial solution to the limited availability of water and nutrients is through their frequent supply through fertigation. But even constant supply (as is practical in closed systems) cannot overcome all the constraints posed by small root volume, as discussed in Chap. 9, and by Bar-Tal et al. (1990, 1995), Bar-Tal and Pressman (1996) and Rieger and Marra (1994). It is therefore important to select the appropriate container size for each specific crop, based on its growth rate and final desired size and growing conditions.

Bar-Tal et al. (1995) investigated the effect of root size on the uptake of nutrients and water by tomato plants, to investigate the effects of root restriction in relation to nutrients supply on transpiration and nutrients uptake. Restriction of the root system resulted in a decrease in root volume compared with unrestricted roots. Severe and mild root restriction nearly stopped the increase in root volume 70 and 130 days after transplanting, respectively. The growth curves of the unrestricted and restricted root systems in both nutrient solutions had a smooth ‘S’ shape, which is described well by the Gompertz growth model (Eq. [1]) (Fig. 13.1).

\[ V_t = V_f e^{-k e^{-bt}} \]  

where \( V_t \) is the root volume at time \( t \) (cm\(^3\)), \( V_f \) is the maximal root volume (cm\(^3\)) and \( b \) and \( k \) are dimensionless parameters. The estimated parameters \( k \) and \( V_f \) were significantly affected by the solution nitrate concentration (Bar-Tal et al., 1996). The rate coefficient value (\( k \)) of the intact root, 0.0228 d\(^{-1}\), was in good agreement with published values of 0.035–0.039 d\(^{-1}\) (Bar-Tal et al., 1994). Root restriction significantly reduced \( V_f \), \( k \) (the rate coefficient, d\(^{-1}\)) and \( b \) (dimensionless). The resulting \( V_f \) of the restricted root was in good agreement with the bag volume.

Root restriction induced an increase in \( F_N \), the nitrogen uptake rate per root unit volume. This indicated an adaptation of the smaller root system to the shoot demand.
13.1 Evolution of Soilless Production Systems

Thus, the smaller root system was more efficient in uptake per unit root weight, in agreement with published data (Jungk, 1974; Jungk and Barber, 1975; Edwards and Barber, 1976; de Willigen and van Noordwijk, 1987; Bar-Yosef et al., 1988). Eshel et al. (2001) found that the efficiency of absorption of K and P by the root increased following removal of part of the roots; however, this was not true for other nutrients. Consequently, the mass or the surface area of the root may affect nutrient uptake of plants grown in substrates flushed frequently with nutrient solution (Fig. 13.2). Root

FIGURE 13.1 Root growth as affected by root restriction. Each point represents a mean of two N−NO₃ solution concentrations (1.0 and 9.0 mmol L⁻¹), except for the mild restriction that was studied only in 9.0 mmol L⁻¹ solution. The vertical bars represent ±LSD₀.₀₅. The curves were calculated with the Gompertz growth model. The values of the parameters were fitted with the NLIN procedure of SAS (based on Bar-Tal et al., 1995).

FIGURE 13.2 Nitrogen uptake rate per root unit volume (F₉) as a function of time and root volume. Each point represents a mean of two N−NO₃ solution concentrations (1.0 and 9.0 mmol L⁻¹), except for the mild volume that was studied only in 9.0 mmol L⁻¹ solution. The vertical bars represent ±LSD₀.₀₅ (based on Bar-Tal et al., 1995).
restriction increased $F_N$; values of 8.0, 13.5 and 25.6 μmol ml$^{-1}$ d$^{-1}$ were obtained at 133 days after transplanting (DAT) for the control and for mild and severe root restriction, respectively.

Root restriction significantly reduced the potassium uptake rate per plant but it had no effect on $F_K$, the potassium uptake rate per root unit volume. The values of the parameter $F_{\text{max}}$ (Michalis–Menten uptake model, Eq. (4) in Chap. 8) (24.9 and 8.8 μmol g$^{-1}$ d$^{-1}$, for the young and old plants, respectively) fell within the range of published data for four different species (Wild et al., 1974; Bar-Yosef et al., 1992).

In the study of Bar-Tal and Pressman (1996) in the aero-hydroponics system, root restriction decreased Ca uptake rate per plant, but there was a trend of increasing $F_{\text{Ca}}$ when root restriction was combined with low K concentration, which is consistent with the ability of the restricted-root plants to maintain Ca concentrations in plant organs similar to those in non-restricted plants. Choi et al. (1997) reported that root restriction by small containers (190 ml) strongly suppressed transport of $^{45}$Ca ions to new leaves and apices relative to the plants in the control containers (20L). Water transport, expressed on leaf area basis, was marginally reduced by root restriction, an indication that calcium transport was more severely limited than water transport. Karni et al. (2001) also obtained a decline in Ca uptake by pepper root due to removal of three quarters of the root system, while the effect on water uptake and status in the plant was marginal.

In conclusion from the above, root restriction reduces both nutrient uptake per plant and nutrient uptake per unit root when the buffer capacity and the rate of replenishment of the growing medium are the limiting factors. When the growing system enables maintaining a constant concentration of each nutrient at the root surface (as is the case in NFT, DFT, aeroponics and with very frequent irrigation pulses), the ability of the restricted root system to meet the plant requirements is not the primary limiting factor. The minimal root size to meet plant nutritional requirement for nitrogen and other mobile nutrients is much smaller than that required for water supply, aeration and other physiological demands. However, the supply of phosphate and calcium may be the limiting factors as a result of restricted root system.

### 13.1.4 ROOT CONFINEMENT BY RIGID BARRIERS AND OTHER CONTRIBUTING FACTORS

As previously mentioned, regeneration of new roots is essential for normal plant development (Stevenson, 1967). Root growth is directed by environmental cues, including touch (thigmotropism) and gravity. Gravity sensing occurs mainly in the columella cells of the root cap. Downward root growth is a natural response to graviti- and hydrotropism, typical to all active roots. A recent study by Massa and Gilroy (2003) suggests that normal root tip growth requires the integration of both gravity and touch stimuli. However, strong mechanical impedance such as the one that results from compact soil layer affects root growth direction (see Chap. 2) and causes clear anatomical and ultrastructural changes in the root apex (Wilson and Robards, 1979). These changes
13.1 Evolution of Soilless Production Systems

Reflect several mechanisms that help root elongation in hard soils and even penetration through compacted layers. Root cap is generally smaller and thus cannot confer the same degree of protection to the root meristem as caps grown without mechanical impedance. Other changes include increased sloughing of border cells; exudation from the root cap that decreases friction and marked increase in root diameter. All these changes help to relieve stress in front of the root apex and to decrease buckling. Whole root systems may also grow preferentially in loose versus dense soil (Bengough et al., 2006). Concomitantly, mechanical impedance considerably reduces the root elongation rate and final root cell size and affects root distribution (Croser et al., 1999). Some of those energy-consuming changes may occur when roots of container-grown plant reach a rigid wall. As these roots can only change course, staying within the confined root zone, root density increases within the root zone. Eventually, root confinement within a limited volume results with reduced root growth (Hameed et al., 1987), similar to what can usually be found in compacted soils (Hoffmann and Jungk, 1995). This reduced root growth can explain the results that were described earlier, connecting root-zone volume with plant performance even under ample supply of water and nutrients.

In container-grown plant, gravitropism and hydrotropism frequently results with the accumulation of root mat on the bottom (Martinez et al., 1993). This part of the root system frequently accounts for a major part of the total root biomass and may be exposed to oxygen deficiency both due to the respiration of an extensive mass of dense roots and as a result of the existence of a perched water layer on the bottom of the container.

The main practical steps that could be applied at the grower level to ease DO deficiency are to optimize container depth, according to the crop size and growth duration and to frequently refresh the DO level using irrigation. Another useful approach is the use of hydroponics or aeroponics, where there is no mechanical impedance, which is practically avoided. However, even in these conditions, increased root density leads, eventually, to growth inhibition (Peterson et al., 1991a; Bar-Tal and Pressman, 1996).

Another important limitation that sometimes occurs in soilless growing systems is the accumulation of regions of high EC within the medium, where irrigation water reaches only through diffusion and in the top layer experiencing a substantial amount of evaporation. This phenomenon limits the useful volume available to the plants. Salt pockets can be formed when drippers are too far from each other and hydraulic conductivity is low. Plants irrigated exclusively with subirrigation will generally experience high EC near the medium’s surface as a result of evaporation-derived salt accumulation (Kent and Reed, 1996). It is important to plan both the irrigation system(s) and the water discharge rate, so that a frequent downward piston-like water movement will prevent this type of salt accumulation (Schwarz et al., 1995). Thus with subirrigation it may be necessary to use a second irrigation system or to plan on hand-watering occasionally so as to leach such excess salts from the upper layer, and to then provide adequate irrigation solution to push these salts completely out of the root zone. The subject of selecting desirable root-zone volume is discussed in Sect. 13.3.
13.1.5 ROOT EXPOSURE TO AMBIENT CONDITIONS

As mentioned in Chap. 2, roots grown in containers are more exposed to extreme ambient temperatures than soil-grown roots, where temperature fluctuations in deep soil layers are minimal. In addition, the relative effect of ambient low vapour pressure deficit (VPD) on water evaporation from the root zone is high, due to the typically high surface to depth ratio, as compared to this of soil-grown plants. The evaporation issue has limited horticultural significance, as normally container-grown plants are well-irrigated, the medium surface is shaded by the plant canopy and the coarseness of the medium results in low capillary movement. It may be important in outdoor nurseries and in newly planted media, where the plant cover is minimal and the effect of advective heat from the surroundings is significant (Seginer, 1994).

Moderate root zone warming (20–25°C) may have a beneficial effect in many cases and is routinely practiced in many propagation nurseries during the rooting stage of stem and leaf cuttings. Elevated temperatures, on the other hand, lead to a significant increase in root respiration rates. Since this is coupled with a sharp decrease in DO levels in the root-zone solution, the result may be detrimental. The combination of high root zone temperature with ammonium as the source of N has a negative effect on the root system and whole plant growth and development (Kafkafi, 1990). Anaerobic processes may occur within the root tissue, significantly lowering its water and nutrient uptake and its growth rate. High temperature may, in some cases, negatively affect the activity of nitrifying bacteria which may, in turn, lead to toxic ammonium levels. Even under Northern Europe condition temperatures within the stone wool slabs in greenhouse vegetable production can reach levels of 30–35°C, greatly affect their incidence of, and susceptibility to, pathogens (van der Gaag and Wever, 2005). Martin et al. (1991) showed a marked effect of the size of the container on the temperature in the middle of the root zone. Summer-time temperatures were 5–6°C lower in 57-L than in 10-L containers.

Practical methods that are used to mitigate high temperatures include adequate irrigation control possibility with occasional pulse irrigation, the use of mulch, a careful choice of the container colour and dimensions.

13.1.6 ROOT ZONE UNIFORMITY

One thing that should not be overlooked when contrasting in-ground field production with soilless production is the matter of uniformity. With in-ground field production, there is frequently variability in soil characteristics within the field. Many times farmers ignore this and simply treat the entire field as having the same soil, but the plants will generally grow and yield differently in the various parts of the field.

With soilless production this is generally not the case. With a properly assembled substrate, mixed using standard best-management practices, each plant experiences essentially the same growing medium as all other plants in the crop as long as drainage and supply of irrigation water is uniform. As such, in soilless production a uniform
management strategy for a particular crop is ideal, while in field production, better productivity would be achieved by customizing irrigation and fertilization for each plant depending on the variations in soil within the field. With innovations in precision agriculture, it can be expected that such optimization will be feasible, yet currently this type of optimization is not yet feasible in field production. With soilless production, on the other hand, such customized optimization is possible although it is questionable how economically feasible it is. As yet, in both soil-based and soilless production, the general strategy is to control irrigation and fertilization for all plants in a crop so as to avoid stress.

13.2 DEVELOPMENT AND CHANGE OF SOILLESS PRODUCTION SYSTEMS

13.2.1 HOW NEW SUBSTRATES AND GROWING SYSTEMS Emerge (AND DISAPPEAR)

One aspect that has had a major influence on the subject of this book is the notion by non-experts that one can grow plants in virtually any granular or porous material. This notion is fuelled by the fact that plants will grow in a variety of substrates, as long as one waters and fertilizes them reasonably well. This notion has led to a nearly routine exploration of various waste materials as growing media. This has resulted in testing of many materials, some of which have been adapted as growing media. Shredded rubber tires, for instance, have been tested. Unfortunately, this material has not yielded a product suitable for widespread use as substrate in the soilless production. On the other hand, when testing coconut husk debris in a few tropical areas of the world, this waste material was found to be horticulturally useful so that coconut coir is now a well-established component of some growing media and even as a substrate by itself. In the same way, in California, the use of redwood sawdust, a waste product from the large lumber industry in the state, was discovered to create a product that behaved quite different from other sawdust materials because its slow decomposition results in a root zone that is very slow to collapse. This makes it an excellent substrate for growing outdoor nursery products that require many months to produce. Thus happenstance and trial-and-error have played a major role in the development of soilless growing media components. And while this approach has also led to somewhat random testing of various combinations of materials in various forms, it is today possible to engineer systems (consisting of various media components, containers, control systems and management practices) that optimize the particular application. Horticulturalists already understand some of these principles. For instance, it is well known that if one transplants a plant from a small pot in which it is growing well to a larger, deeper pot, then specific adjustments have to be made, either in the composition of the growing medium or by installing drainage elements, to continue to get the plant to grow. What the horticulturalist is doing is optimizing for one or two variables based on experience, even if not based on scientific knowledge of the underlying principles.
Several attempts have been made over the years to model and predict the characteristics of growing media consisting of well-defined components. Factors such as particle-size distribution, bulk and particle density were taken into account. Water release curves and rate of shrinkage were successfully modelled (Brown and Pokorny, 1975; Pokorny and Henny, 1984; Pokorny et al., 1986; Bures et al., 1993a,b). Such models enable the prediction of several important properties of new combinations of ingredients.

13.2.2 ENVIRONMENTAL RESTRICTIONS AND THE USE OF CLOSED SYSTEMS

As discussed in Chap. 9, intensive greenhouse production involves several environmental risks. Environmental protection agencies in a growing number of countries require growers to capture and reuse the effluent from soilless production systems so as to minimize these risk. Simultaneously, effluent recycling leads to significant water and fertilizer savings. Moreover, the complicated issue of both temporal and spatially uniform supply of water and nutrients is not relevant if the system is closed so that it enables frequent or even constant flushing.

In view of the dwindling global reservoirs of water and energy (oil) and as a result of environmental regulation, it appears mandatory that most above-ground systems (that allow collection of discharged drainage water) will need to be modified to capture any effluent. As described in Chap. 9, many of the problems involved with such operation have been addressed and many such systems are already in operation. There are a variety of issues that still require solutions, but the primary hurdle for many commercial growers is economic. Even this may be true only on the basis of the individual grower, and not on a national or global basis. In order to promote fast adoption of this practice it is imperative that the true cost of water treatment be known and integrated into their final cost to the costumer. In addition, the future cost for cleaning soil and water resources should be considered. Thus adoption of a closed recirculation system involves careful study of the economic factors and a complete analysis over the long run as to handling of water when it reaches a level of salinity due to non-nutritive ions that makes it impossible to use for in commercial soilless production. As such 100 per cent recirculation is as yet still not possible in areas where the supply water contains ions that the plant cannot use. It should be noted, however, that semi-closed systems normally reduce the amount of effluent by ~90 per cent over a system where no recirculation is practised. It is important that agencies regulating this issue be aware that growers generally must have the flexibility to discard water where some deleterious ion (e.g. Sodium) has accumulated to a level that renders the water toxic to plants. While some argue that water can be cleaned up through water treatment, the result of such treatment is always a brine solution that must be discarded. At present there is no easy solution to this problem, and regulators that attempt to enforce 100 per cent recirculation are imposing a condition that will ultimately put the grower out of business.
13.2.3 SOILLESS ‘ORGANIC’ PRODUCTION SYSTEMS

While ‘organic agriculture’ has very specific meaning to growers and regulators, the general public is rarely knowledgeable about the details that define this area of agriculture and what is involved in certification. The strict rules of most of the Organic Agriculture certification bodies state that in order to be considered as an organically certified crop, it should be grown in soil; yet the attractiveness of this type of agriculture to the general public is based on the desirability of having foods that were not subjected to chemical fertilizers or pesticides. As such it is entirely feasible to accomplish this with soilless production. This notion recently became clear to scientists (Dresboll, 2004) and may, eventually, affect the rules. This is especially true for areas of the world where fertile soil is limited, while food production lags behind the needs.

There is a growing trend of growing food crops without the use of chemical fertilizers and pesticides in soilless culture. This trend, especially developed in Australia and New Zealand, is driven by the public demand for pesticide-free produce and for decreasing the use of oil-derived products (such as chemical fertilizers). Thus, while the requirement of growing crops in soil makes certification of soilless production systems as ‘organic’ unlikely, the forces that drive the demand for organic products may well force changes to the definition or force the emergence of alternatives that are equally attractive to the general public. Such changes have already been noted with the advent of ‘biorational’ pesticides which have changed the way integrated pest management (IPM) is currently practised in conventional field agriculture.

Discussion of the crop protection aspect of these soilless production systems is beyond the scope of the present book but it should be noted that with the advent of biological control methodologies, the certification issue may ultimately be solvable. The subject of plant nutrition as part of an ‘organic’ soilless production system will be briefly described below.

In general, such soilless ‘Organic Systems’ can be based on either substrate or liquid culture. In principle, the aim of fertigation in both types is to provide completely soluble nutrients, but to have them derived from organic sources, rather than synthetic soluble salts. A variety of commercial products exist in the market, mainly based on water extraction of fermented fish, meat, compost (compost tea) or manure residues to make such liquid fertilizers available. The two main drawbacks of these materials are their extremely high cost per a unit of specific nutrient (especially nitrogen) and the fact that the ratio among the various nutrients is usually different from what plants require. Several attempts have been made to formulate an accurate combination of off-the-shelf organic fertilizers, with various degrees of success (Atkins and Nichols, 2002, 2004; Liedl et al., 2004a,b; Jarecki et al., 2005). Significant work in this area is continuing as evidenced by the frequent appearance of new products by various companies.

Development of substrates that can supply nutrients for extended periods of time is driven by the fact that some compost types can provide much of the needed nutrients for extended periods of time (Dresboll, 2004), while simultaneously suppressing many root pathogens (Raviv, 2005). More nutrients can be supplied once the compost’s reservoir
has been exhausted in the form of guano, feather meal or other concentrated organic fertilizers (Raviv et al., 2005). This is schematically depicted in Fig. 13.3. The difficult part of this nutritional program is, on the one hand, how to minimize nutrient leaching from the medium when the plants are young and their consumption is low (zone 2 in Fig. 13.3) while, on the other hand, accelerating the compost mineralization once the plants attained full size (zone 3), so as to maximize compost-derived nutrient uptake by the plant (zone 1). Nutrient leaching can be minimized by effluent recirculation. The decomposition process itself renders the substrate somewhat unstable (see Chap. 11) so that long-term (more than a year) crop production in such systems may not be feasible. Most concentrated organic fertilizers are very expensive, in comparison with chemical fertilizers. For example, guano-derived nitrogen cost $5 per kilogram, more than five times its cost when derived from chemical fertilizers. Compost, on the other hand, is a relatively cheap source of nutrients. However, most of the nitrogen exists within the compost in a recalcitrant form that resists mineralization. The challenge for future researchers is to find ways to accelerate nitrogen mineralization from compost, if possible, in a controlled manner, at times dictated by the grower. The work of Dresboll (2004) elegantly set the stage for this needed effort.

One approach to developing an organic soilless nutrient source is to use a separate reactor in which compost is aerobically brewed to form liquid extract called compost tea. Such systems are already being tested in commercial production, and considerable research is needed to develop methods for sustained uniform delivery of particular nutrients to the plants.

To date, soilless ‘organic’ production has not reached a significant share of the market, but there is considerable development in this area to attempt to solve the hurdles to making such systems economically feasible. In addition to the economical and professional obstacles mentioned above, the current regulations are the main stumbling block, effectively requiring the development of an entirely new system.
13.2 Development and Change of Soilless Production Systems

13.2.4 TAILORING PLANTS FOR SOILLESS CULTURE: A CHALLENGE FOR PLANT BREEDERS

In addition to its importance to the understanding of basic root growth processes, the study of the response of roots to various types of physical stress (such as oxygen deficiency and mechanical impedance) has clear horticultural relevance. Although some root traits such as enhanced ability to capture phosphate (Gahoonia et al., 2001; Bates and Lynch, 2002) and the nature of root biomass, length and architecture (McPhee, 2005; Fita et al., 2006) are starting to receive increased interest, in general the intentional selection of particular root traits has been largely neglected. The above examples were studied with field crops such as barley (*Hordeum vulgare* L.), melon (*Cucumis melo* L.) and pea (*Pisum sativum* L.). When more such responses are elucidated, especially under conditions of soilless culture, that is ample water supply and nutrition, better manipulation of root growth responses to the specific characteristics of these growing conditions will be attainable via appropriate plant breeding or genetic engineering technologies. Some examples for root characteristics sought for soilless culture conditions are increased branching and fine roots formation, so as to continuously provide the plant with actively absorbing root surfaces. In view of the increased importance of closed systems, better sodium and chloride exclusion efficiency is a trait of paramount importance. Root systems that can tolerate higher external concentrations of these ions allow the grower to set a higher threshold before effluent discharge becomes mandatory. As explained in Chap. 9, any such small increase leads to a very significant decrease in the required leaching fraction. Similarly, root systems that can tolerate higher osmotic potential in the rhizosphere can lead to the above-mentioned result, while greatly improving water and nutrient use efficiencies.

Another facet of soilless plant production that could be addressed by breeders is the plant’s response to root zone temperatures. These are typically higher than the temperatures to which plant roots have adapted through evolution. Accompanying higher temperatures is a lower level of dissolved oxygen, so that selecting for plants with low susceptibility to hypoxia could be particularly advantageous in soilless production.

13.2.5 CHOOSING THE APPROPRIATE MEDIUM, ROOT VOLUME AND GROWING SYSTEM

Choosing the appropriate medium for a specific combination of crop and environmental conditions is the subject of numerous scientific papers and several books (Bunt, 1988; Handreck and Black, 2002; Savvas and Passam, 2002). Kipp et al. (2000) provided detailed tabulated information about substrate’s characteristics. Most of the papers dealing with comparisons among substrates or growing systems do not involve explicit economic consideration. Moreover, the results of most of these studies are often affected by arbitrary choices, made by the researchers. For example, if various substrates are irrigated with identical irrigation regimes (‘control’, usually is based on time-controlled irrigation), in spite of their differing physical characteristics, an unfair advantage is given to some of them, while others may be irrigated in a frequency that does not match their properties. Generally
researchers do not make the extra effort to compare substrates using irrigation frequencies based on physical parameters such as water tension, unsaturated hydraulic conductivity, water content or real-time replenishment of transpired water based on weighing lysimeter (some of the few who did were Raviv et al., 2001; Morel and Michel, 2004; Wallach and Raviv, 2005). The use of measurable plant parameters that reflect plant water status is even less common. Irrigation control using methods such as leaf water potential (with pressure chamber); stomatal resistance for water (with diffusion porometer); canopy temperature (with thermocouples or infrared thermometers); flow of water in the stem (with the heat pulse method); and changes in stem diameter (with dendrometer) can be found in research studies but only rarely in horticultural studies. Caron et al. (1998) recommended the use of plant-based measures such as xylem water potential to assess water availability and to control irrigation. However, these methods have not gained popularity in commercial settings. As a general rule it can be stated that reports aimed at comparing media while using uniform irrigation treatments have only limited usefulness. In addition to avoiding biased conclusions, comparative research conducted while fitting the irrigation regime to the medium’s physical characteristics also provides relevant information about optimal irrigation management.

Another factor that may mask media effect is their potential contribution (positive or negative) to nutrient availability. As described in Chap. 6, different media can adsorb or release nutrients. If this is not taken into account while comparing growing media, false conclusions may be reached. Unlike the case of irrigation regime, overcoming this heterogeneity among substrates is rather difficult since real-time monitoring of all nutrients is not practical even under experimental conditions.

Unfortunately we cannot suggest clear answers about the optimal choice of media for specific crop/conditions combinations except to caution the readers about the nature of this kind of pitfall. Researchers should not justify such experimental design based on the fact that such flawed method is frequently found in the scientific literature. Historically, when a large number of growers adopt a specific medium (e.g. stone wool in Northern Europe) it is accompanied by a wide assortment of peripheral elements (structural, knowledge and customized instrumentation) that constitute a substantial economic investment. This results in an inhibition to replace one medium by a newer one, even if proved as somewhat superior. Adoption of a new substrate is more common when a substrate must be replaced occasionally, when a new industry emerges, or when the use of a certain substrate is not free of problems. An example of the former is the replacement by many growers of peat moss by coir due to the fact that peat moss shrinks over the years requiring to be either top-dressed or replaced (Scagel, 2003, and see Chap. 11).

Economics and availability play a major role in substrate component selection. Tuff, for example, is readily available in Israel and in the Canary Islands (under the name Picon) and its cost in these countries and their neighbours is competitive with other substrates; therefore it found a wide use in these countries (Plaut et al., 1973; Perez-Melian et al., 1977; Silber et al., 1994). Similarly, bark compost is widely used in temperate countries, where forestry is a major industry and a large source of wood waste (Pokorny, 1982). In some cases, the need to find solutions for used media lead to
13.2 Development and Change of Soilless Production Systems

the development of yet another new media by their recycling. An example is the incorporation of recycled stone wool as a component in peat-based media (Riga et al., 2003).

As mentioned above, root volume rarely affects shoot/root ratio (NeSmith et al., 1992). It can be assumed that shoot growth is regulated by root growth (Hoffmann and Jungk, 1995; Eshel et al., 2001) while, in an interactive manner, root growth is regulated by the shoot through carbohydrate supply. Modern fertigation techniques enabled growers to save costly greenhouse space and to reduce the expense of substrates by growing plants in small root volumes. High growth rate and high shoot/root ratio are common under these conditions. There is a limit, however, to the shoot/root ratio, as at a certain point the physiological ability of the root to take up water and nutrients to meet the demands of the shoot becomes a limiting factor. In well-controlled experiments, root restriction has been shown to limit plant growth in various species, as manifested in reductions of such growth parameters as leaf area, leaf number, plant height and biomass production (Cooper, 1972; Richards and Rowe, 1977; Carmi and Heuer, 1981; Carmi et al., 1983; Carmi and van Staden, 1983; Ruff et al., 1987; Robbins and Pharr, 1988; Peterson and Krizek, 1992; Choi et al., 1997; van Iersel, 1997; Karni et al., 2000; Haver and Schuch, 2001; Xu et al., 2001; Dominguez-Lerena et al., 2006). In many cases, the initial volume in which transplants are grown affects their performance after transplanting (Bar-Tal et al., 1990; di Benedetto and Klasman, 2004; Dominguez-Lerena et al., 2006). The volume in which the root can expand may affect plant growth either through plant nutrition and transpiration (Brouwer and de Wit, 1968; Hameed et al., 1987; Bar-Tal et al., 1990; Choi et al., 1997) or via root and shoot physiology (Aung, 1974; Jackson, 1993; Haver and Schuch, 2001). In fact, in some cases, the effects of root restriction are not implemented through nutrient deficiency (Carmi and Heuer, 1981; Robbins and Pharr, 1988; Izaguirre-Mayoral and de Mallorca, 1999) or water stress (Krizek et al., 1985; Ruff et al., 1987; Izaguirre-Mayoral and de Mallorca, 1999). In such cases it has been suggested that root restriction stress induces a reduction in the supply of growth substances from roots to shoots and an imbalance in root and shoot hormones (Carmi and Heuer, 1981; Peterson et al., 1991a,b; van Iersel, 1997; Hurley and Rowarth, 1999; Haver and Schuch, 2001). Peterson et al. (1991a,b) showed that root respiration was reduced by root confinement, and concluded that the decline in root respiration capacity represents a decline in root metabolism. Haver and Schuch (2001) found that severe root restriction caused apical dominance that was associated with low ethylene production by the root. Moreover, they showed that exposure of roots to ethylene overcame the apical dominance induced by root restriction. The transfer of growth substances from roots to shoots, hormonal balance and root metabolism are out of the scope of this chapter and of the main subject of this book and will not be discussed further. However, when the crop in question is a finished plant of well-balanced and compact dimensions, a relatively large root volume is advisable.

It has been shown that the depth of the growing container has a more significant effect than the volume on successful plant development (Dominguez-Lerena et al., 2006). Generally the deeper the medium depth, the larger is the ratio of air to water spaces in it. In growing media of all depths, there will be a saturated zone after drainage at the bottom due to the formation of perched water table. In shallow media,
Chapter 13 Growing Plants in Soilless Culture

This saturated zone constitutes a larger percentage of the total root zone volume, thus affecting air/water relations, possibly leading to water logging problems. However, this is not always true. For example, when the development of a fibrous root system of tree transplants is required for subsequent optimal development after transplanting, shallow and wide containers are considered preferable (Milbocker, 1991).

The minimal desirable root-zone volume is usually determined by the grower before starting the crop. Even in cases where one or more transplanting stages are planned, it is essential to plan them in advance, to ensure the crop’s success. Factors that affect final required root-zone volume include the type of crop, its growing duration and season, nature of the chosen substrate, economical consideration such as the cost of various containers, substrate and greenhouse area ('rent'). Logistical considerations, such as transportation costs, may also affect the decision in cases where the potted plant itself is the final product. Some typical examples are listed in Table 13.1.

One common practical consideration for growers that dictates the root-zone volume is the interval between irrigation events. While it would be ideal to tailor the

### Table 13.1 Typical Examples of Required Size of Root Volumes for Various Crops

<table>
<thead>
<tr>
<th>Crop type</th>
<th>Growing duration</th>
<th>Special considerations</th>
<th>Standard volume/plant</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedding plants and vegetable transplants</td>
<td>&lt;60 days</td>
<td>Densely grown</td>
<td>&lt;125 cm³</td>
<td>Kemble et al., 1994; di Benedetto and Klasman, 2004</td>
</tr>
<tr>
<td>Lettuce and other leafy vegetables</td>
<td>&lt;60 days from transplanting</td>
<td></td>
<td>&lt;0.51</td>
<td>Gysi and Allmen, 1997</td>
</tr>
<tr>
<td>Small-size pot plants</td>
<td>3–6 months</td>
<td>Transportation required</td>
<td>0.5–2.01</td>
<td></td>
</tr>
<tr>
<td>Medium-size pot plants</td>
<td>6–9 months</td>
<td>Transportation required</td>
<td>1–41</td>
<td></td>
</tr>
<tr>
<td>Large-size pot plants</td>
<td>1–2 years</td>
<td>Transportation required</td>
<td>10–20 l</td>
<td></td>
</tr>
<tr>
<td>Short-season vegetables and herbs</td>
<td>2–6 months</td>
<td></td>
<td>2–51</td>
<td>Baas et al., 2001</td>
</tr>
<tr>
<td>Long season cut flowers (gerbera, carnations)</td>
<td>9–12 months</td>
<td></td>
<td>3–61</td>
<td>Garibaldi et al., 2004</td>
</tr>
<tr>
<td>Long season vegetables (tomato, pepper)</td>
<td>9–12 months</td>
<td></td>
<td>~101</td>
<td>Tuzel et al., 2001</td>
</tr>
<tr>
<td>Long season vegetables (tomato, pepper)</td>
<td>9–12 months</td>
<td></td>
<td>1–21</td>
<td>Peterson et al., 1991a</td>
</tr>
<tr>
<td>Perennial cut flowers (rose)</td>
<td>3–5 years</td>
<td>Transportation required</td>
<td>5–101</td>
<td>Raviv et al., 1999; Raviv et al., 2001</td>
</tr>
<tr>
<td>Tree saplings</td>
<td>one year</td>
<td>Transportation required</td>
<td>~51</td>
<td>Salifu et al., 2006</td>
</tr>
</tbody>
</table>
irrigation schedule to the needs of the plants, many growers set the irrigation schedule for convenience or to take advantage of available capacity for irrigation. In such circumstances, the root-zone volume should be matched to this interval to assure that the plant does not run out of water.

13.3 MANAGEMENT OF SOILLESS PRODUCTION SYSTEMS

13.3.1 INTERRELATIONSHIPS AMONG VARIOUS OPERATIONAL PARAMETERS

One thing that should be clear from this book is that the large number of variables that interact to form the production system make it nearly impossible for humans to consider (much less to optimize) all these factors simultaneously. As such there is still a lot of room in the marketplace for growing media formulation that are specifically suited for particular applications. Much of what is available today is really a raw material that still requires substantial engineering by the end-user to create an ideal growing situation for plants.

It is important to note that growing media of today are not simply haphazard combinations of a few convenient media components; rather they are elements of engineered horticultural systems tested by marketing forces and adapted by horticulturalists to particular purposes.

All media provide some plant anchorage, while nutrients are often provided by added fertilization. Water and air are provided in the pore spaces of the media. The principal factors affecting air and water status in the growing media are: (1) the media components and ratios; (2) media depth; (3) media handling; and (4) watering practices.

Each of the generally used media components is unique in their properties pertaining to their air/water relations. For example, peat has a comparatively higher content of unavailable water at a given matric tension compared to vermiculite. This variability in the availability of water in different types of media components means no two components are exactly alike in terms of providing water to plants. Similar variability does exist among various media components with regards to wettability (i.e. the ability of dry media to rapidly absorb water when moistened) or drainage characteristics. Airhart et al. (1978) reported that an air dry peat–vermiculite substrate required 5 days to reach 70–78 per cent of moisture saturation while milled pine bark required 48 days to achieve 58–78 per cent saturation. Thus, the kind and ratio of the components in the media mixes have important bearings on the hydrophysical environment in the root zone, which in turn largely determines the performance of the plants grown thereon. In general, moisture retention characteristics of media mixes is a compromise of its individual component corresponding characteristics. However, even when the same components are blended in identical ratios, physical properties may vary due to difference in particle size (Bilderback et al., 2005). Pokorny and Henny (1984) reported that substrates with the same components and ratio were not identical in their physical properties, even though they were assumed to be the same. Differences in physical properties in their study were attributed to the shrinkage and particle-size differences of
the components blended. Variation in identical components occurs if dry components are blended compared to blending moist components. Dry components when mixed tend to fit together tightly and increase bulk density of the substrate compared to when moist components are blended; consequently, air-filled porosity is reduced.

In handling growing media, proper care is necessary to avoid compaction; air space can be drastically reduced by compaction. The moisture content of the media prior to filling containers or bags may also be important. For example, adding water to soilless media mixes filling plug trays causes the media to swell and helps create more aeration. Moistening the media before filling larger containers does not have much benefit.

Apart from the air/water relations of the media mixes imparted by the individual and interactive effects of their components, watering practices have a tremendous influence on their air/water relations. This is due to the fact that both water and air compete for the same pore spaces in the media, where they are nearly mutually exclusive.

### 13.3.2 DYNAMIC NATURE OF THE SOILLESS ROOT ZONE

Soilless production has been in transition ever since it was conceived (see Chap. 1). Initially this type of production was carried out by mimicking traditional methods based on production in soil. The wide array of soils on the planet has led farmers to adapt methods so as to deal with the many physical and chemical properties that abound. The production methods in highly porous soils were assumed to be an excellent initial step for managing production in soilless growing media. However, as more and more artificial components were tested and drawn into use, the physical and chemical properties of growing media became more and more different from soils so that the methods required to be commercially successful changed dramatically. Yet even now, most practitioners view the key elements of soilless production to be driven by water in the limited root zone and avoidance of stress related to water status and plant nutrition.

While this stress-avoidance approach has been successful in attaining excellent commercial results with soilless production, the growth of the industry has resulted in strong commercial competition which continues to push growers to achieve greater efficiencies. This has resulted in the various specialized systems described in Chap. 5 as well as a huge outdoor nursery industry. As a segment of agriculture, it continues to increase both in size and in percentage. If one adds to this the fact that virtually every home owner owns and pampers a number of potted plants, it becomes clear that there is considerable interest in managing the root zone for more than merely survival or stress avoidance.

While the irrigation and fertilization factors described above are certainly ones that cannot be ignored, there are a multitude of other factors that are of equal importance in soilless production. The ones that must be taken into account are those which have the capacity to change rapidly, and especially where the rate of change towards a suboptimal condition can occur within a few days under conditions that may readily occur.

As such it is worthwhile exploring the various root-zone factors discussed throughout this book in the context of how readily each can change from a condition that is generally optimal to one that is suboptimal (or vice versa). Ideally a quantitative
13.3 Management of Soilless Production Systems

approach would be best here, but the numerous circumstances in the real world make this impossible. For this discussion, it is important to separate out effects that occur over the course of a day versus ones that occur faster or slower. There is no need to consider a time frame longer than one week in soilless production since there are no root zone factors that do not have the capacity to change on at least a weekly basis. And therein lies an operational conclusion: while some factors in soils take multiple weeks to change significantly, every factor in soilless production has the capacity to change much more rapidly, even with substrates that are highly buffered.

The major consequence of this capacity for rapid change is that control must involve accurate and rapid sensing of all these conditions in conjunction with implementation of mitigating measures to keep the system as homeostatic as possible. In cases where accurate and effective control is not feasible at the timescales needed, we still attempt to implement some sort of buffering to slow the rapidity of change to a manageable level. In fact, the sole reason why we seek well-aerated media is to provide a passively buffered oxygen situation by allowing oxygen to diffuse into the root zone and ethylene and CO\(_2\) to leave. If we were to force bulk movement of these gases (as we force bulk movement of all other materials through irrigation) then the aeration buffering provided by well-aerated materials would be unnecessary. In fact, in water culture methods, we generally force oxygen into the water by either bubbling air or spraying which force the dissolved oxygen level to saturation.

A major difference between systems that are operated as open versus closed or semi-closed systems is in the moisture regime. While moisture content can change with equal rapidity in both, closed systems are generally characterized by more frequent irrigations, preventing moisture levels from ever declining to levels that would induce even hidden moisture stress in the plants. Thus in a mixture that combines an inert medium such as sand or perlite with one or two organic substrates, the moisture conditions will typically decline to levels that are dryer in open systems than in closed systems. As was pointed out in Chap. 3, one consequence of this is that the unsaturated hydraulic conductivity in open systems is likely to be much lower at times than it is in closed systems. Thus irrigation in the two systems leads to more rapid change in bulk movement of water in closed systems so that during normal operation, the practitioner can count on lateral bulk movement of water to be faster in closed systems than in open systems. Since this bulk movement carries with it dissolved gasses and nutrients, the net flow of these into plants is typically faster in closed systems, even without consideration of the bulk movement due to the more frequent irrigation events.

One stark contrast between soilless and soil-based production is the rapidity in soilless substrates of change during irrigation events in relation to the rates of change between irrigation events. Clearly it is possible to induce very significant rapid change in most of the root-zone variables with irrigation. In fact, one logical conclusion is that dissolved oxygen concentration can be raised significantly through an irrigation event. Thus noting that oxygen declines at an hourly pace between irrigation events in both open and closed systems, a logical conclusion is that irrigation on an hourly basis (practiced in many greenhouse production settings) prevents hypoxic conditions.
Chapter 13 Growing Plants in Soilless Culture

The same is, of course, true for various nutrients, but the rate of decline to deficiency conditions typically takes longer for nutrients than for oxygen. In many soilless production techniques involving stone wool, irrigation intervals of less than 2 h are needed even when there is still ample fertilizer content in the root-zone solution. It can be argued that the current practices have stabilized around a set of water and nutrient supply recommendations that match this time interval and that it is dictated not by water and nutrients, but rather by oxygen.

In large part there is still a lot that is not known about oxygen in the root zone. Some studies have been carried out but scientific research was hampered by lack of sensors that could be used to make in situ measurements at specific points in the root zone of plants growing in soilless growing media. Most such methods in the past have involved taking a sample (which may well result in changing the oxygen concentration of the sample) or measuring a flowing liquid as it passes through a membrane. Most early methods used membrane technology that was consumptive, so that very small changes could not be detected because they were smaller than the oxygen utilization of the instrumentation. Recently new spectrophotometric devices have emerged (Wang et al., 1999) which allow non-consumptive measurement of dissolved oxygen at the tip of a probe that can be inserted in liquid or solid substrates. This has led to the finding that the oxygen concentration in the root zone of plants in soilless substrates is quite variable within the root zone and that it changes very rapidly. We have measured root zones of roses in 3–5-year-old coir where the oxygen concentration declined in the middle of the root zone from 8 ppm (near saturation) to less than 0.5 ppm over a period of 2 h (Flannery, 2007). The degradation level of this particular substrate was not thought to be an issue, but carrying out the same test with brand new coir resulted in diffusion of oxygen into the root zone that was fast enough to compensate for oxygen consumption. It may also be possible that this rapid decline in old coir might have been due to the microbial activity. Regardless of what the cause is, the operative conclusion was that irrigation was the only feasible way to restore oxygen to normoxic conditions in this particular root zone.

Earlier in this chapter, it was shown that the confined root zone has in and of itself a significant effect on the plants and their roots. In general, there is a notion that we can talk about the root zone as being of a particular composition that is uniform throughout the root-zone volume. And while this may well be the case to some extent, one should not jump to the conclusion that the root zone is entirely uniform. In fact, there are significant gradients from top to bottom and from inside to outside, as well as from surfaces on which the sun is shining to those in the shade. From the standpoint of water, there may be a perched water table at the base with declining wetness levels with height. In substrates with steep moisture retention curves, this can mean that the root zone is too wet at the bottom and too dry at the top for optimal root function. And for all substrates, this dictates the minimum and maximum depth to which the substrate can be used. Temperature gradients are quite common with the surface of the substrate being involved in active evaporative cooling even as the sun shining on the black plastic side of the container heats the nearby substrate to temperature that are too hot for humans to handle. Clearly, there is extensive heterogeneity with temperature and this
13.3 Management of Soilless Production Systems

will lead to substantial variation in dissolved oxygen concentration because oxygen solubility ranges from hypoxic to normoxic levels over the temperature range that roots of container-grown plants experience. These temperatures are also linked to the rate of microbial activity and population growth, further contributing to the volatility of the situation with regard to any element for which these microbes compete with the growing plant. It was shown in Chaps. 8 and 9 that utilization of nutrients involves exchange processes that affect pH and EC. Yet despite these dramatic changes in temperature, oxygen, pH, EC and moisture content, the status quo in the industry today does not involve any attempt to sense these variables. Clearly technical developments are needed in this arena so as to develop sensor-based methods for optimizing the root zone.

In fact, closed production systems are really only sustainable by measuring these variables dynamically. Greenhouse soilless production of vegetables is already innovating in this area (see Chap. 5) and there is a significant growth in the use of sensors and instrumentation, coupled with decision-support software, to attempt to stabilize optimal conditions for the plants. For plants growing in liquid culture, this type of control is already in use but even here, commercial settings still rely mostly on buffering by involving a lot of liquid in the system. As such, DFT, with its large amount of water, has less rapid changes (i.e. is more stable) than aeroponics, which is in turn more stable than NFT. As was pointed out in Chap. 5, NFT has not emerged as a widespread commercial system, due to this instability. As we develop instrumentation and control technologies that can replace buffering with active manipulation, we may well find that NFT can be feasible in commercial settings.

Another facet that is frequently ignored by the practitioner is the presence and activity of microbes. In fact, the prevailing notion in commercial production is that it is best to eradicate these as they are viewed to be in competition with or even antagonists to the plants. Thus there is nearly indiscriminate use of fungicides with the purpose of eradicating pathogens, with little consideration as to whether the effect to beneficial microorganisms might not result in greater problems. Chapters 10 and 11 in this book touched on the concept of disease suppressiveness in substrates that is mediated or imparted by micro-organisms. The fact that the complete absence of microbes is decidedly sub-optimal has been well known by practitioners; many will chose to pasteurize rather than sterilize growing media for this reason; or an attempt will be made to re-inoculate sterilized growing media so as to prevent the ‘biological vacuum’.

We now see further evidence that we must treat the microbes as partners in production, rather than tolerable antagonists. In Chap. 9, it is shown that as systems evolve to more closed systems, we must account for the activity of microbes in the conversion of nitrogen forms and that such conversion plays a major role in the dynamics of the pH. Considerably more research is needed to assist growers with methods that manage this pH. Research in this area needs to evolve so that the microbial population is not treated as a difficult unknown, but rather as a set of dynamic populations. We do not yet know what levels of these populations are optimal, exactly which species are ideal partners for soilless plant production, and how to control the root-zone variables so that these subsystems are managed in an ideal fashion. The two chapters in this book that deal with this issue present the state of the art in this area.
There are, of course, various other horticultural actions that subject the plant to sudden changes which translate into rapid changes in the root zone. Soilless culture generally involves conditions where the environment can be controlled dynamically around the plant (e.g. greenhouse production) or where the plant can be moved to another location without disrupting its growth (e.g. container nursery production). Many times such changes are implemented so as to improve lighting conditions for the plants. These actions do have an effect on the plants that translates to the root zone as well. Improving lighting conditions can enhance photosynthetic activity which yields more sugars in the plant for the growth of tissues such as roots. The resulting increase in exudates, microbe activity, nutrient uptake by roots and microbes will result in a more dynamic situation where all variables change more rapidly. Thus a grower needs to be aware that such a horticultural action will have an impact and may require more attention to pH and fertigation management. Also, such a change may result in more rapid increase in leaf biomass and increase the need for air movement around the leaves. This will result with a faster transpiration stream (Chap. 4) which will, in turn, affect water removal from the root zone.

One operational conclusion that can be drawn from this with regard to open systems is that there is a need to maximize transpiration as part of the overall production strategy. This is something that is frequently not understood because our attention to the ever increasing value of water has led us to seek ways to reduce water use by agriculture. However, in soilless production, maximizing transpiration will assure that a steady supply of nutrients reaches the surface of the roots of plants growing in substrate (as opposed to liquid culture) and thus will increase water use efficiency (Raviv and Blom, 2001). Without this, the plant would be dependent on diffusion processes or the bulk movement during irrigation events. With diffusion of nutrient molecules being very slow, and irrigation in open systems being relatively infrequent (a few times per week, driven by water use of the plant), the boundary layer surrounding the roots would be mostly in a nutrient-depleted state.

### 13.3.3 SENSING AND CONTROLLING ROOT-ZONE MAJOR PARAMETERS: PRESENT AND FUTURE

With the advent of the use of computers for control of many processes in agriculture came the possibility of developing production systems that combine sensor technologies and intelligent control to create very specific production systems that marry particular plants (or even specific cultivars) to particular soilless production elements. The chapters in this book dealing with irrigation and fertigation explicitly highlight such systems as being common and dynamically developing to include new sensors, mathematical models and horticultural approaches. For example, integration of technologies to estimate the amounts of each nutrient ion in the root zone is resulting in greater dynamic control over plant nutrition, ultimately allowing greater customization of specific production systems to specific crops.

Much of the technological developments in this area have been driven by opportunity. Moisture sensors are available and significant research has been done to incorporate them into irrigation control systems. Robust-specific ion electrodes for measuring
ions in the root zone have been lacking, so that research in this area has been limited and consequently there are currently no widely used control systems that obtain input about specific ions from the root zone. Once robust versions of such sensors become available, they will be integrated into production systems to dynamically optimize plant nutrition. Currently, some prototype systems exist, but these measure the leachate of soilless production systems rather than the status of the root zone directly.

Similarly, sensing dissolved oxygen concentration in the root zone has been (and continues to be) very difficult so that using this variable as a control variable for manipulating the root zone is as yet not possible. As such there are currently no irrigation systems (or aeration systems) that explicitly control oxygen in the root zone. Therefore our current recommendations involve the use of substrates with high aeration. Should it become feasible to monitor and control oxygen concentration directly, then this recommendation may well change, possibly resulting in new and revolutionary soilless production systems.

While opportunistic exploitation of sensor and controller technology is important in advancing horticultural technology, it should be noted that soilless agricultural production has advanced to such a point, with ever-increasing percentage as part of agriculture, that it is now reasonable for research agencies to explicitly set research priorities to focus on developing sensor technologies that can be incorporated specifically in soilless production systems. In fact, throughout agriculture there are numerous opportunities for advances in ‘Precision Agriculture’. For soilless crop production, development of sensor technologies in conjunction with simultaneous control (and optimization) of moisture, nutrients and oxygen are likely to pay large dividends, pushing production per unit production area to efficiencies never seen before. It could be argued that if human population continues to grow as it has been, and especially in areas that are prime agricultural production areas, then soilless precision agriculture will be needed to avert food shortages.

Thus, one of the recommendations that can be extracted from this information is that horticultural engineering has significant opportunities in the area of integration of sensor technology with dynamic control over the root-zone variables that are the primary constraints to productivity. Over the past 50 years, improvements in this control have resulted in a variety of production systems, each more productive than the previous generation. It is important to note that significant advances in this area are yet possible.

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Chapter 13 Growing Plants in Soilless Culture


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Chapter 13 Growing Plants in Soilless Culture


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