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Synchronisation of supply and demand is necessary to increase efficiency of nutrient use in soilless horticulture

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Abstract

In modern horticulture on artificial substrates effective systems for plant nutrition have been developed for many crops. The efficiency of nutrient use, however, is often low: on average 40 to 80% of all nutrients applied to tomato and cucumber grown on rockwool slabs is leached from the root environment. In soilless systems only the volume of nutrient solution provides buffering for nutrients when supply and uptake of nutrients are not equal. From a simple model of water and nutrient balance for a well-mixed nutrient solution system, relations between nutrient and water leaching were derived, explaining the low nutrient use efficiencies obtained in practice on soilless media. Improvement of nutrient use efficiency largely depends on improving synchronisation of nutrient supply with nutrient demand. The ratio of "uptake concentration" (current nutrient uptake rate divided by current water uptake rate) and the nutrient concentration in the system is a key parameter. Understanding of fluctuations in this ratio, as determined by daily rhythms, weather conditions and growth stages, may lead to intensive plant nutrition systems that are not only effective, but also efficient.

Introduction

The introduction of techniques for soilless culture in glasshouse horticulture has led to a large reduction in the buffering capacity of the root environment for nutrients and water, both through a reduction in size of the root environment and through a low buffering per unit volume. The small buffering capacity offers possibilities for manipulating and rapidly changing the root environment, but it also imposes a need for frequent replenishment and for regulating the nutrient concentration of the solution. Analysis of the minimum required root volume has shown that further reductions are possible. Nutrient uptake is no problem even when root size is restricted, provided that the concentration is in the usual range and the supply of nutrients to the roots is continuously maintained.

As a plant rarely takes up water and the various nutrients in proportion to the external supply, it is continuously changing the composition of the nutrient solution. The smaller the rooted volume, the greater these disturbances are. Problems of maintaining an "ideal" root environment in poorly buffered systems pose a major obstacle to obtaining maximum plant production as well as a high nutrient use efficiency, as will be discussed in this article. As systems with a fast continuous recirculation of nutrient solution are not yet feasible in commercial practice as long as cheap and reliable sterilisation techniques for large amounts of solution are not available, rockwool slabs with drainage-to-waste are the most common system in practice (at least in the Netherlands). Along with frequent trickle irrigations during the day, excess water and nutrients drain from the rockwool slabs continuously. Recently, however, a trend has developed to collect the drainage water for re-use after sterilization (Runia *et al.*, 1988).

Van Noordwijk and Raats (1982) determined the nutrient balance for a cucumber crop grown on rockwool under semi-practical conditions. Only about 30% of the N, P, Mg and K and about 10% of the Ca and Mg applied during the growing season was actually taken up by the crop (harvested fruits plus crop residue at harvest time). Figure 1 shows the results of a survey of water and nutrient use among tomato and cucumber growers (Van der Burg and Hamaker, 1984). Total nutrient (fertilizer) use is directly correlated with the amount of water given in excess of plant transpiration and follows the recommended recipe for the nutrient solutions, which are different for tomato and cucumber. From the estimated uptake of nutrients it can be seen that only 20–60% of the nutrients applied is taken up by the crop, the remainder (40–80%) being lost to soil, surface water or groundwater. The amount of nutrients leached per hectare (up to 1000 kg of nitrogen per growing season) is a matter of serious concern.

In this article I hope to clarify the apparent logic for this low nutrient use efficiency. Improvement of nutrient use efficiency primarily depends on a better synchronisation of nutrient supply with nutrient demand. The point of view expressed here was developed on the basis of detailed observation of root and nutrient distribution in rockwool slabs, analysis of flow patterns of nutrient solution in a rockwool slab between trickler and drains, estimation of nutrient balances over a whole growing season, and a theory on leaching requirements (Van Noordwijk and Raats, 1980; 1982; Van Noordwijk, 1983).

Minimum root volume

Analysis of the minimum root volume for soilless culture systems (De Willigen and Van Noordwijk, 1987) suggests that the required size of the root system for maximum growth is determined by water uptake, according to equation 1:

$$A_r = \frac{E_p}{L_p[\Delta H_p - 2\pi_0\sigma_r^2/(1-\sigma_r)]} \tag{1}$$

where:

A_r = required root surface area per plant [m^2],
E_p = maximum transpiration rate per plant [L/hour],
L_p = hydraulic conductance per unit root surface area [$Lm^{-2}\,s^{-1}\,Pa^{-1}$],
ΔH_p = maximum acceptable matric suction in the leaves [Pa],
π_0 = osmotic potential of the nutrient solution [Pa],
σ_r = reflection coefficient for solutes ($0 < \sigma_r < 1$).

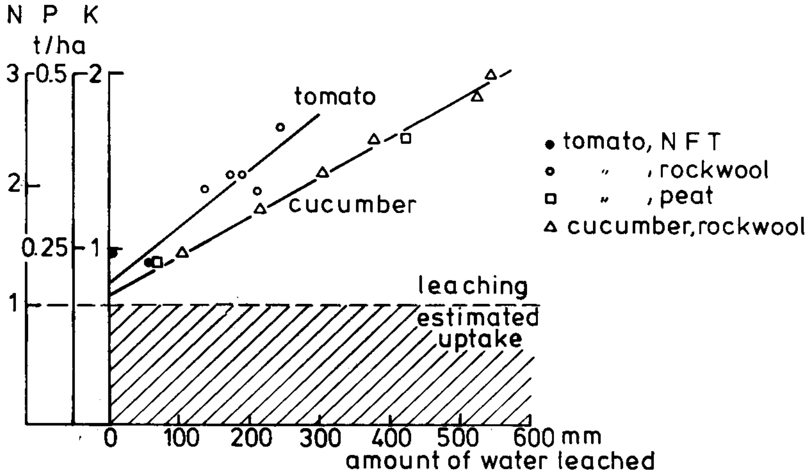

Fig. 1. Fertilizer use in 15 glasshouses in one growing season in relation to the amount of water leached (after Van der Burg and Hamaker, 1984); estimated nutrient uptake for both cucumber and tomato is indicated.

In a number of glasshouse experiments with tomato and cucumber, the following parameters were found to describe the effects of physical limitations to root extension on shoot growth. Reduced shoot growth and/or fruit production was found for root sizes less than A_r:

	L_p 1/(m^2 s Pa)	ΔH_p MPa	σ_r	E_p L/hr	π_0 MPa	A_r m^2
Tomato	$1.2\,10^{-10}$	0.5	0.3	0.2	0.04	0.94
Cucumber	$0.9\,10^{-10}$	0.4	0.3	0.3	0.04	2.3

Cucumber requires 2.5 times more root surface area than tomato. For a uniform root diameter of 0.3 mm, root surface areas of 0.9 and 2.3 m^2 are equivalent to root volumes of 0.14 and 0.35 dm^3, respectively. The external volume required to obtain this minimum amount of roots is also larger for cucumber than for tomato, but both are much smaller than the 10 dm^3 of rockwool currently used.

Reasons for leaching

Losses of water and nutrients are partly due to uneven delivery of solution by the tricklers and uneven growth and uptake by the plants, which cause leaching of excess nutrient solution when the water supply is adjusted to the most-demanding plant with the slowest trickler. Even in completely homogeneous systems, however, an apparent need for leaching of nutrient solution stems from the salt accumulation which would otherwise occur. If irrigation water is used which contains NaCl, accumulation of salts can only be avoided by leaching or by including specific NaCl absorbers (*e.g.* saltmarsh plants) in a recirculation system (P.J.C. Kuipers, pers. comm.). When water of good quality is used, salts accumulating are mainly nutrients supplied in excess of crop demand. This problem consists of two parts: accumulation of all nutrients contained in the solution if the total salt concentration C_s exceeds the "uptake concentration" C_u (nutrient uptake/water uptake), and shifts in the relative concentration of individual ions as the ratio in which they are supplied may not be equal to the ratio in which they are taken up in different growth stages (Van Goor *et al.*, 1989). Analysis of salt distribution patterns in rockwool slabs (Van Noordwijk and Raats, 1980; 1982) showed that small-scale differences in total salt content, as indicated by electrical conductivity (EC) occurred: over a 5 cm distance EC varied by a factor of 2. Relatively high EC values were found in the lowest zone of the slab, between two plants and between tricklers. Ions accumulating in the dead corners are mainly Cl^-, SO_4^{2-}, Ca^{2+} and Mg^{2+}. In a nutrient solution of the recommended composition Ca and Mg are supplied in higher concentrations relative to plant uptake than K, so as to maintain suitable K/Ca and K/Mg ratios for adequate uptake. The necessity to maintain a K/Ca ratio in the root environment which differs from the uptake ratio may be due to the fact that probably only young parts of the root system are involved in Ca uptake, while the whole root length will be active in K uptake. For the young roots the K/Ca uptake ratio may be equal to the ratio supplied, while around the older roots Ca accumulates, unless the solution is thoroughly mixed.

As we may assume that plant nutrient uptake is independent of the external concentration over a considerable range of concentrations, at least for N, P and K (Clarkson, 1985; De Willigen and Van Noordwijk, 1987), the plant has a destabilizing effect on the nutrient solution. As soon as $C_u < C_s$, C_s will tend to rise even more, and as soon as $C_u > C_s$, C_s will decrease further. The ratio of C_u and C_s is therefore an important characteristic of the system. The "ideal" situation of $C_u/C_s = 1$ throughout the growing season is difficult to realise as C_u is continuously changing, mainly due to variation in water uptake during the day and between days of different insolation. Figure 2 shows weekly recordings of C_u/C_s for tomato and cucumber experiments, on a recirculating nutrient solution. When C_s is considered to be constant throughout the growing season, C_u apparently exceeds C_s in the initial part of the growing season, approximately equals C_s during cloudy periods and is considerably lower than C_s during sunny periods. During sunny periods we may therefore expect nutrient accumulation to occur in the root environment

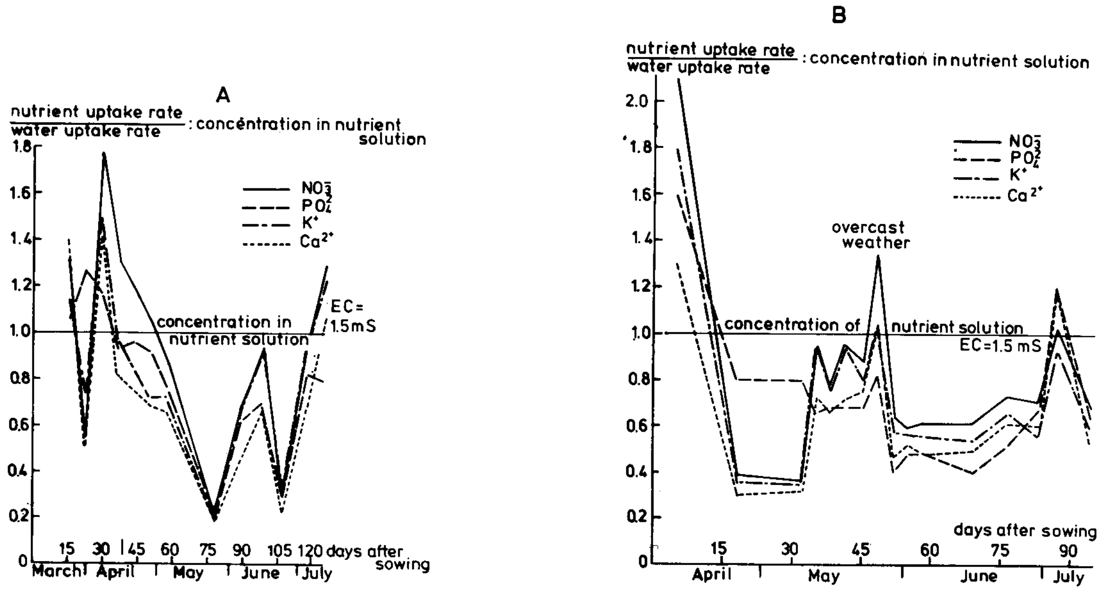

Fig. 2. Uptake concentration C_u (nutrient uptake divided by water uptake) divided by external concentration C_s in tomato (**A**) and cucumber (**B**) experiments on a recirculating nutrient solution.

and the apparent need for washing out these excess salts with nutrient solution to arise.

The concentration of all nutrients in the nutrient solution needed to obtain maximum yields (and/or quality) has been established for many plant species in experiments in which many concentration levels, maintained throughout the growing season, were tested (Sonneveld and Van der Wees, 1980). If in such an experiment a concentration C_s would be tested which equals the average C_u over the whole growing period, the plants would receive insufficient nutrients during some parts of the growing season and would respond by sub-maximum growth and/or quality. From the fluctuations in the C_u/C_s ratio in Figure 2 it is understandable that in the current advice C_s exceeds the average C_u by 30 to 40%. For such a value of C_s nutrient shortages can be avoided. As a consequence, however, during large parts of the growing season nutrients will accumulate in root environment. The relation between C_u/C_s, the degree of salt accumulation that can be tolerated in the root environment, and the nutrient use efficiency obtained can be quantified in a simple model of nutrient and water balance for a well-mixed system.

Nutrient and water balance

The relationship between leaching of water and nutrients and fractional uptake (C_u/C_s) can be formulated simply for a perfectly mixed system such as a rapidly recirculating nutrient solution. For imperfectly mixed systems of low buffering capacity, such as rockwool slabs, this algebraic description may still be a reference. For the water and nutrient balance of a perfectly mixed system (Raats, 1980) we may write:

$$N_a = N_u + N_l \, , \tag{2}$$

$$W_a = W_u + W_l \, , \tag{3}$$

where:

N_a and W_a = input of nutrients and water, respectively, N_u and W_u = uptake of nutrients and water, respectively, N_l and W_l = leaching of nutrients and water, respectively.

We then define "leaching fractions" l_n and l_w for nutrients and water as:

$$l_n = N_l/N_a = 1 - N_u/N_a \, , \tag{4}$$

$$l_w = W_l/W_a = 1 - W_u/W_a \,, \qquad (5)$$

the required relation between l_n and l_w as a function of relative utilisation of the nutrients in the solution c_u is given by:

$$l_n = 1 - c_u(1 - l_w), \text{for } l_w > 0 \,, \qquad (6)$$

where:

$c_u = C_u/C_n$,
$C_s = N_l/W_l$, the system concentration,
$C_n = N_a/W_a$, the concentration added,
$C_u = N_u/W_u$, the uptake concentration.

From (6) we see that for $c_u = 1$, when roots of the plant effectively act as a sponge absorbing the solution as it comes, $l_n = l_w$; for $c_u > 1$ the nutrient solution is depleted and $l_n < l_w$, and for $c_u < 1$ salts are accumulating in the solution and $l_n > l_w$. Figure 3 shows the relation between l_w and l_n according to (6).

The data of Van der Burg and Hamaker (1984) on the nutrient and water balance of tomatoes and cucumber grown on rockwool, presented in Figure 1, fit in well with this scheme for a value of c_u of about 0.6 (compare Table 1). For horticultural practice we thus obtain:

$$l_n = 0.4 + 0.6\, l_w, \text{for } l_w > 0 \,. \qquad (7)$$

From (6) we see that c_u affects l_n in two ways: c_u determines the nutrient excess for l_w approaching 0 and it determines the extra nutrient loss when nutrient solution is washed through the system to the drains. In fact, a third effect exists, as the required leaching of water is at least partly determined by the accumulation of nutrients in the root environment. This last relation can be formulated as follows.

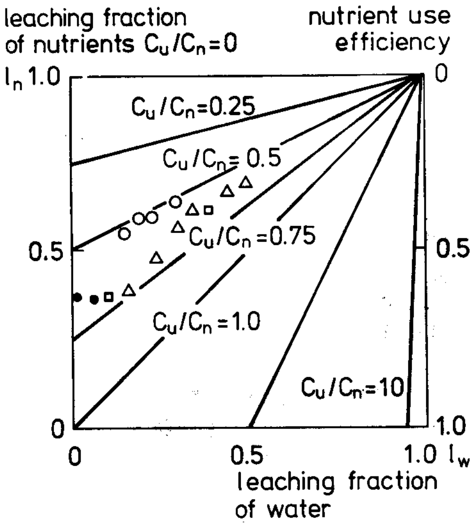

Fig. 3. Relation between leaching fraction of nutrients l_n and leaching fraction of water l_w for a well mixed system, as influenced by $c_u = C_u/C_n$, (equation 6); points refer to the data of Figure 1.

Salt accumulation or depletion in the system is limited to a tolerance factor $c_{s,t} = C_s(h)/C_s(l)$ (Table 1). Such tolerances apparently vary from 1.75 for K and Ca to 5.0 for SO_4. A relation exists between l_n, l_w and $c_{s,t}$:

$$c_{s,t} = C_s/C_n = l_n/l_w \,. \qquad (8)$$

Table 1. Estimated daily uptake concentration, C_u, of nutrients by a tomato crop compared with the recommended composition of the nutrient solution in the rockwool slab (Sonneveld and Van der Wees, 1980). Three system concentrations are shown for each nutrient: lowest $C_s(l)$, desired $C_s(d)$ and highest $C_s(h)$. The range of concentrations tolerated is defined as $C_s(h)/C_s(l)$. Uptake concentration C_u calculated for a daily transpiration of 2.5 l/plant is compared with the desired system concentration $C_s(d)$ in the last column

	Daily uptake per plant (mg)	Uptake conc. C_u	System concentration C_s			Tolerance $C_s(h)/C_s(l)$	Utilisation $C_u/C_s(d)$
			$C_s(l)$	$C_s(d)$	$C_s(h)$		
		$(mg\,L^{-1})$					
N	225	90	84	130	210	2.5	0.69
P	45	18	15	31	47	3.0	0.58
S	50	20	32	64	160	5.0	0.31
K	450	180	160	200	270	1.75	0.90
Ca	100	40	160	200	280	1.75	0.20
Mg	30	12	24	48	72	3.0	0.25

Combining (8) and (6) we find the leaching fraction l_n required if a certain accumulation factor $c_{s,t}$ is accepted, given an uptake ratio c_u:

$$l_n = c_{s,t}(1 - c_u)/(c_{s,t} - c_u)\,. \tag{9}$$

Figure 4 gives some examples of this relation, and shows how for $c_u < 1$ (i.e. $C_n > C_u$) the required leaching fraction depends on the accepted "accumulation" factor $c_{s,t} = C_s(h)/C_s(l)$ (Table 1). For $c_u > 1$ leaching depends on the accepted "depletion" factor $c_{s,t}$. The only way to completely avoid leaching of nutrients is to have $c_u = 1$ or $c_{s,t} = 0$ and $c_u > 1$.

For a value of c_u of 0.6, which is common in horticultural practice, and an accepted accumulation $c_{s,t}$ of 2, the value for the required leaching fraction of nutrients, l_n, is 57%. If N-uptake is 700 kg/ha, nitrogen losses to the environment are 930 kg/ha in this case. If c_u could be increased to 0.8, 0.9 or 0.95, leaching could be reduced to 33, 18 and 9.5% of the amount applied and losses of nitrogen to the environment to 350, 156 and 73 kg/ha, respectively. For $c_{s,t} = 5$ the values would be 24, 12 and 6.2%, respectively, and N-losses would amount to 220, 97 and 46 kg/ha.

In systems which are imperfectly mixed, heterogeneity of salt distribution can be built up; the plant, however, has a tendency to reduce the existing heterogeneity by preferentially taking up water in the area with the lowest salt concentrations (Cerda and Roorda van Eysinga, 1981).

On further analysis the uptake concentration C_u can be split up into two components:

$$C_u = N_u/W_u = \mathrm{NUTE}/\mathrm{WUTE} \tag{10}$$

where:

NUTE = (nutrient concentration in the plant)$^{-1}$ = dry weight per unit nutrient uptake = Nutrient Utilisation Efficiency,
WUTE = transpiration ratio = Water Utilisation Efficiency = dry weight produced per unit water transpired.

Both NUTE and WUTE are quantities about which much information is available. WUTE values in the range 3–7 g L^{-1} are common (De Wit, 1958), relatively high values being typical of C4-types of photosynthesis, relatively low values for plants having a C3 photosynthesis. A value of WUTE of 4 g L^{-1} in combination with an N-content of 2.5% gives a $C_u = 4 \times 0.025 = 0.1$ g L^{-1}, which agrees with the value assumed in Table 1. Variation of C_u around this average value can be accounted for by short-term fluctuations in transpiration ratio and internal concentration.

In equation (1) we used the concept of a reflection coefficient σ_r, which is defined as the fraction of solutes arriving at the root membrane but not passing it. In fact, σ_r is equal to $1 - C_u/C_s$. When $C_u = C_s$, no reflection occurs and when $C_u = 0$, there is a complete reflection. Using this definition and substituting $\pi_0 = R\,T\,C_s$

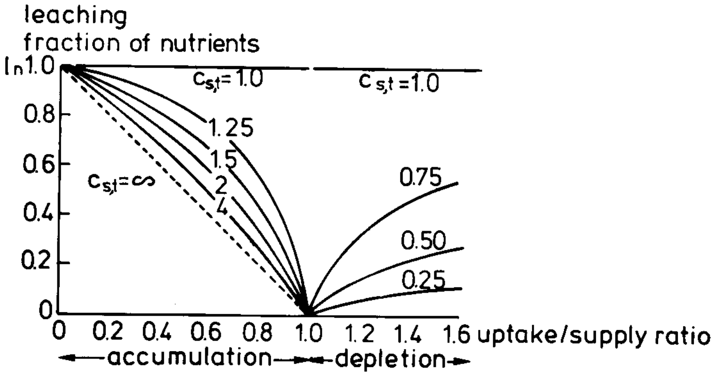

Fig. 4. Leaching fraction of nutrients l_n required in a well-mixed system as a function of uptake/supply ratio c_u and accumulation or depletion factor $c_{s,t}$, according to equation (9).

(where R is the gas constant and T the absolute temperature), we obtain (for $C_s > C_u$):

$$A_r = \frac{E_p}{L_p[\Delta H_p - 2\,R\,T(C_s - C_u)^2/C_u]} \, . \qquad (11)$$

This equation shows that values of C_s considerably exceeding C_u increase the required root surface area, or impede water uptake if the size of the root system remains the same. Although restrictions on water uptake in certain parts of the cropping cycle may help to induce flowering or fruit set, the present use of high EC values is probably far from ideal and other ways of regulating plant growth should be investigated as they may lead to higher nutrient use efficiencies.

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