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Nutrient Management in Recirculating Hydroponic Culture

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Introduction

There is an increasing need to recirculate and reuse nutrient solutions in order to reduce environmental and economic costs. However, managing the nutrient solution is one of biggest challenges in hydroponics. Many research scientists dump out nutrient solutions and refill at weekly intervals. Some authors have recommended automated measurement and control of individual nutrients in solution as essential to nutrient control. However, two decades of research in hydroponics has shown us that dumping and replacing solution is unnecessary. Monitoring ions in solution at frequent intervals is extremely expensive and not always necessary; in fact the rapid absorption and consequent depletion of some nutrients often causes people to add toxic amounts of nutrients to the solution.

Managing nutrients by mass balance.

During the past 18 years, we have managed nutrients in closed hydroponic systems according to the principle of "mass balance," which means that the mass of nutrients is either in solution or in the plants. *We add nutrients to the solution depending on what we want the plant to take up.*

Plants quickly remove their daily ration of some nutrients while other nutrients accumulate in the solution. This means that the concentrations of nitrogen, phosphorous, and potassium can be at low levels in the solution (0.1 mM or a few ppm) because these nutrients are in the plant, where we want them. Maintaining a high concentrations of nutrients in the solution can result in excessive uptake that can lead to nutrient imbalances.

For example, the water removed from solution through transpiration must be replaced and it is necessary to have about 0.5 mM phosphorous in the refill solution. If the refill solution was added once each day, the phosphorous would be absorbed by the plant in a few hours and the solution phosphorous concentration would be close to zero. This does not indicate a deficiency; rather it indicates a healthy plant with rapid nutrient uptake. If phosphorous was maintained at 0.5 mM in the recirculating solution, the phosphorous concentration in the plant could increase to 1% of the dry mass, which is 3 times higher than the optimum in most plants. This high phosphorous level can induce iron and zinc deficiency (Chaney and Coulombe, 1982).

Feeding plants in this way is like the daily feeding of a pet dog, some dogs would be seriously overweight if their food bowls were kept continuously full.

Differential nutrient removal from solution.

The essential nutrients can be put into 3 categories based on how quickly they are removed from solution. Group 1 elements are actively absorbed by roots and can be removed from solution in a few hours. Group 2 elements have intermediate uptake rates and are usually removed from solution slightly faster than water is removed. Group 3 elements are passively absorbed from solution and often accumulate in solution.

Table 1. Approximate uptake rates of the essential plant nutrients.

Group 1. Active uptake, fast removal	NO_3, NH_4, P, K, Mn
Group 2. Intermediate uptake	Mg, S, Fe, Zn, Cu, Mo, Cl
Group 3. Passive uptake, slow removal	Ca, B

One of the problems with individual ion monitoring and control is that the concentration of the group 1 elements (N, P, K, Mn) must be kept low to prevent their toxic accumulation in plant tissue. Low concentrations are difficult to monitor and control. Table 2 shows typical measurement errors associated with the use of ICP emission spectrophotometry for analysis of hydroponic solutions. Nitrogen cannot be measured by ICP-ES. Accuracy for the macronutrients is good, but solution levels of B, Cu, and Mo cannot be accurately measured by ICP-ES. The calculations in this table are for a typical refill solution, *not for the low concentrations that should be maintained in the circulating solution.* The measurement errors for K, P, and Mn can be 10 times higher because the solution levels are lower.

The total amount of nutrients in solution can easily and accurately be determined by measuring the electrical conductivity of the solution. However, because of the differential rate of nutrient uptake, conductivity measurements mostly measure the calcium, magnesium and sulfate remaining in solution. The micronutrients contribute less than 0.1% to electrical conductivity.

Table 2. Typical measurement error associated with the use of Inductively Coupled Plasma Emission Spectrophotometry for analysis of nutrient concentrations in hydroponic solution.

Element	Nutrient Solution Concentration (mM)	ICP Accuracy (mM)	TypicalMeasurement Error (%)
K	3.5	0.1	3
Ca	1.0	0.002	0.2
S	0.75	0.01	1
P	0.5	0.01	2
Mg	0.25	0.002	1
Micro-nutrients	**µM**	**µM**	**%**
Fe	5.0	0.15	3
Mn	3.0	0.3	10
Zn	1.0	0.15	15
B	1.0	3.0	300
Cu	0.1	0.2	200
Mo	0.03	1.0	30x

Developing an appropriate refill solution.

The objective is to develop a recipe for a refill solution that replenishes both nutrients and the water. Plants have evolved to tolerate large nutrient imbalances in the root zone, but in recirculating hydroponic systems, imbalances in nutrient replenishment are cumulative. It is thus important to understand the principles for nutrient replacement, especially when the solution is continuously recycled over the life cycle of a crop.

Traditional nutrient solution recipes, such as Hoagland solution, can be used as refill solution if they are diluted to about 1/3 strength so that the electrical conductivity is kept constant. Hoagland solution, however, is not necessarily the best refill solution for all types of plants.

Two factors must be considered in developing a refill solution:

1) Solution composition.
2) Solution concentration.

Solution composition.

The composition of the solution (the ratio of nutrients) should be determined by the desired concentrations of each element in the plant. These concentrations are similar in the leaves of most dicotyledenous (broadleaf) plants. Several books have recommended values for leaf nutrient concentrations. An excellent book, especially for greenhouse crops is:
"Diagnosis of Mineral Disorders in Plants, Volume 3: Glasshouse Crops" by G. Winsor and P. Adams; 1987; published by the Glasshouse Crops Research Institute, Littlehampton. ISBN 011 2427235.

Foliar analysis is based on the nutrient concentration in leaf tissue because leaves conduct the most photosynthesis and thus have the highest enzyme levels in plants. Average nutrient concentrations of whole plants are usually less than the concentrations in leaves, so a refill solution based solely on leaf tissue concentration will usually over-supply nutrients for stem growth.

Many people think that more is better when supplying nutrients and that it is better to have excess nutrients in the solution than levels that are only adequate. ***This is not true and this thinking leads to dangerous imbalances in nutrient uptake.*** For example, potassium is absorbed rapidly from nutrient solutions. If potassium is supplied at excess levels its uptake inhibits the uptake of calcium and induces calcium and magnesium deficiencies. Keeping potassium at appropriately low levels in the root zone significantly improves calcium uptake and helps to prevent blossom end rot, a common calcium deficiency disorder in tomato fruits.

Because calcium is passively absorbed by plants and is not needed at high levels in fruits, it accumulates over time in nutrient solutions. I have seen it accumulate to 20 mM in some systems, which is ***10 times*** the concentration in Hoagland solution! As shown in Table 3, tomatoes need less calcium and magnesium in the fruits than in the leaves, so these elements should be reduced in the refill solution during fruit growth to reduce their accumulation in the nutrient solution.

Young plants easily develop nutrient deficiencies but rarely develop nutrient toxicities so I like to use an initial starter solution with higher nutrient levels to get the young seedlings going. A refill solution with adequate nutrients for early vegetative leaf growth is usually too concentrated when plants are developing stems and leaves so we alter the composition of the refill solution with the growth stage of the plant to reduce nutrient accumulation in the solution. The life cycle can be divided into 3 stages:

1. Early vegetative growth, which is primarily composed of leaf tissue (starter solution).
2. Late vegetative growth, during which growth is composed of about equal amounts of stem and leaf tissue (vegetative refill solution).
3. Reproductive growth, during which leaf growth is minimal and nutrients are mobilized into seeds or fruits (seed refill solution).

Root growth primarily occurs during early vegetative growth and is much less significant during late vegetative growth. Root growth decreases and even stops during reproductive growth.

Table 3. Approximate optimum nutrient concentrations in different parts of a tomato plant. Lettuce and other vegetative crops would include only the leaf and stem concentrations.

%	Leaves	Stems	Fruits	Roots
N	4	1.5	3	3
P	0.5	0.2	0.5	0.2
K	4	3	4	2
Ca	2	0.5	0.2	0.2
Mg	0.6	0.1	0.2	0.2
S	0.4	0.3	0.2	0.2
mg/kg	**Leaves**	**Stems**	**Fruits**	**Roots**
Fe	100	40	100	800*
Mn	75	20	50	25
B	30	10	30	5
Zn	30	20	30	30
Cu	10	2	10	10
Mo	2	1	1	1
Cl	100	100	100	1

* Iron precipitates on the root surface

Table 4 compares half-strength Hoagland solution with a solution for tomatoes. I derived this solution by multiplying the desired concentrations in leaf, stem, fruit, and root tissues by an assumed transpiration to growth ratio of 200 to 1 (200 liters of water transpired per kg of biomass produced; see the following section on solution concentration). In low humidity environments (with high transpiration rates) these concentrations would need to be reduced to prevent an increase in the electrical conductivity of the nutrient solution. The refill solutions are more dilute at the later stages of the life cycle because the nutrient requirements of stems and seeds are less than for leaves.

Table 4. A Comparison of half-strength Hoagland Solution with a tomato solution for a low transpiration environment. The system is initially filled with the starter solution. Vegetative refill solution is used during leaf and stem growth, the fruit fill solution is used after the leaves stop growing and the fruits are filling.

------- typical tomato solutions -------

millimoles per Liter (mM)	**Hoagland Solution**	**Starter solution**	**Vegetative refill**	**Fruit fill refill**
N	7.5	3	6	3
P	0.5	0.6	0.5	0.5
K	3	3	5	5
Ca	2	2	2	0.3
Mg	1	1	1	0.3
S	1	1	0.6	0.3
micromoles per Liter (µM)	**Hoagland Solution**	**Starter solution**	**Vegetative refill**	**Fruit fill refill**
$FeCl_3$	50	5	5	5
EDDHA chelate	-0-	25	5	5
Mn	4.5	10	15	3
B	23	20	20	20
Zn	0.4	5	2	2
Cu	0.15	1	1	1
Mo	0.05	0.1	0.05	0.05
Cl	9	15	15	15
Si	-0-	100	100	-0-

The rationale underlying the differences between Hoagland's solution and the tomato solution are not obvious, so a discussion of differences is useful.

Nitrogen (N). When nitric acid is used for pH control, about half of the nitrogen is supplied in the pH control solution. Nitrogen in the refill solution can thus be less than in Hoagland's solution. Ammonium nitrate (NH_4NO_3) can be added to the pH control solution if necessary to obtain even higher levels of N in the plants, but ammonium reduces the uptake of other cations so it should only be used if necessary.

Potassium (K). The supply of K is more constant with a lower level in the starter solution and a more concentrated refill solution.

Calcium, Magnesium, and Sulfur can be reduced at the end of the life cycle becuase less is needed in fruits.

Iron (Fe). The use of modern chelating agents like EDDHA (Ciba-Geigy Chel 138Fe) means that iron can be maintained in solution and much lower levels can be used.

Zinc and Copper (Zn and Cu). These elements are ubiquitous contaminants. Hoagland and Arnon in the 1940's and 50's probably got most of these elements from contamination of the solution. Modern plastics, like PVC pipe, greatly reduce copper and zinc contamination.

Chloride (Cl). Slightly higher Cl levels can help the plant take up more cations (like Ca) because an increase in anion uptake promotes an increase in cation uptake. This is called the principle of charge balance. The Cl concentration in the refill solution can be up to 50 or even 100 µM without becoming toxic.

Silicon (Si). A beneficial element. See section on silicon in this paper.

Solution concentration.

The concentration of ions in the refill solution is determined by the ratio of transpiration to growth. Transpiration determines the rate of water removal; growth determines the rate of nutrient removal. A good estimate of the transpiration to growth ratio for hydroponically grown crops is 200 to 400 kg (Liters) of water transpired per kg of dry mass of plant growth. The exact ratio depends on the humidity of the air; low humidity increases transpiration but does not increase growth. Elevated CO_2 closes stomates and increases photosynthesis so the transpiration to growth ratio can decrease to about 200 to 1.

A knowledge of these ratios is useful in determining the approximate concentration of the refill solution. For example, 1/4 strength Hoagland's solution is about right for plants grown in ambient CO_2, but 1/3 strength Hoagland's solution may be required for plants grown in elevated CO_2. Total ion concentration can be maintained by controlling solution electrical conductivity. If the conductivity increases, the refill solution should be made more dilute, but the composition should be kept the same. The electrical conductivity does not change rapidly so it is usually necessary to monitor it only a few times each week. We have successfully used this approach in long-term studies (months) without discarding any solution. This procedure can eliminate the need to monitor nutrient solution concentrations in the solution.

Examples of refill solution concentration calculations.

An analysis of the mass balance of potassium (K) is useful to demonstrate recovery in plant tissue.

Case # 1. Assume a transpiration to dry-mass growth ratio of 300:1 and a desired K concentration in the plant of 4% (40 g kg^{-1}). For every kg of plant growth, 300 Liters of solution went through the plant, so there must be 40 g of K in 300 Liters of refill solution, or 0.133 g L^{-1}. The molar mass (atomic weight) of K is 39 g mol^{-1}. The refill solution must have 0.133 / 39 = 0.0034 moles L^{-1} of K in it, or **3.4 mM K**.

Case # 2. Low humidity. If the transpiration to growth ratio was 400:1 the refill solution should be more dilute by 300/400 or 3/4. 40g in 400 L = 0.1 g L^{-1} divided by 39 = **2.6 mM K**.

Case # 3. If the plant was in a fruit or seed fill stage of growth, potassium requirements might only be about 2% K (20 mg kg^{-1}) in the new growth. If the transpiration to growth ratio was 300:1, the refill solution would be: 20 g K in 300 L = 0.067 g L^{-1} / 39 = **1.7 mM K**.

Nutrient recovery in plant tissue.

As mentioned earlier, the mass balance approach to nutrient management assumes that all of the nutrients are either in the solution or in the plant. Surprisingly few detailed mass balance studies to test this assumption have been conducted, however, studies in our laboratory and studies by Dr. Wade Berry at UCLA clearly indicate that the recovery of several elements is less than 100%, while recovery of some micronutrients is much greater than 100%. Table 5 indicates the average recoveries of elements from solution in six replicate 23-day studies. These recoveries are typical of recirculating hydroponic systems. Because recovery of macronutrients is 50 to 85%, additional macronutrients should be added to the refill solution. Reduced amounts of some micronutrients may be warranted when the contamination is reproducible.

Table 5. Average recoveries of the essential nutrients in plant tissue at the end of six replicate 22 day studies with wheat. The recovery of all of the macronutrients, and iron and boron was 50 to 85% of that added to the nutrient solution (minus what was left in solution at the end of the trial). The recovery of Mn, Zn, Cu, and Mo was greater than 100% because of contamination of the hydroponic solution from elements in the plastics or the magnetic drive pumps. Many different types of plastics were used to build this system and many plastics use zinc and copper as emulsifiers in manufacturing. These recoveries are typical in recirculating hydroponic systems.

Element	% Recovery		Element	% Recovery
N	70		Fe	50
P	75		Mn	280
K	85		B	60
Ca	50		Zn	400
Mg	70		Cu	600
S	50		Mo	1000

Frequency of addition of refill solution.

Because nutrients with active uptake are depleted in hours, it might seem that automatic addition of refill solution is required to avoid depletion. Frequent addition of refill is not necessary. The nutrients that are rapidly absorbed from solution are all mobile in plants, which means that plants can store the nutrients in roots, stems, or leaves and remobilize them as needed. We have done studies with nitrogen in which we spiked the solution once every 2 days and let the solution deplete to near zero (which occurred after about 12 hours). Plant growth was identical to the controls, which were maintained at a constant ample N level. However, we also did another study in which an excessive level of N was added to the starter solution, but the N was not replenished. The plants rapidly absorbed the N until it was depleted to about 20 µM nitrate at 16 days after seedling emergence. These plants had ample nitrate in the leaves at harvest on day 23, but assimilated N and dry mass gain were slightly lower than the controls (at a constant ample N). The results of this study suggest that remobilized nutrients may not be as useful as freshly absorbed nutrients.

It is relatively easy to use a float valve to obtain frequent small additions of nutrients, but this may not result in improved plant growth compared to daily additions of refill solution. In practice, the frequency of addition of refill solution is determined by the

ratio of solution volume to plant growth rate. Small volumes with big plants need frequent refilling of both nutrients and water.

Examples of nutrient concentrations in hydroponic solution over the life cycle.

Figure 1 shows the concentrations of nutrients over a 70 day life cycle of wheat. Note that the concentrations of K, Ca, S, and Mg increased after anthesis on day 35 because less of these nutrients are required in the seeds. The spikes in the concentration of Mn were caused when the solution was analyzed immediately after the addition of refill solution. These measurements were made before we installed a float valve to provide automatic, frequent additions of refill solution. Frequent additions of refill solution would smooth out the concentrations of all of the elements. The plant tissue concentrations of all elements were ample in this study, and, in fact, K and P concentrations were excessive. After this study, we reduced the concentration of K and P in the refill solution to the level indicated in Table 4. The starting K concentration was 4 mM in this study, but our current starting K concentration is 1.5 mM, which is maintained at about 0.5 mM K in the circulating solution by adding 4.5 mM K in the refill solution.

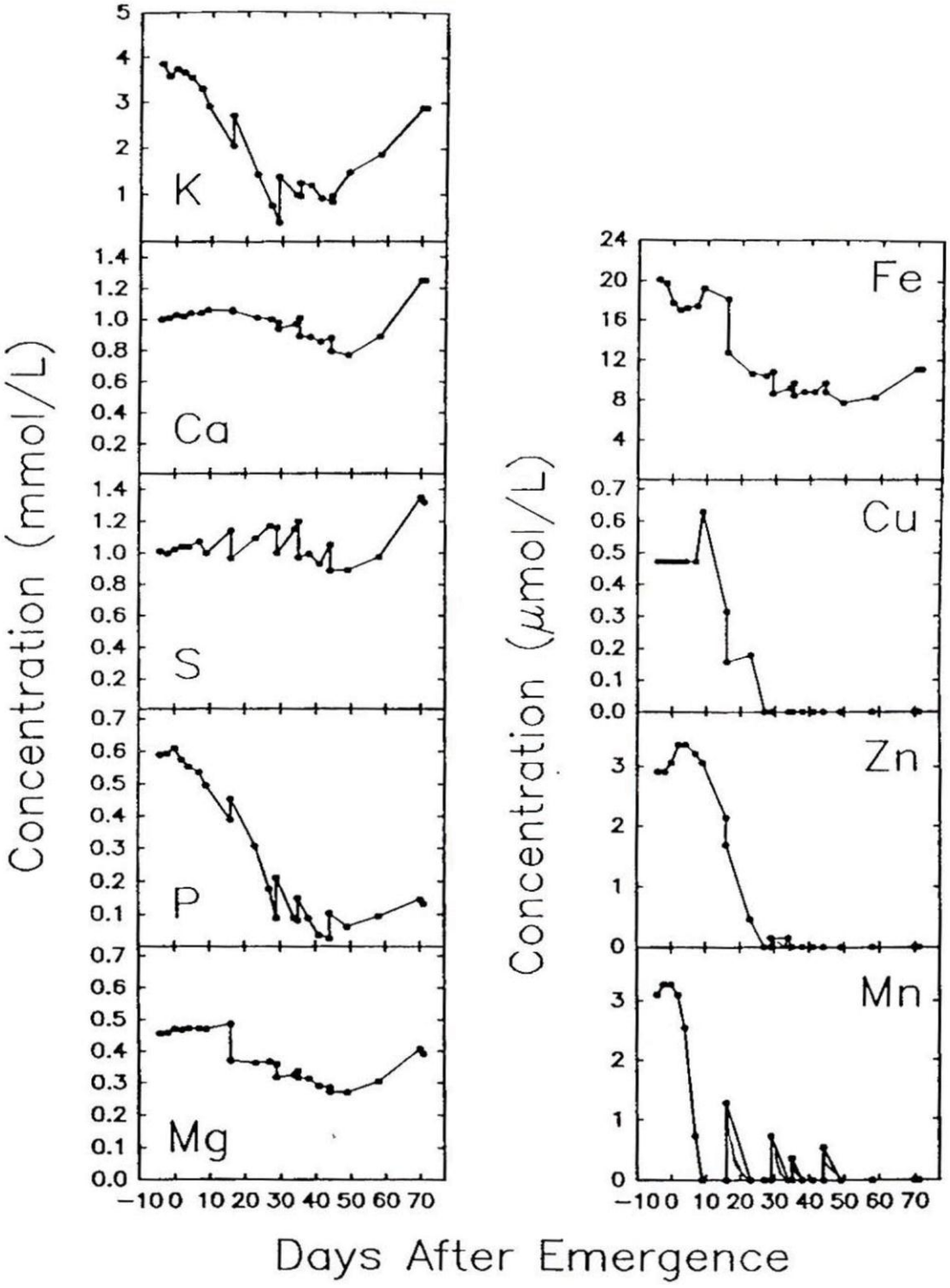


Figure 1. Concentrations of nutrients over a 70-day life cycle of wheat.

Commercial plant analysis laboratories.

Analysis of hydroponic solution is unnecessary, inaccurate, and difficult to interpret, but analysis of plant tissue is useful, accurate, and relatively easy to interpret. All four of the plant analysis books referenced previously provide guidelines for optimum concentrations of nutrients in plant tissue (usually in the youngest, fully expanded leaf blades). I highly recommend sampling plant tissue at intervals during the life cycle to help refine the composition of the refill solution. Tissue sampling becomes less important over time as procedures are refined and optimal nutrient levels in plant leaves are obtained.

The analytical methodology of choice for plant analysis is emission spectrophotometry. Many laboratories around the country analyze plant tissue on a daily basis. Almost all of these are listed in the publication entitled "Soil and Plant Analysis Laboratory Registry for the United States and Canada" (Council on Soil Testing and Plant Analysis, Georgia Univ. Station, Athens, GA 30612-0007; about $15/copy). This provides analytical services offered, contact person, phone and fax numbers. Be sure to check with the laboratory before sending them a sample. Each lab has different recommendations for plant sampling, drying, and shipment. The lab should be able to provide you with an analysis of nutrient toxicities and deficiencies. J. Benton Jones article in the 1993 HSA Proceedings more thoroughly explains details associated with plant sampling and analysis.

As an example of the typical cost of analysis, the 1995 analytical charges at the Soil and Plant Analysis Laboratory at Utah State University are as follows:

ICP-emission spectrophotometry for 22 elements:	$ 17.50
Kjeldahl or LECO Total Nitrogen analysis	$ 10.00
Nitrate-N analysis	$ 9.00
Total nitrogen plus ICP-ES elements (package discount)	$ 22.50

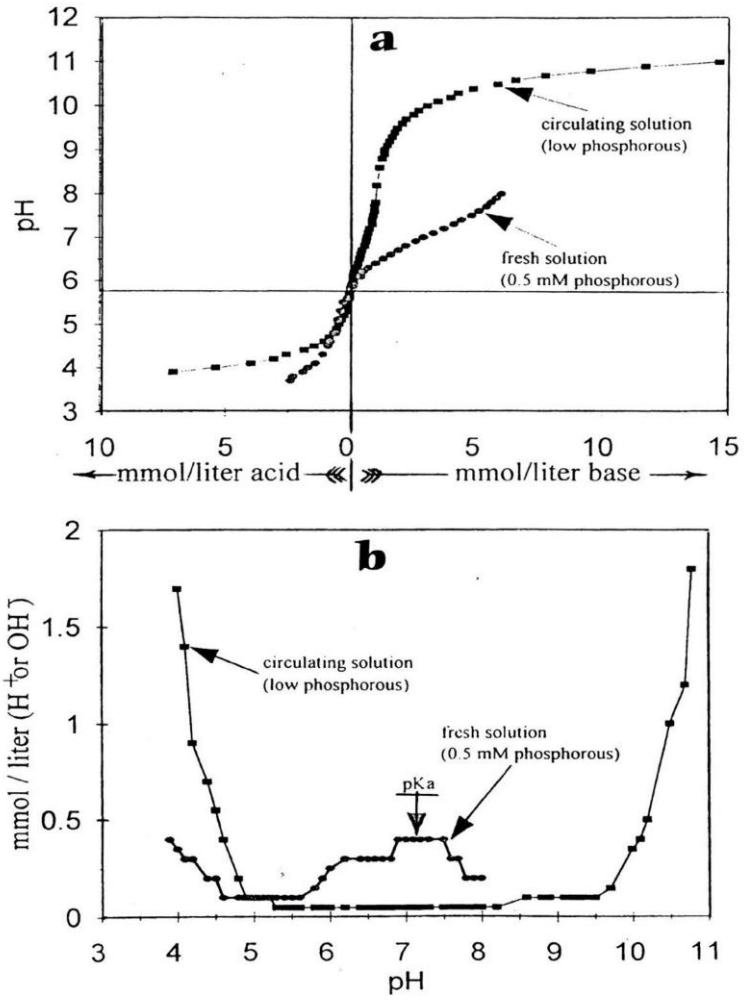
pH monitoring and control.

Is pH control important? Most people assume pH control is essential, but there is considerable misunderstanding about the effect of pH on plant growth. *Plants grow equally well between pH 4 and 7, if nutrients do not become limiting.* This is because the direct effects of pH on root growth are small, the problem is reduced nutrient availability at high and low pH. The recommended pH for hydroponic culture is between 5.5 to 5.8 because overall availability of nutrients is optimized at a slightly acid pH. The availabilities of Mn, Cu, Zn and especially Fe are reduced at higher pH, and there is a small decrease in availability of P, K, Ca, Mg at lower pH. Reduced availability means reduced nutrient uptake, but not necessarily nutrient deficiency.

Unfortunately, hydroponic systems are so poorly buffered that it is difficult to keep the pH between 4 and 7 without automatic pH control. Phosphorous (H_2PO_4 to HPO_4) in solution buffers pH, but if phosphorous is maintained at levels that are adequate to stabilize pH (1 to 10 mM), it becomes toxic to plants. Plants actively absorb phosphorous from solution so a circulating solution, with about 0.05 mM P has much less buffering capacity than the fresh refill solution that is added to replace transpiration losses. Figure

2a is a titration curve of fresh refill solution compared to the recirculating solution. Six mmoles of base were required to raise the pH of fresh solution from 5.8 to 8, but only 1 mmole of base raised the pH of the circulating solution to 8. Figure 2b shows the slopes (derivatives) of the lines in Figure 2a. Figure 2b clearly shows poor buffering of the circulating solution between pH 5 to 9; small amounts of acid or base rapidly change the solution pH. The fresh refill solution is buffered by phosphorous, which has its maximum buffering capacity at pH 7.2. This point is called the pKa of the buffer and it is the point at which half of the phosphorous is in the H_2PO_4 form and half is in the HPO_4 form. In other words, the phosphate ion absorbs and desorbs hydrogen ions to stabilize the pH. Unfortunately, phosphorous is quickly removed from the solution.

We were surprised to find that the circulating solution was better buffered below pH 5 than the fresh solution. The reasons for this are unclear, we cannot identify compounds in the refill solution that provide buffering capacity at pH 4. We are preparing



to repeat these measurements and are investigating this finding.

Figure 2a. Titration curve of fresh refill solution compared to the recirculating solution.
Figure 2b. Buffering of the circulating solution.

How important is maintaining pH 5.8? We control the pH at 4 to study root respiration (to eliminate bicarbonate in solution). We compared growth at pH 4 and pH 5.8 with wheat and were not able to find a significant difference in root growth rate or root metabolism. We now routinely grow wheat crops at pH 4 during the entire life cycle. However, although there is usually a broad optimum pH, it is still best to maintain pH at about 5.8 to optimize nutrient availability. pH levels below 4 may start to reduce root growth, in one study our pH control solenoid failed just after seed germination and the pH went to 2.5 for 48 hours. The roots turned brown and died, but new roots quickly grew back and the plants recovered.

An automated pH control system. Although organic pH buffers can be used to stabilize pH (Bugbee and Salisbury, 1985), in the long run it is better and less expensive to use an automated pH control system that adds acid or base to the solution. These systems require 3 components: a pH electrode, a pH controller, and a solenoid. We have had 7 pH control systems in continuous operation at the Utah State University Crop Physiology Laboratory during the past 8 years. It is useful to pass on our experience with the system components.

pH electrodes. We have not found that expensive electrodes last any longer than cheap electrodes (about 2 years per electrode) so we use cheap electrodes. We currently use a general purpose pH electrode from Omega (model PHE-4201; $49). It appears to be important to avoid rapid flow of solution across the tip of the electrode. Rapid response time is not important and the high flow appears to greatly decrease electrode life and also causes significant calibration drift. We check the calibration of the electrode every 2 to 3 months and adjust it if necessary.

pH controller. When the pH increases to 5.8, a pH controller (model HI981411, $100., Hanna Instruments, Woonsocket, RI, USA, 1-877-694-2662) opens a solenoid that allows nitric acid (HNO_3) to flow into the bulk solution. When nitrate nitrogen is used the solution pH increases as the nitrate is absorbed so only one solenoid is necessary. *The acid inlet should be in close proximity to the tip of the pH electrode so that frequent small additions of acid occur and the bulk solution pH is stable.*

Acid/base solenoid. A peristaltic pump can be used to add acid or base, but a solenoid is less expensive. Proper solenoid selection is important because common solenoids quickly deteriorate from acid corrosion. We use a shielded core acid solenoid from The Automatic Switch Company (ASCO, model D8260G56V or G53V; about $76.). These solenoids do not corrode, but in our experience, about 50% of the diaphragms in the valves failed in less than 2 years in continuous use. The valves are rated for a million cycles so they should last at least 10 years. We are currently working with ASCO to determine the cause of the premature failure. We previously used ASCO valve number D8260G54V, but this valve is not shielded core and corrodes in less than a year, even with 0.1 molar acid. Most plumbing suppliers sell ASCO solenoids, it pays to shop around for good price and quick delivery. Many other companies sell acid resistant valves that may be suitable, but some require a transformer for 24 volt operation.

The total cost (1995) of a pH control system as described above is $350. to $400. depending on availability of system components.

Why add silicon to nutrient solutions?

Although silicon has not been recognized as an essential element for higher plants, its beneficial effects have been shown in many plants. Silicon is abundant in all field grown plants, but it is not present in most hydroponic solutions. Silicon has long been recognized as particularly important to rice growth, but a recent study indicated that it may only be important during pollination in rice (Ma et al. 1989). The beneficial effects of silicon (Si) are twofold: 1) it protects against insect and disease attack (Cherif et al. 1994; Winslow, 1992; Samuels, 1991), and 2) it protects against toxicity of metals (Vlamis and Williams, 1967; Baylis et al. 1994). For these reasons, I recommend adding silicon (about 0.1 mM) to nutrient solutions for all plants unless the added cost outweighs its advantages.

Experiences with Phythium control in hydroponic solution.

The Phythium fungus has been the only serious disease we have encountered in our systems, and disease problems have been relatively rare, particularly when all parts of the system are kept covered to keep dust and dirt particles away from the solution. Every plant pathologist on the planet recommends sanitation as the best control procedure for Phythium, yet many hydroponic systems are not as well sealed as they should be.

Last year, we discovered that Mn deficiency predisposed the plants to Phythium infection. A student worker accidently used $MgCl_2$ in place of $MnCl_2$ for a micronutrient stock solution and we didn't discover the mistake for several months because we were doing short (25 day) studies and there was enough Mn contamination so that no visual symptoms were apparent (growth rate was reduced only about 15% and there was about 10 mg kg^{-1} Mn in the leaf tissue). During this time several of the systems became infected with Phythium. The same systems have never been infected when Mn was adequate. Copper is well known to suppress microbial growth, but increased copper levels are toxic to plants. Manganese and zinc (divalent cations) may have a similar disease suppressive potential, but are less toxic to plants. In the interest of minimizing phythium growth, we have increased solution Mn to a level higher than that required for optimum growth. Careful studies will be required to confirm the beneficial effects of Mn on disease suppression; meanwhile, there is little disadvantage to maintaining manganese, zinc, and copper levels slightly above the minimum required for plant growth.

Designing hydroponic systems: The importance of flow rate.

Most hydroponic systems have inadequate flow rates, which results in reduced oxygen levels at root surfaces. This stresses roots and can increase the incidence of disease. Oxygen is soluble only as a micronutrient, yet its uptake rate is much faster than any other nutrient element.

The nutrient film technique was designed to improve aeration of the nutrient solution because of the thin film of solution, but the slow flow rates in NFT cause channeling of the solution and reduced flow to areas with dense roots. The root surfaces in these areas become anaerobic, which diminishes root respiration, reduces nutrient uptake, increases N losses via denitrification, and makes roots susceptible to infection. The

problems with the nutrient film technique have been discussed by several authors. Bugbee and Salisbury (1989) discuss the importance of flow rate and adequate root-zone oxygen levels.

Isolite: A new substrate for hydroponics.

Many different substrates are used for plant support in hydroponic culture, but one of the unique requirements for research is that the media be easily separated from the roots. Peat, perlite, and vermiculite are good substrates but roots and root hairs grow into these substrates, so they are unsuitable for studies of root size and morphology. Sand can easily be removed from roots, but roots grown in sand are shorter and thicker than hydroponic roots because the sand particles are so dense. We have also found that plant growth in sand is less than in other substrates, presumably because of reduced root growth. Calcined clay (brand names: Turface, Profile, Arcillite) was the medium of choice for research hydroponics for many years because it can easily be removed from roots. Calcined clay, however, has two disadvantages: 1) It is not chemically inert. Different batches supply different amounts of available nutrients and this causes variable results. It can be repeatedly rinsed in nutrient solution to desorb undesirable nutrients, but this adds to its cost. 2) Calcined clay is not a uniform particle size, and the water holding capacity depends on particle size. Not all batches are the same.

We have tested and used an extruded, diatomaceous-earth product called Isolite. Isolite is mined off the coast of Japan where there is a unique diatomaceous-earth deposit mixed with 5% clay. The clay acts as a binder in the extrusion and baking of the diatomaceous-earth. Diatomaceous-earth materials were originally organisms composed primarily of silicon dioxide (SiO_2). Silicon dioxide is physically and chemically inert and these characteristics make it useful for horticultural applications like putting greens and urban trees where the soil is subject to severe compaction. Isolite is available in particle sizes from 1 to 10-mm diameter. Our tests indicate that Isolite is chemically inert and has good water holding characteristics. Its disadvantage is its high cost for small quantities, although it can be reused after rinsing and drying at 80°C.

Microorganisms and organic compounds in the solution: Is filtering useful?

Many people think that filtering the recirculating solution is useful, but we have never filtered our solutions. Our measurements indicate that total organic carbon in the recirculating solution does not exceed 15 mg per liter, even near the end of a 2 month life cycle. About 30% of the organic carbon in the solution is in the chelating agent. Total organic carbon includes the carbon that is in microbial biomass, so it is clear that neither organic compounds nor microorganisms are at high levels in the solution. The solution also appears as clear prior to harvest at 80 days as fresh solution.

Roots leak organic compounds, but there is an equilibrium between microorganisms on root surfaces and the exudates so that compounds are degraded to CO_2 at the root surface. Estimates of the quantity of root exudates vary widely, but there is considerable evidence that carbon efflux increases when plants are stressed (Barber and Gunn, 1974; Smucker, 1984; Haller and Stolp, 1985). Bowen and Rovira (1976) found that roots in solution culture produce smaller quantities of exudate than in soil. Trollenier and Hect-

Buchholz (1984) found that reduced root growth due to inadequate aeration in hydroponic culture was accompanied by a dramatic increase in root microbe population, which they attributed to increased exudation from roots. The bottom line is that healthy roots in a well aerated hydroponic system should not increase the microorganisms or organics in the solution and filtering is thus unnecessary.

Summary: Comments on specific elements.

Nitrogen. Plant requirements for nitrogen are sometimes larger than all of the other elements combined. It can thus be difficult to supply nitrogen in the refill solution without adding excess amounts of other cations. The best solution is to use nitric acid (HNO_3) for pH control. This can supply 50% of the nitrogen needs of the crop without adding excess cations. If extra nitrogen is required, ammonium nitrate can be added to the pH control solution. However, because ammonium decreases the uptake of other cations (K, Ca, Mg, and micronutrients) I do not recommend its use in hydroponic solutions unless extra nitrogen is required by the crop for maximum yields.

Phosphorous and Potassium are rapidly drawn down to µM levels is solution. These low levels do not mean that the plant is starving for these elements, it means that the plant is healthy and actively absorbed these elements from solution.

Calcium requirements are almost 3 times higher for dicots than for monocots (grasses). Calcium is nontoxic, even at high tissue concentrations, but it accumulates in solution if too much is added to the refill solution.

Magnesium is highly mobile and can accumulate to toxic levels in upper leaves if the solution concentration is too high.

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