Application of the “4R” Nutrient Stewardship Concept to Horticultural Crops: Applying Nutrients at the “Right Time”

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SUMMARY. The 4R nutrient stewardship framework presents four concepts to consider when applying fertilizers in a responsible manner; the “right source” of nutrients should be applied at the “right rate” during the “right time” and supplied to the “right place” to ensure their uptake. In this article, we provide ideas to consider when attempting to provide nutrients at the right time. When nutrients are applied at a time when they are not required by the plant, the result can be economic and environmental losses. Oversupply relative to plant demand can result in losses of applied nutrients because of leaching or volatilization. Undersupply relative to demand, especially in the case of phloem-immobile nutrients, may limit plant growth and yield. Several factors interact to affect plant nutrient demand such as growth stage, life history (annual vs. perennial), environmental conditions, and plant health. Techniques such as soil and tissue testing, isotopic labeling, and spectral reflectance have been used with varying degrees of success and expense to measure plant nutrient demand and guide fertilizer decisions. Besides knowledge of plant nutrient demand, efficient nutrient supply also depends on systems that allow precise spatial and temporal delivery of nutrients. Future improvements to the timing of nutrient delivery will depend on improvement in knowledge of plant nutrient demands. For example, targeted gene expression chips show promise for use in rapidly assessing plant status for a broad suite of nutrients. Future developments that allow more precise nutrient delivery or more robust agroecosystems that scavenge available nutrients before they are lost to the environment will also help producers use nutrients more efficiently.

Increased efficiency of fertilization in agriculture is required to mitigate environmental consequences and conserve resources. To reduce fertilizer inputs and maintain productivity, growers must optimize fertilization timing and application rates or use closed irrigation systems. This requires an understanding of plant nutritional needs in relationship to developmental stages.

In a broad sense, nutrient needs of horticultural crops depend on the rate of new biomass production, the nutrient requirements for the production of that new biomass, and the amount of nutrients that may be reallocated from existing plant tissue. Therefore, a thorough understanding

of biomass production of crops throughout the growing season is important in understanding nutrient requirements (Setiyono et al., 2010), but it also is important to take into account that nutrient requirements may change depending on the developmental stage of crops (Malagoli et al., 2005).

Our objective in this article is to describe thought processes that may be followed in attempting to more closely align the timing of nutrient application to plant demand. First, factors that affect timing of plant nutrient demand and methods for measuring demand will be discussed. When fertilizers are timed to meet crop needs, benefits in terms of productivity and profitability may result. Timing of nutrient application also

affects environmental health. Finally, future possibilities to improve the timing of nutrient delivery will be discussed; these depend on both the improvement in knowledge of plant nutrient demands and in the development of precise delivery systems.

Factors that affect timing of plant nutrient demand

Plant nutrient demand integrates several complex and sometimes interacting processes. Nutrient requirements differ for vegetative vs. reproductive organs; further, when reproductive organs develop, they often become a strong sink for nutrients remobilized from vegetative organs. Changes in nutrient requirements depending on crop stage may be especially important in crops with a distinct transition from vegetative to reproductive growth, while it may be less pronounced in crops that are grown solely for their vegetative parts (e.g., leaf vegetables, ornamental foliage plants). The nitrogen (N) demand of poinsettia (*Euphorbia pulcherrima*) varies in relationship to developmental stage. There is a high N requirement during development of lateral branches, but as bracts and flowers develop, N demand is much reduced (Rose et al., 1994). Total N consumption during the growing cycle was reduced by 41% when a variable N rate was applied according to the N accumulation pattern as opposed to applying constant 200 ppm N in the irrigation water (Rose et al., 1994).

Many woody plants have episodic growth patterns in which there are discrete periods of rapid shoot growth (Mattson et al., 2008b). During episodic growth of woody plants, nutrient uptake by the plant often declines (Cabrera et al., 1995; Hershey and Paul, 1983). This appears to be related to carbohydrate allocation during flushes of growth, which is typically directed toward the newly developing shoots and leaves. During the lag phase, carbohydrates are

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
28,3495	oz	g	0.0353
28,350	oz	mg	3.5274×10^{-5}
0.001	ppm	g·L ⁻¹	1000
0.001	ppm	mg·g ⁻¹	1000
1	ppm	mg·L ⁻¹	1

redirected toward stems and roots and N uptake rate increases (Friend et al., 1994; Mattson et al., 2008b). For example, roses (*Rosa* sp.) that are flush harvested so as to produce a new cycle of flower shoot growth exhibit episodic growth patterns, with little biomass accumulation immediately following harvest (Fig. 1). During this period, carbohydrates accumulate within the plant and nitrogen uptake continues at a high rate. As new flower shoots emerge and begin to rapidly grow between days 10 and 20, total nonstructural carbohydrates are directed to these strong sinks and plant carbohydrate content decreases. Because of changing carbohydrate dynamics, the root system declines during this period and consequently, so does plant N uptake (Mattson et al., 2008b). As new flower shoots reach maturity and become net exporters of carbohydrates, the root system recovers as does N uptake.

Nutrient demand also depends on several other parameters including: cultivar (Kelly et al., 2000; Sharifi and Zebarth, 2006; Teo et al., 1992), environmental conditions (Wheeler et al., 1998), the nutritional history of the plant (Mattson and Lieth, 2008a; Subasinghe, 2006; Wheeler et al., 1998), and plant health as affected by abiotic and biotic stresses (Walters and Ayres, 1980). A 4-fold difference in the maximum rate of nitrate (NO_3) accumulation by roots was noted between cultivars of red maple (*Acer rubrum*) seedlings grown

under the same conditions (Kelly et al., 2000). Cultivar choice for field production or selection in plant breeding programs might focus on plants with a high affinity for soil-available nutrients (Sharifi and Zebarth, 2006; Teo et al., 1992) to improve nutrient uptake efficiency. Wheeler et al. (1998) found that growing lettuce plants under varying light levels and NO_3 concentrations affected relative growth rate, which in turn affected plant nutrient demand. Rose plants deprived of N, phosphorus (P), or potassium (K) for up to 20 d exhibited increased absorption of the specific nutrient that was lacking as compared with control plants that had been provided with sufficient nutrients (Mattson and Lieth, 2008a). For N and P, deprived plants showed a 2-fold increase in uptake rates when those nutrients were subsequently introduced as compared with control plants; K deprived plants showed an enhanced affinity for absorbing K at low concentrations.

Measuring timing of nutrient demand

Nutrient needs of crops are commonly determined using soil (or substrate) and tissue analysis. The analyses give clues as to whether fertilizer inputs are required and the rate. Periodic tissue analyses indicate nutrient accumulation patterns within the plant, while nutrient depletion patterns in the soil indicate the degree to which the root zone can store and supply

nutrients for plant uptake. Such information can be used to determine when nutrients are needed by the plant (timing of application) as well as the extent (rate of application) to which nutrients are needed.

There are distinct differences between soil and tissue analysis; soil analysis is best suited to get an idea of the amount of nutrients available for crop uptake, but provides no information about the amount of nutrients in the crop. Tissue analysis can be used to determine the amount of nutrients already taken up by the plants, but is not a good indicator of the amount of nutrients in the root zone that are available for plant uptake. In terms of crop management, the concept of critical nutrient value is sometimes employed. The critical nutrient value is the minimum tissue nutrient concentration (typically from youngest fully expanded leaves) that is required to achieve 90% of optimum growth or yield. As has been long recognized, this method is overly simplistic, and for a given nutrient, the critical nutrient "value" is not really a given value but often a wide range of values that depends on the interactions with several other nutrients in the leaf and other soil and environmental factors (e.g., growing degree days, moisture availability) (Dumenil, 1961). Therefore, commercial nutrient testing laboratories now typically use their accumulated knowledge and data sets to provide guidelines of the acceptable sufficiency range for normal growth/yield (Mills and Jones, 1996).

When the tissue analyzed does not play a large active role in metabolism (e.g., petioles, midrib), tissue analysis can be used to determine nutrient reserves in plants, and thus may be used to detect impending nutrient deficiencies. Petiole and midrib nitrate concentration, in particular, have been reported to be a good indicator of plant N status (Gardner and Roth, 1989; Zebarth et al., 2009). For several crops such as potato (*Solanum tuberosum*), the critical petiole nitrate concentration declines as the crop matures during the growing season (Porter and Sisson, 1991). Ludwick (1990) provides the N, P, and K deficiency and sufficiency levels at different developmental ages for several vegetable and fruit crops based on petiole tissue analysis. Despite their potential, midrib and petiole

Fig. 1. Temporal changes in shoot dry weight, plant nitrogen accumulation, and total plant nonstructural carbohydrate content in 'Kardinal' rose plants during a flower shoot production cycle beginning from harvest of a previous cycle's flower shoots (day 0) until harvest of the current cycle's shoots (day 30). Graph prepared using data from Mattson et al., 2008b; $1 \text{ mg} = 3.5274 \times 10^{-5} \text{ oz}$, $1 \text{ g} = 0.0353 \text{ oz}$.

analyses are not commonly used in most horticultural crops.

Soil analysis provides an index of nutrient levels in the soil, not an absolute amount, since the efficiency of various nutrient extraction methods differs from the efficiency of nutrient uptake by plants. In addition, not all laboratories use the same extraction methods and therefore results may not be comparable from laboratory to laboratory. That also means that crop recommendations need to be based on soil fertility data collected using that same method. In many cases, soil N levels are not measured at all, and soil N availability at the start of the growing season is simply assumed to be zero (Havlin et al., 2005).

Soil/substrate electrical conductivity (EC) is sometimes used as a proxy for fertilizer availability. This approach may have validity when the irrigation water and substrate have a relatively low EC so that perturbations in EC are primarily because of fertilizer inputs. EC monitoring has been widely recommended for use in greenhouse and nursery production (Blythe and Merhaut, 2007; Kang and van Iersel, 2009). The common greenhouse practice of maintaining stable nutrient concentrations in the fertilizer solution does not result in steady-state substrate EC (Kang and van Iersel, 2009). This is due to dynamic changes in evapotranspiration vs. nutrient absorption. Substrate EC measurements can be used to estimate when the fertilizer concentration is too low or high in the substrate. However, increases in substrate EC can also result from the accumulation of ions that are not required in the same proportion as their supply and EC measurements do not provide any information about the availability of specific nutrients but rather indicate the total amount of ions present. In addition, nonessential ions or nutrients that are required in very low amounts, such as sodium (Na) or chloride (Cl), may be present in low quality irrigation water or may be supplied in some fertilizer programs as the counterion in conjunction with a fertilizer ion of interest. While the fertilizer ions are being absorbed, Na, Cl, or other fertilizer ions supplied above the proportion in which they are required may remain behind and accumulate, thereby leading to increased EC (Massa et al., 2008). Therefore, to maintain

a stable level of soil/substrate nutrient availability requires regular changes in fertilization (e.g., Kang and van Iersel, 2009). Similar to measuring root-zone EC, simply measuring nutrient availability in the root zone is not a good indicator of plant demand. Low nutrient levels may simply mean the plant is effectively absorbing the nutrients it needs, and it does not necessarily indicate there is a deficient amount of nutrients. Additional supply may lead to excess accumulation or tissue toxicity in this case (Bugbee, 1995). Although these effects can be seen most easily in recirculating hydroponics (Fig. 2), the same principle applies to other production systems where a near constant supply of low concentration yet adequate nutrients is used (e.g., with use of fertigation or controlled-release fertilizers). When plants are grown hydroponically or in cropping systems where water soluble fertilizers are applied through the irrigation water (fertigation), a mass balance approach to nutrient management may be applied. Nutrients may be applied based directly upon the calculation of the nutrients required to support new biomass growth (Bugbee, 1995). This approach assumes that the desired tissue nutrient concentrations of newly formed tissue are known, and reallocation within the plant is neglected. In addition, an accurate estimate of water

use efficiency (grams of dry matter produced per liter of water used) must be available. The required nutrient solution concentrations can be calculated from:

$$\begin{aligned} \text{Required nutrient concentration in} \\ \text{solution (milligrams per liter or ppm)} \\ = \text{tissue nutrient concentration} \\ \text{(milligrams per gram)} \times \text{water} \\ \text{use efficiency (grams per liter)} \end{aligned}$$

Note that this approach assumes that all applied nutrients are available to the crop; in situations where irrigation is excessive, nutrients are leached below the root zone. Nutrients may also precipitate and form insoluble salts, such as phosphates in low pH soils and many micronutrients at high pH (Havlin et al., 2005). Nutrients may also be converted or incorporated into volatile compounds (as is common with N). Such effects need to be taken into account when supplying nutrients using the mass balance approach.

While plant tissue or soil tests can provide valuable information as to nutrient demand and availability, more comprehensive methods are employed to measure the timing of whole plant nutrient demand. In sequential harvest experiments, representative plants are destructively

Fig. 2. Nutrient concentration in a recirculating hydroponics solution. The initial nutrient solution contained 50 ppm nitrogen (N), 130 ppm potassium (K), and 20 ppm phosphorus (P), but concentrations of these nutrients decreased rapidly during the first 30 d, even though the solution was replenished as needed. Therefore, the low concentrations of N, P, and K do not indicate deficiencies, but instead indicate very effective uptake of these nutrients by the crop. As can be seen from day 30 to 120, concentrations of these nutrients increase every time the solution is replenished but quickly drops back to almost 0 ppm as the crop takes up these nutrients. Sodium (Na), which is not efficiently taken up by the crop, accumulates in the nutrient solution throughout the growing cycle (data courtesy of D.J. Barta and K. Henderson); 1 ppm = 1 mg·L⁻¹.

harvested periodically during a crop production cycle. The plants may be divided into organs of interest, such as woody roots, fine roots, stems, leaves, and reproductive organs. The biomass and nutrient concentration of each set of organs is determined, and by multiplying the two together, one can determine plant and organ-specific nutrient accumulation over time. By looking at organ-specific changes in nutrient concentration over time, the ability of older tissues to serve as sources of nutrients for new tissues can be estimated; this is called the plant functional nutrient storage pool (Rosecrance et al., 1998). Following this approach, Mattson et al. (2008b) estimated that remobilization of stored nutrients supplied $\approx 20\%$ of the N, P, and K required by newly growing flower shoots of flush harvested rose plants. A recent study on apple (*Malus $\times$ domestica*) also demonstrates how useful this approach is for understanding plant nutrient requirements in terms of amount and timing (Cheng and Raba, 2009). Pistachio (*Pistacia vera*) tends to yield heavy loads in alternate years. In the year when trees were not heavily fruiting, N, P, and K storage was 7 $\times$, 14 $\times$, and 2 $\times$ as much, respectively, as the alternate year when the heavy crop load was a strong sink for available nutrients and carbohydrates (Rosecrance et al., 1998).

Stable nutrient isotope labeling can be used to more directly address the source of nutrients for uptake and the dynamics of nutrient allocation and remobilization. Deng et al. (1989) supplied ^{15}N -depleted ammonium sulfate to walnut (*Juglans regia*) trees during the prior year or the current year to determine the contribution of previously stored N on current year growth. N from the previous year accounted for roughly 60% of xylem N during spring growth up to the mature flower stage. By determining the source of nutrients for new plant growth, isotope studies can help to improve the efficiency of fertilizer application. For example, ^{15}N -enriched ammonium nitrate was applied to sweet cherry (*Prunus avium*) during the early spring or summer; by analyzing ^{15}N recovery in whole trees, it was determined that early spring was more efficient than summer applications (66% vs. 37% N recovery) (San-Martino et al., 2010).

Nondestructive imaging techniques have also been used to monitor nutrient status. In this approach, the reflectance of specific wavelengths of light from a leaf/canopy is related to nutrient status. For example, chlorophyll meters assume that most red light is absorbed by chlorophyll, but a greater proportion of near IR light is transmitted (Markwell et al., 1995). This principle is used by nondestructive chlorophyll meters [SPAD 502 (Konica Minolta Sensing, Osaka, Japan), CCM-200 (Opti-Sciences, Hudson, NH)] to estimate leaf chlorophyll concentrations, which can then be used to predict tissue nitrogen concentration. Although Scotford and Miller (2005) note that it is difficult to determine if whole canopy spectral differences in cereal crops are due to N, P, K, or S status, spectral reflectance techniques that employ multiparametric models with multiple wavelengths of light may be able to predict concentration of various nutrients. Menesatti et al. (2010) developed spectral reflectance correlations to tissue N, P, K, calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), and manganese (Mn) concentrations in individual citrus (*Citrus* sp.) leaves. When the suite of nutrients was examined together for an individual leaf, the predictive value of the model [coefficient of correlation (r^2)] ranged from 0.883 for Mg to 0.481 for P. Individual leaf spectral reflectance shows the most promise for estimating nutrient demand, while remote aerial reflectance is better suited to young plants without a fully formed canopy. Sensing of large canopies measures mainly the uppermost leaves, while many deficiencies, especially those of phloem-mobile nutrients, initially cause symptoms in the lower part of the canopy (Scotford and Miller, 2005).

Plasticity in nutrient timing

Often it is not practical, or necessary, to perfectly synchronize nutrient application with crop demand. When crops are not precisely and regularly irrigated, it is most practical to deliver nutrients directly onto or incorporated within the soil. Soils/substrates exhibit varying capacities to retain nutrients in the root zone in a plant available form. In an optimum case the soil would retain the majority of applied nutrients in useable form across the entire crop growing

cycle. In this best-case scenario, fertilizer application would need to take place only once in a crop cycle. Several properties affect the ability of soils to retain nutrients. The direct effect of pH on nutrient solubility/precipitation is also affected by soil pH buffering capacity (BC). The greater a soil's BC, the more resistant it is to rapid fluctuation in pH based on external factors. A soil's BC also determines how often lime applications are needed, and how much lime needs to be applied to maintain soil pH within the optimal range (Havlin et al., 2005). The soil cation exchange capacity (CEC) and anion exchange capacity (AEC) are quantitative measurements that estimate the substrate's ability to attract, retain, and exchange positively or negatively charged ions, respectively. It is desirable for the substrate/soil to have relatively high CEC/AEC so that fertilizer ions are not lost because of leaching below the root zone. In soils, high clay, organic matter content, or both generally increase CEC, while sand has a low CEC (Havlin et al., 2005). The AEC of soils generally is much lower than the CEC and much of the phosphate and nitrate is therefore present in the soil solution rather than bound to soil particles making these nutrients susceptible to leaching (Brady and Weil, 2008). Similarly, nitrate and phosphate are easily leached from soilless substrates (Chen et al., 2001) and need to be resupplied continuously/periodically in the irrigation water to assure an adequate supply for the plants.

Besides the ability of soil to retain and supply nutrients, plants have the ability to reallocate certain nutrients to meet the needs of actively growing parts. N, P, K, sulfur (S), and Mg are readily transported in the phloem and are referred to as phloem mobile (Epstein and Bloom, 2005). Calcium and, in many plants, boron (B) are phloem-immobile; and the remaining nutrients are intermediately mobile (Epstein and Bloom, 2005). Boron is mobile in sorbitol and mannitol-transporting species, which include most tree fruits in the Rosacea family (Brown and Shelp, 1997). Phloem-mobile nutrients do not need to be continuously supplied in the root zone to enter tissues through the xylem; they can be redirected from more mature source tissues to sink tissue. In a plant, this

may take the form of some organs storing nutrients in excess of current needs for later reallocation or reallocation of nutrients from mature/senescing tissues. Cabrera et al. (1996) found that roses starved of N for 4- or 8-d intervals in a hydroponic nutrient solution showed the same yield as plants supplied N continuously. This demonstrated that mature parts of the rose plant could store and resupply enough N for at least 8 d of growth. Interestingly, when plants that were initially deprived of N were resupplied, N uptake increased 2–3 fold vs. control plants (Cabrera et al., 1996). In winter oilseed rape (*Brassica napus*), roughly one-third of the N in pods came from root N uptake, while the remaining two-thirds of the N came from remobilized sources (Malagoli et al., 2005).

Productivity

Although plants have the ability to reallocate nutrients, nutrient deficiencies, even if they are temporary, can reduce crop productivity. By applying nutrients to a crop when needed, an optimal nutrient supply can be assured and reductions in productivity can therefore be minimized. Where fertigation is not used or irrigation is inefficient, it may not be practical to make several fertilizer applications in sync with crop demands over the growing cycle. In this case, each pass through the field with equipment leads to increased labor and energy costs and may lead to soil compaction. Nevertheless, split nutrient applications may be made so as to reduce the potential for loss of nutrients to the environment. The efficacy of split nutrient applications is complex and depends on field soil conditions. For example, Conry (1995) found that the efficacy of split N application on spring-sown barley (*Hordeum vulgare*) depended on field soil conditions; it improved yield on light gravelly soil and did not affect yield on heavy textured soils.

Root activity may be reduced during periods of heavy vegetative or reproductive growth (Mattson et al., 2008b), as well as after the start of crop senescence (Malagoli et al., 2005). Crops may still be responsive to nutrient applications during these periods, but soil applications may not be effective. Thus, during periods of low root activity, foliar nutrient applications can be a viable alternative. Foliar sprays of micronutrients are commonly applied

in orchard crops, but even foliar applications of macronutrients (N, K) can be effective (Weinbaum et al., 2002). It appears that the uptake efficiency of foliar applied nitrogen is dependent on the background tree N status in apple (Cheng et al., 2002) and hydrangea (*Hydrangea macrophylla*) (Bi and Scagel, 2008).

Environmental health

Timing fertilizer application is also important to reduce losses to the external environment. By applying nutrients at the right time and matching supply and demand, crop nutrient uptake efficiency is high. When nutrient supply is higher than demand, losses may occur due to physical processes (leaching, runoff, and volatilization), chemical processes (precipitation, exchange), or microbial transformations (e.g., denitrification) (Shaviv and Mikkelsen, 1993). Besides the economic consequences, lost nutrients may cause environmental damage such as eutrophication from N and P runoff, ammonia volatilization which can result in acid rain, or emission of nitrous oxides which is an ozone-depleting substance and greenhouse gas (Shaviv and Mikkelsen, 1993). Nitrate can also render drinking water unsafe. The rate at which these processes occur depend on a wide range of field and environmental conditions such as soil temperature, moisture, and pH (Havlin et al., 2005). Because of these various losses of nutrients to the environment in open-loop agriculture systems, the most effective way to enhance nutrient efficiency is to match supply to the temporal demands of the crop (Zebarth et al., 2009). Where this is difficult or economically impractical, the use of enhanced efficiency fertilizers such as controlled- or slow-release fertilizer products should be considered (Obreza and Sartain, 2010). Similarly, application of nutrients in the form of organic matter (from animal manures or crop residues) can reduce nutrient losses because a portion of the nutrients contained is stabilized and is released over time through mineralization. However, the release rate of nutrients from organic sources depends on environmental and soil conditions and is difficult to predict. Closed loop agriculture (such as recirculating hydroponics) or the use of water detention and

recycling ponds can improve nutrient retention (Shukla et al., 2010) but will not prevent all nutrient losses (such as from volatilization or precipitation).

Profitability

When nutrient supply is not sufficient to meet demand, plant growth and ultimately quality and yield may be reduced. Attempts to alleviate nutrient deficiencies after they have impacted the plant can be expensive as they may involve additional field applications or more costly foliar applied materials. For some important agro-nomic crops, a well-developed set of protocols can be followed to make fertilizer (typically N) applications based on informed knowledge of soil nutrient availability and crop demand. In eastern Canada, a N credit system has been developed for corn (*Zea mays*) production to account for N that may already be in the soil pre-planting because of preceding legume crops, manure addition, or soil N mineralization (Zebarth et al., 2009). Similarly, pre-planting or pre-sidedress soil nitrate tests may be conducted to more precisely determine the need for additional N inputs.

Nutrient applications in excess of plant demand also represent economic losses. Where detailed record-keeping has taken place or sophisticated sensing equipment is available, fertilizer can be applied in a site-specific manner, i.e., applied in variable amounts to account for within-field variability instead of applying uniformly across a field (Bongiovanni and Lowenberg-DeBoer, 2004). Schumann (2010) reported on the use of sensing technology in citrus production in which fertilizer was applied to a field on a tree-by-tree basis based on presence and size of trees. The system was useful because diseases losses of trees caused spatial heterogeneity in the field.

Future improvements

Improvements in supplying nutrients in relationship to plant demand will rely on an increased scientific understanding and methodology of crop nutrient demand as well as improved delivery and retention systems. It is not always practical, or needed, to precisely understand the timing of plant nutrient demands. Where a multitude of diverse species are grown in the same operation such as the majority of

ornamental greenhouse and nursery operations in the United States, it may be impossible to determine nutrient demands for the hundreds of species and cultivars that are grown. In these diverse systems, species-specific nutrient delivery typically does not occur (Yeager et al., 2010). Therefore, the most pragmatic approach may be to focus on nutrient forms with a reduced risk of loss to the environment such as controlled-release fertilizers or other enhanced efficiency fertilizers (Obreza and Sartain, 2010; Shaviv and Mikkelsen, 1993), improved delivery systems such as microirrigation and moisture sensing, or improved nutrient capture and reuse such as detention and recycling basins employed by many nurseries (Mangiafico et al., 2008).

In regard to technologies to detect plant nutrient status, methodologies such as spectral reflectance may be combined with remote sensing or use of global positioning system (GPS) and geographic information system (GIS) to detect patterns on a large scale and to apply nutrients precisely (e.g., precision agriculture) (Bongiovanni and Lowenberg-DeBoer, 2004). Barriers to such implementation include the necessity of cultivar specific calibration for spectral reflectance technology (Zebarth et al., 2009) as well as a database on plant yield/nutrient demands in relationship to growth stage and local soil nutrient availability (Schumann, 2010).

Advances in molecular biology may be the next frontier for rapidly detecting nutrient needs. When tomato (*Solanum lycopersicum*) seedlings were exposed to phosphorus-, potassium-, or iron-deficient conditions, differential expression of specific regulatory and transporter genes could be detected within 1 h using a microarray (Wang et al., 2002). Similarly, microRNAs (miRNA) can effect posttranslational gene expression by silencing targeted genes. Several miRNAs were found to respond to nutrient stress (deficiency or toxicity) in common bean (*Phaseolus vulgaris*) (Valdés-López et al., 2010). Future research might determine a broad suite of genes known to be involved in nutrient signaling and absorption. Such a microarray might eventually allow for rapid and inexpensive determination of status (sufficient, deficient, toxic) of all relevant nutrients in a plant. Similar to other techniques (reflectance, tissue analysis), significant research would be

needed to identify these genes and relate and calibrate their expression to specific cultivars and field conditions. In addition, molecular techniques could be used in breeding programs focused on more efficient root uptake of nutrients. The vast majority of breeding has focused on improved yields, quality of the harvested products, or both. Although breeding efforts have resulted in more drought, heat, or cold tolerant cultivars of many crops, nutrient uptake has received little attention. Since the uptake mechanisms of many nutrients has been elucidated in detail and genes encoding nutrient transporters have been identified (e.g., Feng et al., 2011), this knowledge could be applied in breeding programs. For example, if the expression of genes encoding high-affinity transporters can be increased, this perhaps could increase nutrient uptake efficiency.

Besides potential high-tech approaches, a return to more natural approaches may also be beneficial, such as the use of organic residues to supply slow release nutrients as they are mineralized, and cover crops to retain nutrients that would be otherwise leached or volatilized. Finally, the traditional paradigm has been supplying nutrients to meet plant demands, perhaps this should be shifted to adjusting crops and agroecosystems to be tuned to nutrient supply. An in-depth understanding of mineralization of nutrients in cover crops, crop residues, or both could be used to match those mineralization patterns to the nutrient requirements of various crops. Matching supply and demand in such a way results in more sustainable production systems and may be especially beneficial in organic production.

Finally, efficient nutrient use not only depends on the correct timing of nutrient applications but also on using the optimal amount and form of fertilizers and applying those in the optimal location. Those topics are discussed in companion papers from this workshop (Bryla, 2011; Gaskell and Hartz, 2011; Mikkelsen, 2011; Santos, 2011).

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