Application of the "4R" Nutrient Stewardship Concept to Horticultural Crops: Selecting the "Right" Nutrient Source

Mark Gaskell[1,3] and Tim Hartz[2]

ADDITIONAL INDEX WORDS. **fertilizer source, fertilizer use efficiency, nutrient use**

SUMMARY. **Nutrient management practices must be tailored to the crop, environment, and production system if nutrient efficiency and environmental water quality protection are to be achieved. This requires consideration of fertilizer choice, placement, application rate, and timing. These factors have been characterized as the "4Rs" of nutrient stewardship—right material, right placement, right rate, and right timing. The factors affecting the choice of fertilizer material have been described previously for agronomic crops, and include plant nutritional requirements, soil conditions, fertilizer delivery issues, environmental risks, product price, and economic constraints. Although those factors are applicable to all crops, the unique features of intensive horticultural production systems affect their interactions. This article discusses fertilizer choice as it affects productivity, profitability, sustainability, and environmental impact of intensive horticultural crop production. Diverse fertilizer materials are available for specialized application to provide nitrogen, phosphorus, potassium, and other plant nutrients for different horticultural needs. These fertilizer sources can be formulated as dry or liquid blends, but increasingly higher solubility materials are used to target plant growth needs even in field operations. Composts can have useful applications—particularly for certified organic production—but their high cost, bulk, and relatively low efficiency limit their use. Profitability can be affected by fertilizer cost—typically a relative small percentage of overall costs in intensive production systems—and the improved efficiency of these specialized materials often improves profitability. There are also sustainability issues with the manufacture, transport, and efficient use of different fertilizer sources. Such factors as soil chemical reaction changes, effects on soil salinity, and loss of organic matter also can adversely affect sustainability, but systems are available to maintain soil quality while using more efficient fertilizer sources.**

The multiple factors affecting the choice of fertilizer material source can include plant nutritional requirements, soil and climate conditions, fertilizer delivery issues, environmental risks, and economic constraints (Mikkelsen et al., 2009). Intensive horticultural production systems involve a wide range of management options that affect interactions among these factors. Nitrogen (N) is available in the form of urea, ammonium (NH_4), or nitrate (NO_3), or as combinations of these forms; anhydrous ammonia is seldom used on horticultural crops. A large body of hydroponic research has documented a general improvement in plant growth when nutrient solutions contain more NO_3-N than NH_4-N; most hydroponic production is now accomplished with nutrient solutions containing predominately or solely NO_3-N. Another reason for favoring NO_3-N in nutrient solutions for the production of fruiting crops [tomato (*Solanum lycopersicum*), pepper (*Capsicum annuum*), etc.] is the suppression of blossom end rot (BER); NH_4-N can reduce calcium (Ca) uptake and induce the disorder (Bar-Tal et al., 2001).

In field production, the choice of N form is more complicated. Urea and NH_4 fertilizers are readily converted to NO_3 through hydrolysis and nitrification reactions, at least at soil temperatures above 68 °F (Havlin et al., 2005). Regardless of fertilizer N form applied, NO_3-N concentration usually exceeds that of NH_4-N in well aerated, temperate soils (often by an order of magnitude), and NO_3-N represents the majority of crop N uptake (Haynes, 1986). In colder soils nitrification is slower, and NO_3-form fertilizer may provide more rapid plant N uptake. Although the use of NO_3-N during fruit development is a common recommendation for field-grown tomato and pepper to prevent BER, documentation linking NH_4-N application and BER severity in field production is less compelling than in greenhouse culture.

The various forms of ammonium phosphates comprise the majority of phosphorus (P) fertilizers used in horticultural production. High purity mono and diammonium phosphate and potassium mono and diphosphate are commonly used for nutrient solutions and specialty fertilizers for the greenhouse and ornamental industries. Ammonium phosphates or polyphosphates dominate the market for soil-applied P. Phosphoric acid also has specialty uses in both greenhouse and field production; for example, it can be injected into drip irrigation systems where other P sources may form precipitates with Ca in the irrigation water. Since all these fertilizers supply P in PO_4^- form, the choice of product for a particular purpose is based on factors such as cost, solubility, companion ions supplied, or effect on soil or solution pH.

Potassium chloride and potassium sulfate constitute the overwhelming majority of potassium (K) fertilizer use on horticultural crops, with potassium nitrate and potassium thiosulfate used more sparingly. Potassium chloride, the least expensive K source, is avoided by growers of chloride-sensitive crops [e.g., strawberry (*Fragaria ×ananassa*)], some tree fruits, and ornamentals (Maas, 1984). Potassium thiosulfate offers higher solubility than potassium sulfate and an acid soil reaction, but at considerably higher price. Potassium carbonate has a basic soil reaction, but also at a higher price.

This paper was part of the workshop "Examining the 4R Concept of Nutrient Management: Right Source, Right Rate, Right Time, Right Place" held on 4 Aug. 2010 at the ASHS Conference, Palm Desert, CA, sponsored by the Plant Nutrient Management (PNM) Working Group.

[1]Farm Advisor, University of California Cooperative Extension, 2156 Sierra Way, San Luis Obispo, CA 93401

[2]Extension Vegetable Specialist, Department of Plant Sciences, University of California, Davis, CA 95616-8780

[3]Corresponding author. E-mail: mlgaskell@ucdavis.edu.

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
1.1209	lb/acre	$kg \cdot ha^{-1}$	0.8922
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

Potassium nitrate is a staple of nutrient solutions and is valued as an N and K source suitable for fertigation.

Advanced technology is employed to manipulate these basic materials to produce a myriad of specialized fertilizer products, to enhance their ease of handling and application, and to modify their nutrient availability characteristics. High purity soluble complete fertilizer blends are a staple of the greenhouse industry and are increasingly used in open field or protected culture (high tunnels, shade houses, etc.) where drip irrigation is used. Macronutrient blends are widely available in both dry and liquid form. A number of chemical treatments to enhance nutrient availability are available. These include urease inhibitors to reduce ammonia volatilization loss from urea and nitrification inhibitors to delay nitrification (and therefore leaching potential) from urea or NH_4 fertilizers. A more recent development is blending dicarboxylic polymers with P fertilizer to minimize P precipitation with soil Ca and aluminum (Al) (Tindall, 2007).

The most important technology to modify fertilizer nutrient availability is chemical coating to create extended nutrient release. Controlled-release fertilizers (CRF) have been used in horticultural production for decades. Although a number of coating technologies have been developed, polymer coating dominates the market today; the chemical composition and coating thickness control nutrient release. A wide range of industry-specific products have been developed. The container nursery production and landscape maintenance industries heavily rely on CRF technology. Because of much higher cost per unit of nutrient than conventional fertilizers, to date the use of CRF in open field production has been limited; strawberry production is the only segment of the industry in which CRF use is routine. However, increasing concern regarding nutrient loss from agriculture and development of less expensive CRF products may stimulate CRF use.

Organic production methods rely primarily on cover cropping and the application of manure composts and other animal byproducts to provide nutrients (Gaskell et al., 2007). Legume cover crops typically take up or fix between 100 and 200 lb/acre N. Soil conditions, cover crop carbon: nitrogen (C:N) ratio and degree of lignification at the time of soil incorporation govern the N mineralization rate of the residue. Residues with C:N ratios >20 provide little N availability, while higher N content residue may mineralize up to half its N content during the cropping season following incorporation.

Composts have relatively slow N mineralization rates and typically provide less than 20% of N content in the season after field application; compost with <2% N content will be an insignificant source of N (Hartz et al., 2000). Composts are excellent sources of P and K for organic production (Nelson and Mikkelsen, 2008). The K content is equally available, and P content at least 70% as available, as inorganic fertilizer sources. High N content animal byproducts (fishery wastes, blood and feather meal, seabird guano, etc.) mineralize rapidly in warm, moist soil, with the majority of N available for plant uptake within several weeks of soil application. However, the high cost of these materials limits their use.

Profitability

Fertilizer generally constitutes a smaller proportion of production costs for horticultural crops than for agronomic crops. For example, in California lettuce (*Lactuca sativa*) and processing tomato production, fertilizer typically represents ≈10% of total preharvest cost, whereas for corn (*Zea mays*) or wheat (*Triticum* sp.) production fertilizer is ≈20% of preharvest cost. In greenhouse or tunnel production systems, fertilizer cost may be even a smaller percentage of overall costs. Since marketability and value often hinge on meeting exacting standards for size and cosmetic appeal, growers are hesitant to change their established fertilizer choices to marginally reduce cost. That is not to say that growers are indifferent to fertilizer costs; the worldwide escalation of fertilizer prices in 2008 induced many growers to reconsider their fertilizer programs, both the materials used, and application rates. Rather, fertilizer choice for horticultural crop growers is generally more dependent on the effect on crop performance than on price. Even small improvements in crop yield, timing, or quality justify the use of more expensive fertilizer products.

Fertilizer cost is only one aspect of profitability. Compatibility with other elements of the production system is critical, and it plays an important role in fertilizer choice. Reducing labor cost for fertilizer application is one factor favoring the use of CRF in container ornamental production. Where fertigation is used in microirrigation systems, certain fertilizers present less chance of chemical precipitation that could degrade the irrigation system. Many growers using fertigation prefer liquid fertilizer formulations for convenience and enhanced precision, since fertilizer can be split into multiple events, reducing the risk of leaching between applications. Where dry products are used, those that solubilize quickly and have minimal impurities are favored.

Cropping system sustainability

There are several ways in which fertilizer choice can affect the sustainability of a cropping system. One is the environmental impact of manufacturing and transport. Fertilizer production is an energy-intensive business. Ammonia manufactured by the Haber-Bosch process using natural gas is the feedstock for most inorganic N fertilizers. Mining, refining, and transport of P and K fertilizers also require substantial energy and have other potential environmental impacts as well. However, there are no clear criteria on which to rank the manufacturing footprint of common macronutrient fertilizers.

Another sustainability issue is soil degradation. Many inorganic fertilizers, including all urea and NH_4-containing products, reduce soil pH. In alkaline, calcareous soil this may be beneficial, at least in the short term, but in much of the country the use of acid-forming fertilizers can increase the requirement for liming. Fertilizers can also contribute substantially to soil salinity, and their use can affect leaching requirements. Selecting fertilizer materials on the basis of salt index may be a valid approach for growers of salt-sensitive crops or for those dealing with saline soils or irrigation water. N and K fertilizers generally have much higher salt indices than P sources and present a greater danger of plant toxicity when placed in close proximity to germinating seeds (Havlin et al., 2005).

The argument has been made that the use of high analysis, inorganic fertilizers enables an intensive production system that discourages soil building practices and results in diminished soil quality and environmental degradation (Van Loon et al., 2005). Indeed, protecting soil quality is one of the main rationales for organic production. Organic practices such as cover cropping and application of organic soil amendments to augment fertility will generally increase soil organic C, microbial activity, biological diversity, and aggregate stability (Mitchell et al., 2000). However, it is not the use of inorganic fertilizers per se that results in a decline in these soil quality parameters but rather the other features of intensive field production: intensive tillage, limited soil C input, and in some cases chemical fumigation. Combining soil building practices with efficient fertilizer use can safeguard crop productivity while maintaining soil quality.

Environmental health

Soil fertility management can have profound impact on the environment. Air quality can be diminished by the emission of ammonia and nitrous oxide from agricultural fields. Surface application of urea can result in significant ammonia volatilization; subsurface application or delivery in irrigation water can minimize this problem. The emission of nitrous oxide, a potent greenhouse gas, is stimulated by high soil NO_3-N concentration and saturated soil conditions. Since NO_3-N is usually the dominant form of soil mineral N regardless of fertilizer N form, control of nitrous oxide emission is less an issue of fertilizer choice than of fertilizer rate and irrigation management.

Water quality degradation often results from intensive horticultural production. Across the country, horticultural crop growers face increasing regulatory pressure to curb N and P loss from their operations (Majsztrik et al., 2010). Elevated levels of NO_3-N in groundwater and soluble N and P in surface water are geographically linked with centers of concentrated horticultural production. Although the ultimate solution to this problem will require changes in all aspects of production, fertilizer selection will be part of that process. The advantage of CRF is maximized in production systems in which leaching potential is significant. This is the case with container production of ornamentals. Most field studies documenting the value of CRF were conducted on light-textured soils and in environments receiving significant in-season precipitation; potato (*Solanum tuberosum*) production in Florida (Hutchinson, 2005) and Minnesota (Zvomuya and Rosen, 2001) fit this profile. Likewise, the value of CRF for citrus (*Citrus* sp.) production in Florida (Obreza and Rouse, 2006; Paramasivam et al., 2001) has been attributed in large part to reduced N leaching potential in the sandy soils and high rainfall characteristic of the production area. However, in semiarid areas and on heavier soils, CRF has not consistently improved crop production or limited nutrient loss (Hartz and Smith, 2009). In such situations, fertilizer rate, irrigation management, and crop rotation are more important than fertilizer selection in minimizing environmental water quality impact.

Selection of fertilizer products containing the correct balance of nutrients to meet field-specific needs can reduce nutrient loss to the environment. Out of habit or convenience, growers may apply a fertilizer containing nutrients that are not needed, or which do not contain the ratio of nutrients appropriate to a particular field situation. Hartz et al. (2007) reported that California lettuce growers routinely applied preplant P fertilization, even in fields far above the agronomic soil P threshold. Similarly, CA strawberry growers usually apply CRF before planting, nearly always using a product containing N, P, and K. However, a 2009–10 field survey showed that the majority of fields had elevated soil P and K availability and did not require fertilization with those elements (T.K. Hartz, M. Bolda, and M. Gaskell, unpublished data). This is not strictly a problem with conventional farming practices. Animal manures typically contain a higher P:N ratio than plant tissue. Organic growers who rely on composted manure to provide plant-available N can increase soil P to an environmentally problematic level.

Suggestions for future improvement

Improved nutrient stewardship will be required to meet the challenges of increasing horticultural crop production to accommodate an expanding population while safeguarding soil, air, and water resources. Improvement of nitrification inhibition technology could improve N efficiency; most of the currently available inhibitors have serious limitations. For example, 3,4-dimethylpyrazole phosphate (Wu et al., 2007) is not registered for use in the United States. Dicyandiamide (Fry et al., 1989) has sufficiently high solubility that its effectiveness is limited under leaching conditions. Continued development of fertilizer coating technology to improve the synchrony of nutrient release and crop uptake and to reduce the product cost could stimulate greater use of CRF in field production for a range of horticultural crops. The continued worldwide expansion of microirrigation offers the potential to improve both irrigation and fertilizer use efficiency. This irrigation revolution should stimulate the development of new fertilizer products suitable for fertigation and possessing enhanced availability characteristics.

Literature cited

Bar-Tal, A., B. Aloni, L. Karni, J. Oserovitz, A. Hazan, M. Itach, S. Grantz, A. Avidan, I. Posalski, N. Tratkovski, and R. Rosenberg. 2001. Nitrogen nutrition of greenhouse pepper. I. Effects of nitrogen concentration and NO_3:NH_4 ratio on yield, fruit shape, and the incidence of blossom-end rot in relation to plant mineral composition. HortScience 36:1244–1251.

Fry, W.W., D.A. Graetz, S.J. Locascio, D.W. Reeves, and J.T. Touchton. 1989. Dicyandiamide as a nitrification inhibitor in crop production in the southeastern USA. Commun. Soil Sci. Plant Anal. 20:1969–1999.

Gaskell, M., R. Smith, J. Mitchell, S. Koike, C. Fouche, T. Hartz, W. Horwath, and L. Jackson. 2007. Soil fertility management for organic crops. Univ. of California Publ. 7249.

Hartz, T.K., P.R. Johnstone, E. Williams, and R.F. Smith. 2007. Establishing lettuce leaf nutrient optimum ranges through DRIS analysis. HortScience 42:143–146.

Hartz, T.K., J.P. Mitchell, and C. Giannini. 2000. Nitrogen and carbon mineralization dynamics of manures and composts. HortScience 35:209–212.

Hartz, T.K. and R.F. Smith. 2009. Controlled-release fertilizer for vegetable production: The California experience. HortTechnology 19:20–22.

Havlin, J.L., J.D. Beaton, S.L. Tisdale, and W.L. Nelson. 2005. Soil fertility and fertilizers. Pearson Prentice Hall, Upper Saddle River, NJ.

Haynes, R.J. 1986. Uptake and assimilation of mineral nitrogen by plants, p. 303–378.

In: B.R. Christie (ed.). Mineral nitrogen in the plant soil system. Academic Press, Orlando, FL.

Hutchinson, C.M. 2005. Influence of a controlled-release nitrogen fertilizer program on potato (*Solanum tuberosum* L.) tuber yield and quality. Acta Hort. 684:99–102.

Maas, E.V. 1984. Salt tolerance in plants, p. 57–75. In: B.R. Christie (ed.). Handbook of plant science in agriculture. CRC Press, Boca Raton, FL.

Majsztrik, J., A.G. Ristvey, and J.D. Lea-Cox. 2010. Water and nutrient management in the production of container-grown ornamentals. Hort. Rev. 38:253–297.

Mikkelsen, R., G. Schwab, and G. Randall. 2009. The four fertilizer rights: Selecting the right source. Crops Soils 42(3): 28–31.

Mitchell, J., M. Gaskell, R. Smith, C. Fouche, and S. Koike. 2000. Soil management and soil quality for organic crops. Univ. of California Publ. 7248.

Nelson, N. and R. Mikkelsen. 2008. Meeting the phosphorus requirement on organic farms. Better Crops 92(1):12–14.

Obreza, T.A. and R.E. Rouse. 2006. Long-term response of 'Hamlin' orange trees to controlled-release nitrogen fertilizer. HortScience 41:423–426.

Paramasivam, S., A.K. Alva, A. Fares, and K.S. Sajwan. 2001. Estimation of nitrate leaching in an Entisol under optimum citrus production. Soil Sci. Soc. Amer. J. 65:914–921.

Tindall, T.A. 2007. Recent advances in P fertilizer technologies—Polymer coatings and available technology. Proc. Western Nutrient Mgt. Conf. 7:106–110.

Van Loon, G.W., S.G. Patil, and L.B. Hugar. 2005. Agricultural sustainability: Strategies for assessment. Sage Publications, London.

Wu, S., L. Wu, Q. Shi, Z. Wang, X. Chen, and Y. Li. 2007. Effects of a new nitrification inhibitor 3, 4-dimethylpyrazole phosphate (DMPP) on nitrate and potassium leaching in two soils. J. Environ. Sci. (China) 19:841–847.

Zvomuya, F. and C.J. Rosen. 2001. Evaluation of polyolefin-coated urea for potato production on a sandy soil. HortScience 36:1057–1060.