Workshop

The “4R” Nutrient Stewardship Framework for Horticulture

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Additional index words. **right source, right rate, right time, right place, integrated plant nutrient management, performance indicator, nutrient use efficiency, fertilizer**

Summary. **Improving plant nutrient management is important for environmental, economic, and social considerations. The adoption of the “4R” nutrient stewardship framework (right source, right rate, right time, and right place) provides a basis for examination of the underlying scientific principles behind fertilizer use. These 4R concepts are based in global principles related to chemistry, biology, physics, and economics, but the selection of specific practices is adjusted to individual field conditions, relying on local expertise and data. Various stakeholders have input in the selection of nutrient management practices, and their objectives may not always coincide. The development of performance indicators to measure the progress made by adoption of the 4R management techniques needs to be decided by stakeholders.**

Nutrient management for horticultural crops is complex, requiring the integration of biological, chemical, and economic factors. The global food requirement continues to grow, and fertilizer is presently estimated to be responsible for at least half of the current food supply (Erisman et al., 2008; Stewart et al., 2005). Responsible nutrient management and sustainable horticultural production must include consideration of environmental, economical, and social components (Fig. 1). While successful production systems address all three of these components, the focus and attention that each individual component receives depends on stakeholder expectations and may change with improvements in knowledge and practice.

Appropriate management of plant nutrients varies widely depending on the specific objectives of the stakeholders. These groups may include farmers, local organizations, government regulators, and the general public. All of these groups have an interest in food production and can give input on how plant nutrients are used. There is considerable effort to develop “best” management practices (BMP), but there is not always consensus on what is best and these different groups often have competing interests. Management decisions on what is best or right are not only based on scientific data, but include ethical considerations and value judgments that change depending on the objectives of the stakeholders.

With varied expectations of what nutrient management means to different stakeholders, the path to achieve economic, environment, and social goals may sometimes be in conflict. For example, in some areas, environmental targets may be the highest priority. In other regions, specific social goals or economic objectives may be most important. Additionally, these priorities continue to change as society, technology, and scientific knowledge advances.

General fertilizer recommendations are a useful start to guide nutrient application, but they often fail to consider complex crop rotations common in horticultural production. They also cannot predict differences that regularly occur in external factors, such as rainfall, pest pressures, and temperature. Additionally, forecasts of global climate change predict that the occurrence of erratic weather patterns will become more common, requiring additional flexibility to respond to changing conditions.

Plant nutrient management is fundamental to many current global sustainability issues. The direct link of soil management to food production must be addressed to achieve acceptable progress on these challenges. As a comprehensive framework to guide nutrient management decisions, it is universally recognized that it is in our best interests to use the right source of nutrients, in the right rate, at the right time, and in the right place—termed the four rights or 4R. A systematic review of these four factors will greatly assist in selecting the best combination of on-farm practices to meet the desired outcomes.

What are the performance goals?

A method for tracking improvement in nutrient use and successful adoption of management practices requires selection of performance indicators and deciding what to measure. The most common measurements have traditionally been profitability

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	$\text{kg}\cdot\text{ha}^{-1}$	0.8922

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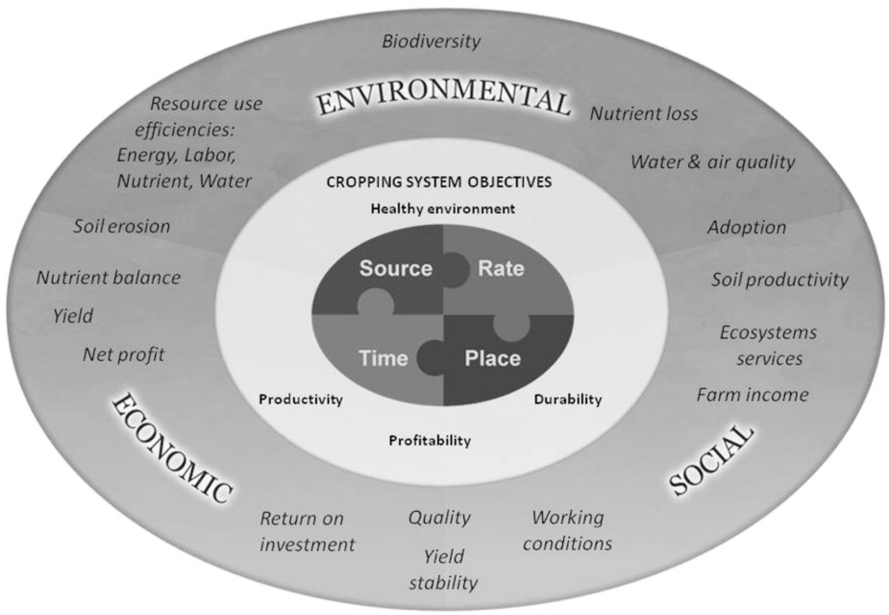

Fig. 1. Conceptual illustration of the 4R framework for fertilizer best management practices. Selecting the right nutrient source, applied at the right rate, right time, and right place, helps to achieve crop management objectives of productivity, profitability, sustainability, and environmental protection. These contribute to larger social, economic, and ecological objectives set by the stakeholders (Bruulsema et al., 2009).

and productivity, but sustainability and environmental health must also be addressed (Fig. 1). The impact of BMP adoption also depends on the scale being considered. All stakeholders need to contribute to the discussion of performance indicators to achieve a satisfactory outcome. Some of examples of performance indicators (Table 1) are given by Bruulsema et al. (2008).

To integrate various sustainability goals with nutrient management decisions in the field, many factors need to be considered. Some of these include:

Productivity. The primary measure of most cropping systems is the yield per unit land area per unit time. Productivity for many horticultural crops also includes measures of harvest quality. Nutrient management decisions will have a major impact on both of these parameters. A number of economic and biological efficiency factors can also be included in measuring productivity (such as return on investment or the flow of energy). Nutrient use efficiency is a goal that is commonly discussed, but this term has many different definitions and they vary greatly with the temporal consideration. Examples of these definitions are given in Table 2 to illustrate the need for precise terminology.

Profitability. This is determined by the difference between the cost of production and the value of the final product. It is measured in the net profit per unit area per unit of time. Profitability considers the economic efficiency of the production practices—the yield increase that results from each cropping practice decision.

Cropping system sustainability. This refers to the long-term impact of management decisions on natural resources. A durable system is one where the soil, water, and air resources are not degraded over time. Many management decisions have an impact that extends beyond the current season.

Environmental health. Crop production can have direct and indirect impacts on soil, water, and air quality. These impacts can be primarily local in nature or may involve global processes. Management decisions that improve nutrient use efficiency will generally lead to minimizing losses although there may be competing interests that lead to different environmental goals. For example, promoting denitrification to minimize nitrate movement to water can pose a conflict between the goals of reducing greenhouse gases and water quality targets.

The 4Rs

The 4R nutrient stewardship framework is based on universal scientific principles that can serve to guide the selection of management practices that support the goals of sustainable development (Fig. 1). Decisions regarding fertilizer source, rate, time, and place are all interlinked with each other and cannot be separated. Regulatory approaches that address only a reduction in nutrient application rate are overly simplistic and often fail to accomplish their overall objectives.

The 4R principles are science based and apply to both global and field-specific conditions. However, the choice of individual practices will vary depending on climate, soils, available technology, local knowledge, and the cultural setting, but this framework provides a systematic selection of the best mix of practices to be implemented.

Right source. This decision matches a specific nutrient source or fertilizer material with the crop needs and soil properties. Proper fertilizer selection insures that appropriate nutrients are applied to individual fields to meet specific objectives and unnecessary fertilization is avoided (Mikkelsen et al., 2009). The selection of the nutrient source is also governed by factors such as product availability in a farmer's locale, application equipment, economics, and plant requirements. Nutrient interactions and material compatibility need to be considered too. A review of fundamental properties of the most commonly used fertilizers is available from the International Plant Nutrition Institute (IPNI, 2011).

The proper use of enhanced efficiency fertilizers (those that increase nutrient availability/uptake and decrease losses to the environment compared with a reference fertilizer) can offer a variety of benefits in some horticultural situations, including increased yields, reduced fertilization rates, and multiple environmental benefits. A comprehensive summary of enhanced efficiency fertilizers and their appropriate use has been recently published (Trenkel, 2010).

Right rate. The concept of applying the right rate is simple, that is to provide just enough nutrients to meet production and quality goals, but no more. In practice, these are not straightforward decisions (Phillips et al., 2009). In addition to preplant

Table 1. Examples of performance indicators for fertilizer best management practices related to crop management objectives (adapted from Bruulsema et al., 2008).

Management objective	Performance indicator	Description
Productivity	Yield	Amount of crop harvested per unit of land per unit of time.
	Quality	Amounts of crop components harvested (sugar, protein, minerals, etc.) or other attributes that add value to the harvested product.
	Nutrient use efficiency	Yield or nutrient uptake per unit of nutrient applied.
	Water use efficiency	Yield per unit of water applied or available. Relevant to both irrigated and rain-fed production.
	Labor use efficiency	Labor demand and supply are linked to the number and timing of field operations.
	Energy use efficiency	Crop yield per unit of energy input.
Profitability	Net profit	Reflects both the volume and value of crop produced, per unit of time, relative to all costs of production. There are difficulties in measuring externalities that have not been attributed an economic value.
	Return on investment	Similar to net profit, adding consideration of capital investment and amortization.
Cropping system sustainability	Soil productivity	Reflects changes in soil fertility levels, soil organic matter, and other soil quality indicators.
	Yield stability	Resilience of crop yields to variations in weather and pests.
	Farm income	Improvements in livelihood.
	Working conditions	Quality of life issues.
	Adoption	Proportion of producers using particular BMPs. Often easily measured, but context is important.
Healthy social and biophysical environment	Water and air quality	Concentration and nutrient loading in water bodies in the watershed or airshed. Difficulty in monitoring at farmscale.
	Ecosystem services	Difficult to quantify, but important to identify. Can include crop dependence on natural predators and pollinators, link to outdoor recreation, hunting, fishing, etc.
	Biodiversity	Difficult to quantify—can be descriptive.
	Soil erosion	Degree of soil coverage by actively growing crops and crop residues.
	Nutrient loss	Loss of nutrients to water and air. Since there are many pathways, these can be difficult to measure at the farm level.
	Nutrient balance	A total account of nutrient inputs and outputs, at the soil surface or farmgate. The requirement for nutrient inputs is often linked to the increasing nutrient removal with harvested products as yields increase.

fertilization, in-season adjustments may need to be made to account for environmental variables (such as rain or drought). Selecting the right rate begins with first establishing reasonable yield goals and assessing the soil nutrient supply (through soil testing) and then monitoring the plant nutrient status with tissue analysis or field scouting. Prediction of nutrient release from organic sources during the growing season must also be factored into this decision. An assessment of both fertilizer efficiency and economic return will be needed. For many important horticultural crops, there is insufficient information regarding crop response to applied nutrients in modern high-yielding environments.

RIGHT TIME. Applying nutrients at the right time involves synchronizing soil nutrient availability with periods of crop demand (Stewart et al., 2009). This objective begins first with understanding the basics of crop development and knowing when periods of peak nutrient demand will occur. After the crop growth pattern is understood, a variety of practices can be appropriately employed [such as pre-plant starters, multiple (split) fertilizer applications, controlled-release fertilizers, fertilizer additives (such as nitrification inhibitors or urease inhibitors), fertigation, and foliar applications]. There are usually practical considerations related to field operations that need to be integrated in the decisions (e.g., soil conditions, stage of plant growth, and application equipment).

There is a scarcity of information on the timing of nutrient uptake for many horticultural crops. Without an understanding of crop development patterns, it is difficult to consistently meet nutrient demands. For example, Horneck and Rosen (2008) reported nutrient accumulation data for potato (*Solanum tuberosum*). They demonstrated that potato has a very high demand for nitrogen between 40 and 80 d after planting (Fig. 2). Similarly, the potassium demand for potato peaks ≈60 to 90 d after planting. Excessive nitrogen present in the soil before the peak demand period or after the majority of the uptake has occurred can have negative impacts on yield, quality, and the environment. Acquiring more of this type of information for all crops would allow strategic fertilization to occur and improve nutrient efficiency.

RIGHT PLACE. Nutrients must be placed in a soil zone where they are accessible to plant roots (Murrell et al., 2009). The dynamics of soil and root interactions in fertilized areas needs further exploration. The placement of fertilizer is often indicated by the soil properties, crop rooting patterns, and available technology. Application of fertilizer in concentrated bands is often a preferred way of improving efficiency, but there are many circumstances when broadcast/incorporation techniques are preferred (e.g., to prevent root pruning). The chemical and biological reactions of each nutrient in the soil and their combined impact on bioavailability also need to be considered. For example, nitrogen fertilizers that are susceptible to volatile ammonia loss (such as urea and manures) should not be left on the soil surface for prolonged periods.

Table 2. Examples of definitions of nutrient use efficiency (NUE) for nitrogen (N) and phosphorus (P) (from Snyder and Bruulsema, 2007).

NUE term	Calculation[z]	Reported examples
Partial factor productivity of applied nutrient (PFP)	Y/F	40 to 80 units of cereal grain per unit of N
Agronomic efficiency of applied nutrient (AE)	$(Y–Y_0)/F$	10 to 30 units of cereal grain per unit of N
Partial nutrient balance (removal to use ratio) (PNB)	U_H/F	0 to greater than 1.0—depends on native soil fertility and fertility maintenance objectives <1 in nutrient deficient systems (fertility improvement) >1 in nutrient surplus systems (under-replacement) Slightly less than 1 to 1 (system sustainability)
Apparent crop recovery efficiency of applied nutrient (RE)	$(U–U_0)/F$	0.1 to 0.3—proportion of P input recovered first year 0.5 to 0.9—proportion of P input recovered by crops in long-term cropping systems 0.3 to 0.5—N recovery in cereals (typical) 0.5 to 0.8—N recovery in cereals (best management)

[z] F = quantity of nutrient applied (as fertilizers, manures, etc.), Y = yield of harvested portion of crop with applied nutrient, Y_0 = yield in control plot with no applied nutrient, U = total nutrient uptake in aboveground crop biomass with nutrient applied, U_H = nutrient content of harvested portion of crop, U_0 = total nutrient uptake in aboveground crop biomass with no nutrient applied.

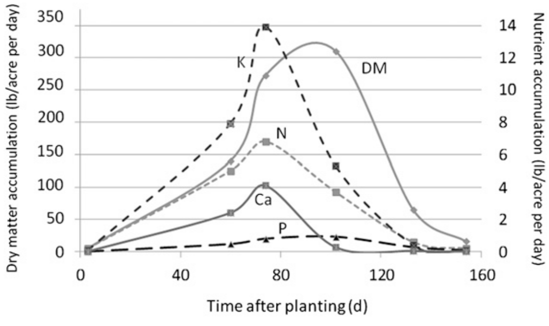

Fig. 2. Example of nutrient accumulation pattern information needed to improve fertilization practices. Nitrogen (P), phosphorus (P), potassium (K), and calcium (Ca) nutrient accumulation patterns, and dry matter (DM) production by 'Russet Burbank' potato grown in central Oregon (from Horneck and Rosen, 2008); 1 lb/acre = 1.1209 kg·ha⁻¹.

Precision placement of fertilizer for many horticultural crops has been shown to be more effective than broadcast applications. Precision placement sometimes presents an opportunity to maintain productivity while reducing application rates. For example, band placement in the soil may provide the young plant roots with an adequate concentration of nutrients during the early growth period when root length is limiting nutrient uptake. Innovations in GPS-guided field operations have aided in the task of precision placement.

Application to horticulture

In horticultural production, the value of the harvest is frequently impacted more by quality and shelf life than total yield. The 4R nutrient management decisions will have a major impact on these parameters and are beyond the scope of this paper. For example, Battilani (2008) described that both the time and source of N have a significant impact on the yield and quality of several crops. Similarly, Neilsen et al. (2010) reported that nitrogen management practices impacted the color, firmness, and storage of apples. The impacts of other nutrients, such as potassium and calcium, on harvest quality are also well documented. (Lester et al., 2010; Marcelle, 1995).

Water management is inseparable from nutrient management practices for achieving stewardship goals. Improved soil moisture sensors and micrometerological modeling can be used to more precisely deliver water to growing crops. Careful irrigation practices are essential for improving nutrient use efficiency. Both insufficient and excessive moisture can result in plant stress, lower yields, impaired quality, and heighten the risk of unwanted nutrient loss. The growing use of fertigation allows considerably more flexibility in selecting the most appropriate combination of 4R practices (Kafkafi and Tarchitzky, 2011).

The need for considering all of the 4Rs together is illustrated by the practice of foliar fertilization. Certain nutrient sources are more effective at providing foliar nutrition than others (right source). Foliar sprays must be sufficiently concentrated to provide a significant response by the plant, yet excessively high concentrations of nutrients can damage leaf tissue because of osmotic effects (right rate). It is critical that foliar nutrients be applied at a time when the leaves are permeable to nutrient penetration, and the nutrient addition can provide crop benefits (right time). If the foliar spray does not reach the leaf surface, or it drips from the leaves before it can be assimilated, then there is little value from the foliar spray (right place). A similar discussion of the 4Rs can be made for systems using fertigation. Additional research is needed to understand the interactions between these 4R factors.

There is sometimes a misconception that "commercial fertilizers" (as a source) contribute more to environmental and management problems compared with organic sources. However, a number of long-term studies have shown that nitrate leaching losses are frequently enhanced when organic manures are the sole nutrient source (Bergstrom et al., 2008). Similarly, many of the issues related to phosphorus enrichment of surface water result from runoff off leaving fields receiving animal manure (Kleinman et al., 2007; Tarkalson and Mikkelsen, 2004). These examples illustrate that the 4R concepts need to be applied to all fields receiving nutrients, regardless of source.

The 4R framework for nutrient management is a component of a decision-making process occurring on each field. It fits within integrated plant nutrient management (IPNM), a comprehensive approach to optimize plant nutrient supply from *all* sources. Alley and Vanlauwe (2009) explained that the goals of IPNM are to nourish the crops while minimizing environmental impacts. This is done by: 1) assessing the residual nutrient supply in the soil, 2) determining the soil productivity potential (realistic yield goals), 3) calculating the nutrient requirement for the specific site and yield goal, 4) quantifying the available on-farm nutrient resources, 5) calculating the supplemental nutrients that must be acquired, and 6) developing a plan to optimize nutrient use through appropriate practices.

Consideration of the right source, rate, time, and place for integrated nutrient management allows the objectives of sustainable cropping to be addressed. These 4R principles should be based in locally adapted horticultural and soil fertility research, with appropriate stakeholder input. When this is done, both the benefits and risks of fertilizers can be balanced for sustainable crop production.

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