Localized Application of Fertilizers in Vegetable Crop Production

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Abstract Localized applications of fertilizers are alternatives to broadcast applications across the entire field surface for economic, environmental and technological reasons. These alternative methods are the modified broadcast method, the banding application method, and the fertigation method used with drip irrigation. Beginning with the scientifically established fact that root system architecture of plants responds to fertilizer placement, this chapter covers first environmental regulation in the United States, the nutrient losses through leaching, the methods used for measuring nutrient loads, nutrient load estimates, the main factors that affect nutrient loads in field production, and some common strategies used for reducing nutrient loss (nitrification inhibitors, grafting and irrigation management). Using the vegetables grown on Florida's sandy soil as an example, the second section outlines the principles and practices for localized fertilizer applications to vegetable crop production. In commercial vegetable production, soil testing is the foundation for all sound fertility programs. The implementation of the soil-test recommendation requires (1) the selection of the proper rate, source, timing and placement of fertilizer, (2) the correct conversion of nutrient rates provided by the soil test results (N, P_2O_5 or K_2O needed on a per hectare basis) to that of organic amendments, cover crop residues or fertilizers on a length-of-row basis, and (3) custom-built, well-calibrated equipment. In commercial production, localized fertilizer applications need to be adjusted to the production system capabilities and constraints (flat ground or raised beds; direct-seeded or transplanted crop; irrigation method; and/or mulching). A well-planned fertilization program requires

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F. Tei et al. (eds.), *Advances in Research on Fertilization Management of Vegetable Crops*, Advances in Olericulture, DOI 10.1007/978-3-319-53626-2_6

an irrigation schedule to maximize nutrient-use efficiency and yield potential while reducing the risk of nutrient losses due to leaching.

Keywords Modified broadcast • Banded fertilizer • Starter fertilizer • Fertigation • Best management practice • Leaching • Controlled-release fertilizer • Nutrient load • Lysimeter • Cover crop • Nitrification inhibitors • Grafting • Crop nutritional requirement • Standard bed spacing

1 Introduction

For economic, environmental and technological reasons, localized applications of fertilizers have emerged as alternatives to broadcast applications across the entire field surface. Despite their negative effect on soil biological cycles and the generation of gases and particulates through burning, slash-and-burn methods used widely in early agriculture and still today in some parts of the word, were the first use of inorganic fertilizer for the production of cultivated plants (Brady 1996; Palm et al. 1996). Broadcast applications of fertilizers are still used today in vegetable production for the application of liming materials, soil amendments, composts and manures. The application of nutrients through overhead irrigation systems is another form of broadcast application.

In contrast to these methods, "localized applications of fertilizer" refers to application methods that place fertilizer only on a portion of the field, typically near the seeds, the transplants or the plants. Also, localized fertilizer application may reduce nutrient losses from the areas of the field where crop roots are not present. These alternative methods to the broadcast application method are (1) the modified broadcast method (fertilizer is applied in large swaths only where the raised beds will be formed), (2) the banding application method (material is applied near the seeds or plants as starter fertilizer or banded sidedress fertilizer), and (3) the fertigation method with drip irrigation (soluble nutrients are applied to the root zone through the drip irrigation; Table 1; Figs. 1, 2, 3 and 4). Localized applications of fertilizers are used to increase the uptake rate of applied nutrients, thereby reducing the application rates, the fertilization cost and reduce the environmental impact of vegetable production. The effectiveness of fertilizer applications is measured by the Nutrient Use Efficiency (NUE).

The NUE of crop plants can be expressed as the yield of nutrient [the most studied are with nitrogen (N) and phosphorous (P)] produced by each unit of available nutrient in the soil. This NUE is usually divided into two processes: uptake efficiency (the ability of the plant to remove nutrients from the soil normally present as nitrate (NO_3^-), ammonium (NH_4^+) or phosphate ions ($H_2PO_4^-$ or HPO_4^{2-}), and the utilization efficiency (the ability of the plant to transfer the N and P to the shoot and reproductive plant parts). Improvements in NUE by vegetable crops is accomplished mainly through changes in cultural practices in the field (including fertilizer placement, timing of application and source selection, and irrigation management)

Table 1 Selected attributes of fertilizer application methods used in vegetable crop production

Attribute	Application method: Broadcast	Modified broadcast	Starter	Banded	Injected
Timingof application	Preplant	Preplant	At planting	Preplant or sidedress	Sidedress
Fertilizer type	Granular	Granular	Liquid	Granular or liquid	Liquid
Common nutrient content	Lime, sulfur, organic materials, composts, N, P and K for direct-seeded crops	Compost, N, P, K, Ca, Mg, micronutrients	Mostly P, some N, some K	Organic materials, compost Mostly N, P, K	Mostly N, K
Unit of application[a]	$kg{\cdot}ha^{-1}$	$kg\ HA^{-1}$	$L\ HA^{-1}$	$L\ HA^{-1}$ or $kg\ HA^{-1}$	$L\ HA^{-1}$

[a]1 HA = linear meters of bed (or row) in one hectare at standard bed (or row) spacing

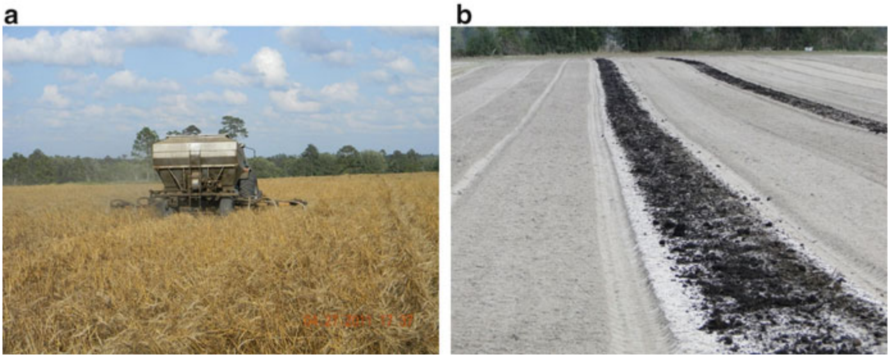

Fig. 1 Modified broadcast application of (**a**) granular fertilizer into the cover crop and (**b**) poultry litter onto bare soil. Note in (**a**) the three tubes on each side that apply fertilizer where the raised beds will be formed (Photo credits: (**a**) Joel Love, and (**b**) Robert Hochmuth)

and alterations of the architecture of the root system. Improvements in utilization efficiency may be achieved through breeding and molecular biology.

Since in this book fertilizer sources are already covered under *"Organic matter mineralizationas a source of nitrogen"*, "*Fertilizers: Criteria of choice for vegetable crops"*, and *"Crop rotation as a system approach for soil fertility management in vegetables"*, this chapter covers first general topics related to localized fertilizer applications (root response to fertilizer application, environmental regulation in the United States, nutrient losses through leaching, methods used for measuring nutrient loads, nutrient load estimates, field factors affecting nutrient loads, and strategies for reducing nutrient loss). Using the vegetables grown on Florida's sandy soil as an example, the second section outlines the principles and practices for localized fertilizer applications to vegetable crop production.

Fig. 2 Banded application of fertilizer on the bed shoulders and under the plastic mulch during the preparation of a seepage-irrigated tomato field in South Florida (Photo credit: Monica Ozores-Hampton)

Fig. 3 Banded sidedress applications of granular fertilizer to (**a**) potato (Solanum tuberosum) rows, (**b**) sweet corn (Zea mays) plants, and (**c**) sweetpotato (Ipomoea batatas) vines (Photo credits: Lincoln Zotarelli (**a**), and Robert Hochmuth (**b**, **c**))

Fig. 4 Liquid fertilizer tank mounted on a pallet, containing liquid 8-0-8 and used for the injection of N and K into the two drip irrigation systems using Mazzi injectors. Note on each system (from *right* to *left*), the back flow prevention device, the injection port, the pressure gage, the screen filters (in *red*), and the solenoid valve (in *black*; photo credit: Robert Hochmuth)

2 Root Response to Localized Fertilizer Application, the Environmental Impact of Vegetable Crop Production and Strategies for Reducing Nutrient Loss

2.1 Vegetable Crops Root Growth, Shoot Growth and Yield Response to Fertilizer Placement

Root architecture responds to fertilizer application and placement. Early work established that exposure of barley *(Hordeum vulgare)* plant roots to high concentrations of N, P or potassium (K) fertilizers caused a localized promotion of the initiation and subsequent extension of both first- and second-order lateral roots (Drew 1975; Fritsh and Nichols 1975). Since then, these results have been documented with many food crops that adjust their root architecture to low N and P conditions through inhibition of primary root growth, promotion of lateral root growth, enhancement of root hair development and cluster root formation (Garnetti et al. 2009; Muñoz-Arboleda et al. 2006; Niu et al. 2012; Zotarelli et al. 2009).

As reviewed by Lea and Azevedo (2006), some of the genes involved in NO_3 uptake include at least four different transport systems: (a) constitutive high-affinity (cHATS), (b) nitrate-inducible high-affinity (iHATS), (c) constitutive low-affinity (cLATS) and (d) nitrate-inducible low-affinity (iLATS). Two families of genes encoding NO_3^- transporters have been identified in plants: NO_3^- transporters *NRT1* and *NRT2*. In *Arabidopsis thaliana,* over 50 members of the larger *PTR* family to which the *NRT1* genes belong and seven members of the *NRT2* family have been identified. A family of five NH_4^+ transporter genes designated *AMT1;1* to *AMT 1;5* were originally identified in *A. thaliana*, which were related to cyanobacterial NH_4^+ transporters, while in tomato (*Solanum lycopersicum*), only three *AMT1* genes were isolated. Both plants had a second *AMT2* sequence more related to transporters isolated from *Saccharomyces cerevisiae* and *Escherichia coli*.

Progress in molecular biology in the last decade have identified many genes involved in root architecture response to nutrient presence in the soil, mostly with P (Beebe et al. 2006; Richardson et al. 2005). Although the response of a root system to locally available nutrients can be predicted in general terms, the precise degree and direction of growth cannot be anticipated (Robinson 1994). The mechanisms for activating alterations in root architecture in response to P deprivation depend on changes in the localized P concentration, and transport of or sensitivity to growth regulators such as sugars, auxins, ethylene, cytokinins, nitric oxide, reactive oxygen species and abscisic acid (Niu et al. 2012). In the process, many genes are activated, which in turn trigger changes in molecular, physiological and cellular processes. As a result, root architecture is modified, allowing plants to adapt effectively to the low-P environment (Niu et al. 2012; Smith and Smet 2012).

Genes that respond to P deficiency can be grouped into 'early' genes that respond rapidly and often non-specifically to P deficiency, and 'late' genes that impact the morphology, physiology or metabolism of plants upon prolonged P deficiency (Hammond et al. 2004). The use of micro-array technology has allowed researchers to catalogue the genetic responses of plants to P deficiency. Genes whose expression is altered by P deficiency include various transcription factors, which are thought to coordinate plant responses to P deficiency, and other genes involved in P acquisition and tissue P economy (Hammond et al. 2004).

Phosphorus availability and uptake by plants is enhanced by mycorrhizae. Under limiting-P conditions, plants may obtain adequate P through modifications to root architecture, carbon metabolism and membrane structure, exudation of low molecular weight organic acids, protons and enzymes, and enhanced expression of the numerous genes involved in low-P adaptation. These adaptations may be less pronounced in mycorrhizal-associated plants. The formation of cluster roots under P-stress by the non-mycorrhizal species white lupin (*Lupinus albus*), and the accompanying biochemical changes exemplify many of the plant adaptations that enhance P acquisition and use (Ramaekers et al. 2010; Vance et al. 2003).

Improvements in accessing scientific literature and computing capabilities in the last decade have made it possible to compile, analyze, and interpret many independent experiments together. This methodology is known as meta-analysis (Cochran 1954). In brief, a meta-analysis is performed on some measure of the effect of the treatment relative to the control from each trial. This so-called "effect size" standardizes the response and allows for comparisons between studies. The effect size is calculated as the ratio of experimental treatment mean divided by the control mean. Once a thorough literature search is performed, the main steps of a meta-analysis are (1) categorizing the literature (strategies and treatment definition), (2) characterization of main environment and management factors, (3) extracting variable values and building a database, and (4) performing the statistical analysis.

This methodology was used to determine mycorrhizal responses to N, P, and atmospheric CO_2 in field studies. A meta-analysis showed that mycorrhizal abundance decreased 15% under N fertilization and 32% under P fertilization, while elevated CO_2 elicited a 47% increase (Treseder 2004). Nitrogen effects varied significantly among studies, and P effects varied significantly among lead investigators. Most other factors did not affect mycorrhizal responses. These results suggest that mycorrhizal fungi levels may increase substantially under elevated CO_2, but decline moderately under P additions (Treseder 2004). Another meta-analysis concluded that mycorrhizal colonization was increased most by inoculation (29% increase), followed by shortened fallow (20%) and reduced soil disturbance (7%) (Lekberg and Koide 2005). The effect of crop rotation depended on whether the crop was mycorrhizal. Increased colonization resulted in a yield increase in the field of 23% across all management practices. Biomass at harvest and shoot P concentration in early season were increased by inoculation (57% and 33%, respectively) and shortened fallow (55% and 24%). Reduced disturbance increased shoot P concentration by 27%, but biomass was not significantly affected. Biomass was significantly reduced in 2% of all trials in which there was a significant increase in colonization. Irrespective of management practice, an increased mycorrhizal colonization was less likely to increase biomass if either soil P or indigenous inoculum potential was high (Lekberg and Koide 2005).

2.2 The Nutrient Gradient System

A practical application of Drew's findings (1975) that crops roots respond to the localized application of N, P and K is the nutrient gradient system used for vegetable crops grown with seepage irrigation (Geraldson 1970). Seepage irrigation consists of the management of a shallow water table perched on an impermeable soil layer found at the 1–2 m depth. Basic components of the gradient-mulch system include 70–90 cm-wide flat-topped soil beds raised to 25–30-cm above ground, covered by full polyethylene mulch. Based on soil test results, 0–30% of the N and K, and 100% of P and micronutrients are broadcast applied into the bed. The remaining N and K are applied as two bands (one near each bed shoulder) in 5-cm deep groves (Fig. 2). Seepage irrigation maintains a constant water table level at the 40–45 cm depth. Intermittent ditches are also provided for irrigation and drainage purposes from a precisely leveled field with a slope of about 10 cm every 100 m. With this fertilizer placement, a three-dimensional concentration gradient decreasing with distance from the surface-applied fertilizers is superimposed on the moisture-air gradient. Thus, the root from a germinating seed or transplanted seedling can develop in that portion of the bed where the most favorable levels of nutrients, moisture, and air occur. Once the root system becomes established in a favorable portion of the soil bed, nutrients and moisture must continue to be supplied as they are removed by the root; soluble nutrients move by gradient diffusion from the band to the root. The less soluble nutrients mixed in soil bed continue to become available by equilibrium action, also as removed by the root.

Unlike in other production systems where water and nutrient availability fluctuate, the nutrient gradient system allows for vegetable crops roots to have a constant access to water and nutrients (Sato and Morgan 2012).

In broad terms, nutrient pollution occurs when nutrients move outside of the target application area (typically the root zone) through leaching or erosion (caused by rainfall or irrigation), nutrient cycling (Cockx and Simonne 2014; Simonne and Morgant 2013) or accidental non-target application. Off-target movement of nutrients may occur during the production season or when the fields are left fallow after the last harvest. Hence, all BMP efforts are focused on keeping nutrients in the root zone and on managing fields year round (FDACS 2015; Hartz 2006; Simonne et al. 2010). Any loss of nutrient reduces the effectiveness of the fertility program.

2.3 Environmental Regulations in the United States

In response to the public awareness of environmental issues, section 303(d) of the US Clean Water Act (US Congress 1977) required that states identify impaired water bodies and establish Total Maximum Daily Loads (TMDLs) for pollutants entering these water bodies. Best Management Practices (BMPs) are defined as specific cultural and/or structural practices aimed at reducing the negative environmental impact of agricultural production while maintaining or increasing yield and productivity. Mounting evidence exists world-wide that these two constraints are compatible (Singh and Ryan 2015). The role of the states was to define how the Clean Water Act was to be implemented at the local level. In 1987, the Florida legislature passed the Surface Water Improvement Act requiring the five Florida water management districts to develop plans to clean up and preserve Florida lakes, bays, estuaries and rivers. In 1999, the Florida Watershed Restoration Act (Florida Senate 1999) defined a process for the development of TMDLs. A TMDL represents the quantity of a pollutant a water body can accept and still have its water quality parameters consistent with its intended use. Based on the water body, the pollutants may be a nutrient (typically N or P), an organic compound or a microorganism.

The Florida Department of Agriculture and Consumer Services (FDACS) released and adopted by rule 5M-8 the first version of the "*Water Quality and Quantity Best Management Practices for Florida Vegetable and Agronomic Crops*" manual in 2005 and released an updated version in 2015 (FDACS 2015). Jointly developed by professionals from FDACS, the University of Florida, the water management districts and commodity groups, this manual outlines all the possible BMPs that farmers may implement. Agronomic and vegetable crops growers officially join the BMP program by (1) developing a BMP plan for their land and (2) signing a notice of Intent (NOI) to implement BMPs. Growers with a signed NOI receive a presumption of compliance with water quality standards and are eligible for cost share programs (FDACS 2015).

The "first generation BMPs" outlined in the 2005 version of the BMP manual proposed a multitude of approaches including fertilization plans and irrigation schedules (FDACS 2015). Second generation BMPs intensely focus on water and nutrient management and include controller-based real-time irrigation scheduling (Cardenas-Laihacar and Dukes 2010; Zotarelli et al. 2008a, b), low-pressure drip-irrigation (Poh et al. 2011a, b), the use of the Soil Phosphorus Storage Capacity Index to predict the risk of P loss outside the root zone through leaching or erosion (Florida Statute 1994; Rice et al. 2013), controlled-release fertilizers (Guertal 2009; Morgan et al. 2009; Simonne and Hutchinson 2005), amendments that increase soil water holding capacity such as biochar (Biederman and Harpole 2013; Singh et al. 2010), polymers (Bavernik 1994), or zeolites (Ming and Allen 2001; Sepaskhah and Yousefi 2007)], and amendments that increase soil organic matter content such as manures (Ulén 1999), compost (Hepperly et al. 2009) or cover crops (Hartwig and Ammon 2002; Tonitto et al. 2006).

Since the late 2000s, the Florida Department of Environmental Protection (FDEP) has been developing and approving Basin Management Action Plans (BMAPs; http://www.dep.state.fl.us/water/watersheds/bmap.htm). BMAPs are the blueprint for restoring impaired water bodies by reducing pollutant loadings to meet the TMDLs. Each plan includes a comprehensive set of strategies such as permit limits on wastewater facilities, urban and agricultural BMPs, conservation programs, financial assistance, and revenue generating activities. These plans are developed with input from local stakeholders and are adopted by Secretarial Order to be enforceable. In watersheds with adopted BMAPs, agricultural producers must either implement FDACS-adopted BMPs or conduct water quality monitoring prescribed by FDEP or their water management district.

2.4 Nutrient Loss Through Leaching

Leaching is the vertical movement of soluble nutrients with the water front while erosion is the loss of soil particles through water surface movement. Hence, water is the driver of these two processes which ties nutrient management with water management. Early estimates of nutrient loss to the environment measured nutrient concentrations in shallow wells or in suction lysimeters. While these measures are relatively easy to collect and may be compared to established thresholds, they have the limitations that (1) they are affected by precipitation, (2) it is difficult to clearly define what area of the soil or water body the sample represents, and (3) because concentrations are intensive measures, they cannot be added. Yet, many studies have reported seasonal and temporal variations in nutrient concentrations in vegetable fields.

Nutrient in solutions tended to be low in undisturbed ecosystems (<1.00 mg L^{-1} of NO_3-N; Chinnasamy and Hubbart 2014) whereas in intense vegetable production systems, NO_3-N concentrations of up to 20–33 mg L^{-1} were reported in Sri Lanka with potato (*Solanum tuberosum*) grown on bare ground (Rajakaruna et al. 2005) and 35–40 mg L^{-1} NO_3-N in Florida with tomato (*Solanum lycopersicum*) and pumping (*Cucurbita pepo*) produced with plasticulture (Simonne et al. 2006). These levels exceed by several factors the acceptable NO_3-N concentrations in potable water allowed by the World Health Organization (10 mg L^{-1} of NO_3−N). As an alternative, research has focused on the direct measure of nutrient loads lost under the root zone of vegetable crops. Nutrient loads are expressed in kg·ha^{-1} and have the advantage of being additive.

2.5 *Nutrient Loads*

2.5.1 Determination of Nutrient Loads

Nutrient load may be determined indirectly or directly. The indirect approaches of measuring load include nutrient flow models and nutrient balances. Nutrient flow models are important tools for evaluating the impact of nutrient leaching on water quality at the watershed level, and play an important role in designing agricultural and environmental policies. Direct methods for calculating load at the field level are resin traps, soil sampling, or drainage lysimeters (Farneselli et al. 2008; Pampolino et al. 2000; Zotarelli et al. 2007). While each of these methods has its own advantages and limits, small, in-row drainage lysimeters are emerging as a practical tool for direct load measurements (Gazula et al. 2006; Migliaccio et al. 2006; Zotarelli et al. 2008a,b). A partial vacuum may be added to drainage lysimeters to prevent water logging without compromising the accuracy of the results (Evett et al. 2006). The accuracy of drainage measurement (+/− 0.0013 mm) was nearly two orders of magnitude better than that of the lysimeter weight measurement (1 mm), ensuring that the continuous drainage measurement may be included in the weight balances determination of evapotranspiration (ET) without diminishing the accuracy of ET values (Evett et al. 2006). The limitations of these methods are (1) installation requires soil disturbance, (2) sample collection may be time consuming, and (3) the sampling tubes of some lysimeters that may be near the soil surface (for sample collection) may interfere with tillage.

2.5.2 Nutrient Load Estimates

Several compilations of published in-field load estimates for vegetables crops are available (Khai et al. 2007; Ramos et al. 2002; Simonne et al. 2010; Ulén 1999). These estimates ranged from 1 to 400 kg.ha^{-1} of N, and varied based on crops, cultural practices, rainfall pattern, slope, and irrigation/fertilizer management. The methodology used for extrapolating load calculations to a per-hectare basis also affected the final number. Hence, efforts should be made to standardize protocols and methodology for in-field load estimation. At least, research reports should clearly provide the actual load estimate together with the calculations (and assumptions) used to extrapolate the results at the field level. In calculating nutrient loads, equal importance should be given to the determination of the volume of soil affected by the nutrient movement as to the estimation of the nutrient concentration since the load is calculated by multiplying one with the other (Farneselli et al. 2008).

2.5.3 Field Factors That Affected Nutrient Loads

A meta-analysis reviewed those strategies that have proven effective in reducing NO_3-N leaching and aimed at quantifying the scale of reduction that can be achieved (Quemada et al. 2013). Forty-four scientific articles that investigated four main strategies (water and fertilizer management, use of cover crops and fertilizer technology) were used to create a database with 279 observations on NO_3-N leaching and 166 on crop yield. On average, management practices that adjust water application to crop needs reduced NO_3-N leaching by 80% without a reduction in crop yield. Improved fertilizer management reduced NO_3-N leaching by 40%, and the best relationship between yield and NO_3-N leaching was obtained when applying the recommended fertilizer rate (Quemada et al. 2013). Replacing a fallow with a non-legume cover crop reduced NO_3-N leaching by 50% while using a legume cover crop did not further reduce NO_3-N leaching (Quemada et al. 2013).

In another meta-analysis on experiments that compared crop yield, NO_3-N leaching, or soil NO_3-N levels between conventional (receiving inorganic fertilizer with a winter bare fallow) and diversified systems [using either (1) a non-legume over-wintering cover crop that was amended with inorganic fertilizer or (2) a legume over-wintering cover crop with no additional N fertilizer], vegetable yields under non-legume cover crop managements were not significantly different from those in the conventional, bare fallow systems, while average leaching was reduced by 70% (Tonitto et al. 2006). However, yields under green manure fertilization were not significantly different from those in the conventional systems when legume biomass provided $\geq$110 kg N ha^{-1} (Tonitto et al. 2006). On average, NO_3-N leaching was reduced by 40% in legume-based systems relative to conventional fertilizer-based systems. Post-harvest soil NO_3-N status, a measure of potential N loss, was similar in conventional and green manure systems suggesting that reductions in leaching losses were largely due to avoidance of bare fallow periods (Tonitto et al. 2006). Nevertheless, in-field estimates provide a practical basis for educating growers and improving their cultural practices especially when rainfall and irrigation amounts and distribution are provided. These results support the current BMP approach that grower education should focus on irrigation management, fertilizer management, and cover crop use.

2.5.4 Strategies for Reducing the Risk of Nutrient Leaching

The main strategies currently available to reduce nutrient loss discussed here include using nitrification and ureases inhibitors, grafting, and irrigation management.

Nitrification and urease inhibitors may reduce N losses, thereby increasing crop N-use efficiency. However, their effect on crop yield is variable. The use of the common nitrification inhibitors (dicyandiamide (DCD) and 3,4-dimethylepyrazole phosphate (DMPP)) and the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) may be recommended in order to increase both crop yields and N use efficiency (grand mean increase of 7.5% and 12.9%, respectively) as shown in a meta-analysis (Abalos et al. 2014). However, their effectiveness was dependent on the environmental and management factors of the studies evaluated. Larger responses were found in coarse-textured soils, irrigated systems and/or crops receiving high N rates. In alkaline soils (pH $\geq$ 8), the urease inhibitor NBPT produced the largest effect size. Given that their use represents an additional cost for sweet corn (*Zea mays*) farmers, understanding the BMPs to maximize their effectiveness is paramount to allow effective comparison with other practices that increase crop productivity and N-use efficiency (Abalos et al. 2014).

Vegetable grafting is a cultural technique that consists of establishing in the field or in a greenhouse a plant that is made by the union (through hole insertion, tongue approach or cleft grafting) of two other plants –the rootstock and the scion. Grafting is commercially practiced worldwide in tomato, pepper (*Capsicum annuum*), egg-plant (*Solanum melongena*), cucumber (*Cucumis sativus*), watermelon (*Citrullus lanatus*) and small melons (*C. melo*) production (Lee 1994). Grafted plants have expressed “grafting vigor”, a concept that reflects that the phenotype of the grafted plant is more than the addition of the two separate phenotypes of the root stock and scion. On one hand, grafting is viewed as a promising tool to increase resistance to soil-borne diseases (King et al. 2008), fruit quality (Rouphael et al. 2010), and tolerance to abiotic stresses (Schwarz et al. 2010), salinity (Choi et al. 2011) and heavy metals (Savvas et al. 2010). On the other hand, grafting increases production costs (two seeds are needed; survival rate during healing may be variable), requires skilled labor or expensive grafting equipment, and occasional results in external rooting of the scion (Lee 1994). Yet, although grafting increased the total cost of field-grown tomato production, the increase in marketable fruit yield may generate in some cases a significant gross economic return that may offset the cost of using grafted transplants (Djidonou et al. 2013a). However, these results were based on a small-plots research study and not in commercial fields.

The grafting vigor and the potential of grafted plants to show enhanced water and NUE has been actively investigated in recent years in the hope of making grafting a BMP (Simonne et al. 2010). Most studies of grafted vegetable responses to fertilization and irrigation have been made with specific scion-root stock combinations. Schwarz et al. (2010) noticed that limited information exists on the effect of grafting on nutrient uptake or on the choice of scion for the enhancement of NUE. Most studies of the potential benefits of using grafted plant for improved NUE were conducted with cucurbit or solanaceous crops. In greenhouse conditions, melon plants grafted onto ‘Dinero’, ‘Jador’, and ‘P360’ (*Cucurbita moschata* Duchesne $\times$ *C. maxima* D.) rootstocks needed 5.7, 5.2, and 6.1 mM of NO_3^-, respectively, to reach half-maximum shoot dry weight, whereas plants grafted onto ‘PS1313’ rootstock and the control treatment (non-grafted plants) needed 9.1 and 13.1 mM of NO_3^-, respectively (Rouphael 2010). Under field conditions, increasing the N fertilization rates from 0 to 120 $kg \cdot ha^{-1}$ increased the total and marketable melon yields, whereas the NUE decreased (Rouphael 2010). When averaged over all N rates, the marketable yield, NUE, and N uptake efficiency were higher by 9%, 11.8%, and 16.3%, respectively, in 'Proteo' grafted onto 'P360' than in non-grafted 'Proteo' plants (Rouphael 2010). Mini-watermelon plants 'Minirossa' either non-grafted or grafted onto 'Macis', 'Vita' (*Lagenaria siceraria* [Mol.] Standl.), 'PS1313', and 'RP15' (*C. maxima* D. × *C. moschata* D.) rootstocks grown in hydroponics were compared based on shoot dry biomass, leaf area, root-to-shoot ratio, SPAD index, shoot N uptake, and nitrate reductase activity 40 days after transplantation in response to NO_3 concentration in the nutrient solution (0.5, 2.5, 5, 10, 15, or 20 mM of NO_3^-). Mini-watermelon grafted onto 'Vita' rootstock needed the lowest NO_3- concentration (1.31 mM) in the nutrient solution to reach half maximum shoot dry weight (Colla et al. 2011).

In another experiment, the suitability of 'Vita' as a rootstock with high NUE to improve crop performance and NUE of grafted mini-watermelon plants was evaluated under field conditions (Colla et al. 2011). Increasing N rates from 0 to 100 kg ha^{-1} improved total and marketable mini-watermelon yields. When averaged over N rates, the marketable yield, NUE, N-uptake efficiency, and N-utilization efficiency were significantly higher by 39%, 38%, 21%, and 17%, respectively, in 'Minirossa' grafted onto 'Vita' compared to non-grafted 'Minirossa' plants (Colla et al. 2011). Increasing the N fertilization rate from 0 to 60 kg ha^{-1} to 'Proteo' melon grafted on 'P360' increased melon yield by 21%, whereas increasing the N rate from 60 to 120 kg ha^{-1} increased melon production by only 10% (Colla et al. 2012). Similarly, increasing N fertilization rate from 0 to 50 kg ha^{-1} to mini-watermelon 'Minirossa' grafted on 'Vita' increased mini-watermelon yield by 47%, whereas increasing N rate from 50 to 100 kg ha^{-1} increased mini-watermelon yield by only 5% (Colla et al. 2012). When averaged over N rates, the yield, and NUE were higher by 10%, and 12%, respectively in 'Proteo' grafted onto 'P360' than in non-grafted 'Proteo' plants and by 39%, and 38%, respectively in 'Minirossa' grafted onto 'Vita' than in non-grafted 'Minirossa' plants (Colla et al. 2012). Hence grafting melon and mini-watermelon plants onto selected rootstocks can be used as a quick and effective method to improve productivity and increase NUE in cucurbits (Colla et al. 2011, 2012).

Tomato plants were grown in a fumigated field with 12 combinations of two drip-irrigation regimes (50% and 100% of commonly used irrigation regime) and six N rates ranging between 56 and 336 kg·ha^{-1}). In 2010, the 50% irrigation regime resulted in higher total and marketable yields than the 100% irrigation regime (Djidonou et al. 2013b). Plants grafted onto 'Beaufort' or 'Multifort' rootstocks showed an average increase of 27% and 30% in total and marketable fruit yields, respectively, relative to non-grafted plants. Grafting significantly increased tomato yields, whereas grafted plants showed greater potential for yield improvement with increasing N rates compared with non-grafted plants. Greater fruit set and higher average fruit weight as a result of grafting were observed in both years. Grafting with the two rootstocks significantly improved the irrigation water and N use efficiency (Djodonou et al. 2013b). These results support the use of grafting as a BMP. These results also emphasize the need to control and report irrigation regimes (amount and frequency) in all scientific studies presenting results on vegetable crops responses to fertilizer rates, NUE or nutrient losses below the root zone. Further research should seek to develop rootstocks with enhanced water and nutrient uptake capabilities.

Current fertilization recommendations for vegetable crops production were developed with non-grafted plants. Yet, grafted tomato yield was significantly influenced by N rates, but similar yields were achieved at 168 kg·ha^{-1} and above (Djodonou et al. 2013b). Since the current recommendation for tomato production is 224 kg·ha^{-1} (Vallad et al. 2014), these results suggest the need for developing irrigation and N fertilization recommendations specifically for grafted tomato production. Due to increased water and N use efficiency, current recommendations for non-grafted tomato plants may result in over-irrigation and/or over-fertilization.

While this approach has produced practical information about the benefits of grafting on water and NUEs, it is unrealistic to expect that irrigation and fertilization requirements will be specifically developed for all the possible scion/root stock combinations. Instead, an exhaustive scientific study of this topic may require a genetic approach and a molecular explanation of the grafting vigor (Ruiz et al. 1997). After observing that the ability of grafted melon to absorb N, K and Mg was greater than that of those grown on their own roots, Min et al. (2006) stated that grafting had changed the character of melon's nutrient absorbability. In addition, self-grafting (which involves a single genotype) did not increase tomato yield as compared to the standard method (Djidonou et al. 2013b). Since no DNA movement from root stock to scion (or vice versa) is expected, distance gene expression may occur through the transport of RNAs through the graft union in the phloem. Harada (2010) compiled the endogenous RNA having long-distance transportability through sieve elements. Recent molecular biology advancements open the way for the targeted development of vegetable varieties (grafted or not) with improved water and NUEs (Bindraban et al. 2015; Ruiz et al. 2006). One approach is to develop an understanding of the plant response to different N regimes, especially to N limitation, using various methods including transcription profiling, analyzing mutants defective in their normal response to N limitation, and studying plants that show improved growth under N-limiting conditions (Kant et al. 2010).

Irrigation management is another method available to control nutrient leaching. In the field, most vegetable crops are irrigated with furrow irrigation, seepage irrigation, overhead irrigation or drip irrigation (Allen et al. 1998; Fereres et al. 2003; Locascio 2005). Scheduling irrigation is to determine when to irrigate and how much to apply. For all irrigation methods, the components of an irrigation schedule are (1) determining a target irrigation volume based on reference evapotranspiration (ETo) and crop age; (2) adjusting this amount based on soil moisture measurement (Thompson et al. 2007a); (3) determining the contribution of rainfall; (4) developing a rule for splitting irrigation, and (5) keeping irrigation records (Dukes et al. 2010, 2012; Simonne et al. 2012) (Table 2). Excessive water (from irrigation or rainfall) may move soluble nutrients below the root zone, especially in coarse-textured soils (Simonne et al. 2014). Despite some common misconceptions, "pulsing" irrigation (splitting a longer irrigation into shorter ones) did not increase the lateral movement of water in mulched beds on sandy soil when drip irrigation was used (Poh et al. 2009).

Drip irrigation management should be adjusted to soil conditions. Using computer simulations, Cotte et al. (2003) established that (1) drip irrigation may improve plant water availability in medium and low permeability fine-textured

Table 2 Generic irrigation schedule and fertilizer plan for vegetable crop production

Generic irrigation schedule
1. Select a target irrigation volume based on weather demand [assessed through reference evapotranspiration (ETo) or Class A Pan evaporation (Ep)] and crop stage of growth
2. Fine tune schedule based on daily soil moisture measurements (soil water tension or volumetric water content)
3. Determine the contribution of rainfall to crop water needs
4. Follow a rule for splitting irrigation volume (highest volume for one event before leaching is expected)
5. Record date and amount of rainfall and irrigation events
Generic fertilizer plan
1. Soil test, understand the recommendation and make the correct calculations
2. Lime if necessary
3. Apply organic amendments (cover crop, compost, or manure)
4. Incorporate the preplant fertilizer; then sidedress or develop a weekly fertigation schedule, adjusting amount to crop growth stage
5. Use foliar fertilization (this practice is recommended for the application of micronutrients to high-pH soils when need)
6. Assess the efficacy of the fertilizer program through leaf sampling or petiole sap analysis
7. Trap residual nutrients at the end of the season with a cover crop
8. Record date of application, material, placement and source of all fertilizer used

soils, providing that design and management are adapted to account for their soil hydraulic properties, (2) in highly permeable coarse textured soils, water and nutrients move quickly downwards from the emitter, making it difficult to wet the near surface zone if emitters are buried too deep, and (3) changing the fertigation strategy for highly permeable coarse-textured soils to apply nutrients at the beginning of an irrigation cycle can maintain larger amounts of nutrient near to and above the emitter, thereby making them less susceptible to leaching losses.

The risk of nutrient leaching caused by the mismanagement of irrigation is not uniform throughout the growing season in greenhouse and field production. Typically, major leaching events occur when soil N concentrations are high and water is moving through the soil profile (Meisinger and Delgado 2002). Based on a greenhouse industry survey, total irrigation during the first 6 weeks after crop establishment was generally excessive, being >150% and >200% of modelled crop evapotranspiration (ETc) in 68% and 60% of greenhouses, respectively (Thompson et al. 2007b). During the subsequent period, applied irrigation was generally similar to modelled ETc, with only 12% of greenhouses applying >150% of modelled ETc (Thompson et al. 2007b). Similar observations were made with corn (Spalding et al. 2001), strawberry (*Fragaria annassa*) (Guimera et al. 1995), tomato (Vázquez et al. 2006) and watermelon (Simonne et al. 2014) when excessive irrigation was observed during the vegetative period. Hence, educational efforts should focus on irrigation and fertilizer management early in the season.

While all these concepts related to localized fertilization application are the focus of intense research from a wide array of scientific fields, progress in field productivity, resource management, and environmental impact depends on the degree of application of the research advances by vegetable producers. Using vegetable production in Florida as an example, the following section summarizes the practical application of these concepts to field production.

3 Principles and Practices for Localized Fertilizer Applications to Vegetable Crops

3.1 Vegetable Crops and Production Systems

Vegetable crops are produced using many different production systems. Large-seeded crops like sweet corn, snap bean (*Phaseolus vulgaris*), English pea (*Pisum sativum*), southernpea (*Vigna unguiculata*) or okra (*Abelmoschus esculentus*) are typically direct seeded, whereas transplants are usually used for the establishment of small-seeded crops such as tomato, bell pepper, eggplant, lettuce (*Lactuca sativa*), cabbage (*Brassica oleracea* var. capitata), broccoli (*B. oleracea* var. italic) or onion (*Allium cepa*)]. Due to the cost of seeds and low germination rates in the field, large-seeded triploid (seedless) watermelon crops are also established using transplants. Large-seeded crops such as small melons, cucumber, summer or zucchini squash (*Cucurbita pepo*) may be direct seeded or transplanted. Other vegetable crops are vegetatively propagated: daughter plants (strawberry), vine cuttings or "slips" [sweetpotato (*Ipomoea batatas*)] or "seed pieces" (potato) are used for field establishment. Direct-seeded crops, sweetpotato and potato crops are usually grown on flat ground or small uncovered or open beds, whereas transplanted and strawberry crops are usually established on raised beds. Raised beds may be covered with a polyethylene mulch or remain uncovered. Polyethylene-mulched beds may be used to grow one, two (double cropping) or three (triple cropping) crops. Crops may also be direct-seeded or transplanted into a cover crop. Vegetable crops may be grown as dry-land crops in areas with fine-textured soils and/or during the rainy season. In other cases, vegetable crops may be irrigated with furrow, seepage, overhead (center pivots, linear moves, travelling guns, or sprinklers) or drip irrigation. All these combinations of establishment method, soil preparation and irrigation method affect the fertilizer programs used.

3.2 Overview of Crop Nutritional Requirements (CNR) and Soil Testing Methods

The amount of nutrients needed to produce economical yields is called the crop nutritional requirement (CNR) (Liu et al. 2015). The CNR may be provided by the soil, organic amendments, cover crops residues, or fertilizers. Soil-test methods exist to determine the potential nutrient contribution from the soil, and therefore by difference, the amount of nutrients needed to be supplied by amendments, cover crop residues and/or fertilizers. Soil testing consists of soil sampling and drying, and an extraction step followed by chemical analyses (Mylavarapu 2009). Routine analyses measure the amount of extracted nutrients, salinity, and pH of a soil. The selection of an extracting solution (also called "extractant") is based on soil pH, cation exchange capacity (CEC) and organic matter content. Many extractants are used worldwide and little standardization exists among regions or countries. Single-element extractants may be grouped as acid extractants, chelating agents, buffered salt solutions, or unbuffered salt solutions (Houba et al. 1996; Jordan-Meille et al. 2012; Rauret 1998). In contrast to single-element extractants, Universal extractants are extracting mixtures that have been calibrated for most essential nutrients (Jones 1990; Zhang et al. 2013). They are popular among soil testing laboratories because they allow for the diagnosis of most elements based on a single extraction step. Soil test ratings are associated with a probability of yield response to additions of the nutrient.

For all these production systems, the proper development and implementation of soil-test based fertilizer programs for vegetable crop production require the appropriate selection of the source, rate, timing and placement of the fertilizer. Fertilizer rates may be found in production recommendation publications (Hochmuth 2003; Kemble 2014; Vallad et al. 2014). Timing and placement are often linked based on the form (granular or liquid) and the equipment used. This section covers (1) the basic concepts of soil testing and (2) fertilizer recommendations for vegetables grown in Florida; the placement, timing and calculation of (3) starter fertilization rates, (4) modified broadcast fertilizer rates, (5) banded fertilization rates, and (6) liquid fertigation rates. Finally, examples of how to properly calibrate fertilizer application equipment, how to adjust fertilizer rates when non-standard bed spacings are used, and how to estimate the nutrient contribution of broadcast-applied composts and manures to the nutrition of vegetable crops established on raised beds are provided.

3.3 Principles and Practices for Localized Fertilizer Applications to Vegetable Crops

3.3.1 Principle 1

The four pillars of vegetable production are (1) a marketing plan, (2) a fertilization plan, (3) an irrigation schedule, and (4) a pest management plan. Nutrients and water management are linked. All efforts to correctly manage nutrients may be negated by an inadequate irrigation program.

3.3.2 Principle 2

Fertilizer placement and application method are affected by crop method of establishment, irrigation method, and mulching (Table 3).

Table 3 Summary of fertilizer application methods used for crops grown in Florida with the main production systems

Irrigation method	Typical crops in Florida	Fertilizer application method				
		Broadcast	Modified broadcast	Banded	Injected	Foliar fertilization
Bare ground						
Seepage	Potato, cabbage, celery, radish, green bean, sweet corn, broccoli. summer squash, cucumber	Lime or sulfur when needed. 30–50% of the N and K, and 100% of P and micro-nutrients for closed-row crops	Preplant "bottom" or "cold" mix with 30–50% of the N and K, and 100% of P and micro-nutrients	Sidedress	N/A[a]	Recommended for micronutrients for crops grown on calcareous soils
Overhead	Green bean, sweet corn, sweet potato, broccoli		Preplant application of 30–50% of the N and K, and 100% of P and micro-nutrients	Sidedress	N/A	Most of the N and K included in irrigation water are taken up by the roots
Drip	Pumpkin, watermelon, small melons	Lime or sulfur when needed	Preplant application of 0–50% of the N and K, and 100% of P and micro-nutrients	Possible, not practical	Daily or weekly liquid fertilization	Recommended for micronutrients for crops grown on calcareous soils

First crop grown with polyethylene mulch						
Seepage	Tomato, bell pepper, eggplant, watermelon, small melons	Lime or sulfur when needed	Preplant "bottom" or "cold" mix with 30–50% of the N and K, and 100% of P and micro-nutrients	Dual bands on shoulder ("hot" mix)	N/A	Recommended for micronutrients for crops grown on calcareous soils
Drip	Tomato, bell pepper, eggplant, strawberry watermelon, small melons		Preplant application of 30–50% of the N and K, and 100% of P and micro-nutrients	Possible, not practical	Daily or weekly liquid fertilization	
Second or third crop grown in sequence on the same polyethylene mulch (double or triple cropping)						
Seepage	Summer squash, cucumber, watermelon, small melons	Not possible	Not possible	N/A	Weekly injection of liquid or dry fertilizer on the bed shoulders using a fertilizer wheel	Recommended for micronutrients for crops grown on calcareous soils
Drip	Small melons, cabbage, cucumber, watermelon	Not possible	Not possible	Possible, not practical	Daily or weekly liquid fertilization	

[a] N/A = not applicable

3.3.3 Principle 3

Fertilizer recommendations for vegetables grown in Florida are based on soil testing, and include (1) a base recommendation and (2) supplemental fertilizer applications allowed after (a) a leaching rain event (defined as a cumulative rainfall amount of 7.62 cm in 3 days or 10.16 cm in 7 days), (b) a measured “low” plant nutrient content established after leaf analysis or petiole sap testing, or (c) an extended harvest season (Table 4).

3.3.4 Principle 4

The “RRRRight” way to apply fertilizer is to (1) use the *Right Source* (what material should be used?), (2) use the *Right Rate* (how much material should be used)?, (3) applied at the *Right Time* (when should it be applied)?, and (4) positioned at the *Right Place* (where in the field and in relation to the crop roots should the fertilizer be placed?) (Hochmuth et al. 2014; Liu et al. 2015). This concept provides a blueprint for record keeping: date, crop growth stage, fertilizer formula or grade, quantity, placement, tractor operator, tractor speed, and weather conditions.

3.3.5 Practice 1

Startup (or “pop up”) fertilization: Phosphorus is an essential element for root growth and it may not be readily available to seeds and transplants when soils are cool (<12–15 °C) and/or damp. Starter solutions containing P, and some N and K (as mono-potassium phosphate, ammoniated and triple superphosphate together with ammonium nitrate or potassium nitrate) may promote early growth by supplying available P. Overall, starter solutions represent a small percentage of the total fertilizer program (10–20 $kg \cdot ha^{-1}$ of P_2O_5). For seeded crops, starter solutions may be applied in a band (as granular or liquid) 5 cm to the side of the seed and 5-cm deep. For transplanted crops, starter solutions are often dissolved in the transplant water and applied in the transplant hole. In this case, the solution is delivered by gravity from a tank located above the wheel that punches the holes in the polyethylene mulch. Holes in the wheel deliver the starter solution directly and only into the transplant hole.

3.3.6 Practice 2

Based of crop planting pattern and size of the root system, fertilization may be calculated and implemented based on field surface (broadcast application) or on length of planted rows (starter, modified broadcast, banded or injected fertilizer). Standard bed or row spacings have been determined for most vegetable crops

Table 4 Nitrogen and potassium recommendations for strawberry grown with plasticulture in Florida on sandy soils testing "low" in Mehlich-3 phosphorous and Mehlich-3 potassium[a]

Production system			Recommended-base fertilization					Recommended-supplemental fertilization	
				Injected					
				Growth period					
	Nutrient	Total	Preplant	First 2 weeks	Sept. to Jan.	Feb. and Mar.	April	"Low" plant nutrient content	Extended harvest season
		$kg \cdot HA^{-1}$	$kg \cdot HA^{-1}$	$kg \cdot HA^{-1}$ day^{-1}				$kg \cdot HA^{-1}$ day^{-1} for 7 days	
Drip irrigation, raised beds and polyethylene mulch	N	168	0–45	0.34	0.67	0.84	0.67	0.67–0.84	
	K_2O	168	0–45	0.34	0.67	0.84	0.67	0.67–0.84	
	P_2O_5	134	134	0	0	0	0	0	

[a]1 HA = 8333 m of beds; Source: Vallad et al. 2014; Conversions from original units made using 1 lb/A = 1.12 kg/HA

Table 5 Standard bed spacings and corresponding length of row (or bed) in one surface unit for the main vegetable crops grown in Florida[a]

Row spacing	45 cm	60 cm	75 cm	90 cm
Crop	Bean	Cabbage	Sweet corn	Potato, sweetpotato
Linear meters of row/ha	22,222	16,667	13,333	11,111
Bed spacing	120 cm	150 cm	180 cm	240 cm
Crop	Strawberry	Small melons	Tomato, bell pepper, eggplant	Watermelon
Linear meters of bed/ha	8333	6667	5556	4167

[a]Conversions from original units made using 1 ft = 30 cm; 1 acre = 43,560 sq-ft; 1 ha = 10,000 m^2

(Table 5). The length of bed (LBF, linear feet of row) in one acre may be calculated by dividing 43,560 sq-ft in 1 acre by bed spacing (BS): LBF (ft/acre) = 43,560 (sq-ft/acre) /BS (ft). The length of bed (L, meters of row, m) in one hectare may be calculated by dividing 10,000 m^2 ha^{-1} by the bed spacing (BS): L (m HA^{-1}) = 10,000 (m^2 ha^{-1})/BS (m). Note that 1 ha refers to a 1-ha field; 1 HA represents the standard length of row or bed at standard bed spacing.

3.3.7 Practice 3

Vegetable crops may be planted at bed spacings other than the standard ones when (1) fields are double or triple cropped, (2) limited land is available, or (3) when varieties with compact-growth habits are used. In this case, the conversion is done by expressing the recommended rate at standard bed spacing in kg/100 m of bed (Table 6).

3.3.8 Practice 4

The benefits of soil testing and correct fertilizer calculations are lost when application equipment is incorrectly calibrated (Table 7).

3.3.9 Practice 5

The contribution of cover crops, composts or manures that are broadcast applied over the entire field surface may be determined by identifying (1) the amount of material accessible by the roots and (2) the material mineralization rate (Table 8). In this example, the total nutrient supply made by a 10 t/ha application of compost was 140 kg·ha^{-1} of N, 160 kg·ha^{-1} of P_2O_5, and 84 kg·ha^{-1} of K_2O. However, only 15% (21/140), 35% (56/160), and 41% (34/84) for the muskmelon and 13% (18/140), 46% (74/160) and 52% (44/84) for the snap bean, of the total nutrient content in the compost are available to the first crops for N, P_2O_5, and K_2O, respectively.

Table 6 Adjustment to nitrogen fertilizer rates when non-standard bed spacings are used for (1) mini-watermelons and (2) a strawberry-muskmelon double crop sequence[a]

Crop	Length of bed ($m\ HA^{-1}$) [at standard (S) or reduced (R) bed spacing (m)]	Fertilizer rate based on planted surface $kg{\cdot}HA^{-1}$	Fertilizer rate based on unit row of bed kg/100 m	Fertilizer rate based on field surface $kg{\cdot}ha^{-1}$
Preplant application				
Watermelon	4167 [8 S][b]	56[b]	56/41.62 = 1.34	56
Mini watermelon	5556 [6 R][c]	56[b]	1.34[d]	$1.34 \times 55.56 = 74$
Mini watermelon	6667 [5 R][c]	56[b]	1.34[d]	$1.34 \times 66.67 = 89$
Injected fertilizer				
Strawberry	8333 [4 S][b]	168[b]–0[b] = 168	168/ 83.33 = 2.02	168
Muskmelon	6667 [5 S][b]	168[b]–56[b] = 112	112/ 66.67 = 1.70[d]	112
Muskmelon following strawberry	8333 [4 R][e]	168[b]–0[f] = 168	1.70[d]	$1.70 \times 8333 = 140$

[a]Non-standard bed spacings may be used (1) when land is limiting, (2) when compact-growth habit cultivars are used (mini watermelons, for example), or (3) two or three crops are grown consecutively on the same plastic-mulched beds (double or triple cropping)
[b]From the production recommendations
[c]Reduced bed spacing allowed by smaller vine growth of mini watermelons
[d]Fertilizer rate based on length of row remains constant for all the bed spacings for the same crop
[e]The bed spacing of muskmelon is that of the first strawberry crop
[f]Double cropping does not allow the placement of broadcast-incorporated preplant fertilizer; all the fertilizer needs to be injected

3.3.10 Practice 6

When plasticulture (raised bed culture, drip irrigation and polyethylene mulch) is used, preplant N and K_2O fertilizer is typically applied using the modified-broadcast method and incorporated into the raised bed; the remaining N and K_2O is applied through daily or weekly injections of liquid fertilizer (Table 9).

3.3.11 Practice 7

Though popular in the industry for N and K, foliar fertilization recommendations in Florida are usually limited to the application of micronutrients to crops grown on calcareous soils. Leaf anatomy (impermeable cuticle only interrupted by lenticels and stomata) is not conducive for using the leaf as a means of delivering large amounts of nutrients into the plant. High pH (>7.5) in these soils make soil applications of micronutrients inefficient as they rapidly react to become plant-unavailable hydroxides. Hence, foliar fertilization should be used for application of

Table 7 Calibration of fertilizer application equipment for (1) a banded application of pine bark and (2) a modified-broadcast application of chicken manure

Banded application of ammoniumnitrate and potassiumchloride
Situation: For soils testing "low" in Mehlich-3 K, N and K_2O fertilization recommendation for tomato grown with seepage irrigation consist of applying 56 kg·HA^{-1} of N and K_2O broadcast incorporated in the bed and 168 kg·HA^{-1} of N and K_2O applied equally in two bands placed approximately 30 cm off the bed center on each side. If a mixture of ammoniumnitrate and potassiumchloride is used, how much fertilizer needs to be applied to each band in 1 meter of row?
Ammonium Nitrate (NO_3NH_4; 34-0-0): 100 × 168/34 = 494 kg·HA^{-1} of NO_3NH_4 needed to supply 168 kg·HA^{-1} N rate
Potassium Chloride (KCl; 0-0-60): 100 × 168/60 = 280 kg HA^{-1} of KCl needed to supply 168 kg·HA^{-1} K_2O rate
The total amount of NO_3NH_4-KCl blend needed is 494 + 280 = 774 kg·HA^{-1}.
1 ha of tomato contains 10,000/1.8 = 5556 m of bed and 2 × 5556 = 11,112 m of band.
Hence, each band will contain 774/11,112 = 0.070 kg·m^{-1}.
Spreader calibration for the banded fertilizer
Situation: We need to calibrate the fertilizer spreader on a 10-m long tarp. Each tube is calibrated individually. How much weight of N-NH_4-KCl blend should be collected on the tarp if the spreader is well calibrated?
The target application rate calculated above was 0.070 kg m^{-1} of band. If the tarp is 10-m long and a single spreader is used, we should collect 10 × 0.070 = 0.7 kg of blend/10 m
The tractor operator makes 3 passes and collects 0.53, 0.58, 0.55 kg each time. Is this spreader calibrated? What do we do?
Make sure the tractor speed is constant over the tarp; check for uniformity of material; check for holes in the soil (uneven discharge)
Run 1 : (0.53 + 0.58 + 0.55)/3 = 0.553 kg (target: 0.70 kg)
Error: (0.553–0.70)/0.70 = –21%
The fertilizer is currently under-applied at a rate of 21%. Calibration must be improved!
So, the options are to (a) decrease tractor speed or (b) change settings to increase discharge rate based on the type of spreader used. Changes are made. The tractor operator makes 3 new passes and collects 0.68, 0.73 and 0.72 kg each time. Is this better?
Run 2 : (0.68 + 0.73 + 0.72)/3 = 0.71 kg (target: 0.70 kg)
Error: (0.71–0.70)/0.70 = +1.4%
The fertilizer is over-applied at a rate of 1.4%. This means that 170 kg·HA^{-1} of N and K_2O are applied instead of 168 kg·HA^{-1} of each. This is acceptable. The equipment is considered calibrated.
Modified-broadcast application of chicken manure and spreader calibration
Situation: We want to apply 50 kg N HA^{-1} using chicken manure (25 kg N t^{-1} @ 50% N available to first crop) to bell pepper grownon 180-cm centers. How much chicken manure should we collect on a 10-m long tarp?
10,000/1.8 = 5556 m of bed HA^{-1} on 180-cm bed spacing
So, we need 2000 kg·ha^{-1} = 2000 kg /5556 m of bed = 36 kg/100 m of bed
If we make a 10-m long run, we should collect 2000 × 10/5556 = 3.60 kg of chicken litter.
Trial runs need to be made as described above for the compost example.

Table 8 Contribution of organic materials to a fertilization plan based on crop planting pattern and mineralization rate

<table>
<tr><td colspan="2">Broadcast application of compost</td></tr>
<tr><td colspan="2">Situation: We want to apply 10 t·ha^{-1} of compost costing \$ 67t^{-1} + \$15 t ha^{-1} for spreading and transportation; compost has a fertilizer analysis of N 2%, P 1% and K 1% (dry weight basis), moisture content is 30%.</td></tr>
<tr><td colspan="2">Question 1: What rate of compost is this?</td></tr>
<tr><td colspan="2">10 t ha^{-1} =10,000 kg/10,000 m^2 = 1 kg m^{-2}</td></tr>
<tr><td colspan="2">We will apply 1 kg m^{-2} of compost, uniformly over the entire field, then we will incorporate it.</td></tr>
<tr><td colspan="2">Question 2: How much does this application cost?</td></tr>
<tr><td colspan="2">10 t × (\$67t^{-1} + \$15t^{-1} for application and transport) = \$820ha^{-1}</td></tr>
<tr><td colspan="2">Question 3: How much N, P_2O_5 and K_2O does this compost application provide?[a]</td></tr>
<tr><td colspan="2">Fertilizer analysis N 2%, P 1% and K 1% (dry weight basis) and moisture content: 30%</td></tr>
<tr><td colspan="2">Dry weight applied: 10,000 × 0.70 = 7000 kg</td></tr>
<tr><td colspan="2">Nutrient contributions:</td></tr>
<tr><td colspan="2">N: 7000 × 0.02 = 140 kg N ha^{-1}</td></tr>
<tr><td colspan="2">P: 7000 × 0.01 = 70 kg of P = 70 × 2.2910 = 160 kg P_2O_5 ha^{-1}</td></tr>
<tr><td colspan="2">K: 7000 × 0.01 = 70 kg of K = 70 × 1.2047 = 84 kg K_2O ha^{-1}</td></tr>
<tr><td colspan="2">Situation (ctd). We made a uniform broadcast application of compost. Good! Are the crop roots having access to all the compost? What will happen to the nutrients from the compost that was applied between the rows? Are all the nutrients available to the first crop? The twoside-by-side cases below show examples of a crop grown with plasticulture (Case 1: muskmelon) and of another crop grown on bare grown (Case 2: snap bean).</td></tr>
<tr><td>Case 1. We grow muskmelons on 75-cm wide beds and rows spaced 150-cm apart, how much nutrients will be accessible (under the plastic)?</td><td>Case 2. We grow snap beans on 45 cm row spacing and the roots grow 15 cm on each side, how much nutrients will be accessible (under the rows)?</td></tr>
<tr><td>In this case, only 75/150 = 50% of the compost will be under the plastic. Nutrients accessible to the muskmelon plant (assuming the roots system is mostly under the polyethylene mulch):</td><td>In this case, (15 + 15)/45 = 30/45 = 66% of the compost will be accessible by the roots. Nutrients accessible to the snap bean plants:</td></tr>
<tr><td>N: 0.50 × 140 kg = 70 kg of N</td><td>N: 0.66 140 kg = 92 kg of N</td></tr>
<tr><td>P: 0.50 × 160 kg = 80 kg of P_2O_5</td><td>P: 0.66 × 160 kg = 106 kg of P_2O_5</td></tr>
<tr><td>K: 0.50 × 84 kg = 42 kg of K_2O</td><td>K: 0.66 × 84 kg = 55 kg of K_2O</td></tr>
<tr><td colspan="2">Typically, 10–30% of N (we will use 20%), 70–80% of P (we will use 70%), and 80–90% of K (will we use 80%) will be available to the crop established immediately after compost application. How much nutrients will be available (released during the first crop and accessible to the roots)?</td></tr>
<tr><td>Nutrients available to the muskmelons (HA^{-1}):</td><td>Nutrients available to the snap beans (HA^{-1}):</td></tr>
<tr><td>N: 0.20 × 70 = 14 kg of N</td><td>N: 0.20 × 92 = 18 kg of N</td></tr>
<tr><td>P: 0.70 × 80 = 56 kg of P_2O_5</td><td>P: 0.70 × 106 = 74 kg of P_2O_5</td></tr>
<tr><td>K: 0.80 × 42 = 34 kg of K_2O</td><td>K: 0.80 × 55 = 44 kg of K_2O</td></tr>
</table>

[a]P × 2.29 = P_2O_5; K × 1.2 = K_2O; 1 HA = linear meters of bed (or row) in one hectare at standard bed (or row) spacing

Table 9 Example of fertilization rates used in conventional strawberry production: Granular modified broadcast preplant application rate and liquid injected weekly rate

Fertilizer program for strawberries
Situation. We are growing strawberries at a standard bed spacing of 120 cm. The soil test recommendation is 168-0-168 N-P_2O_5-K_2O ("high" P, "very low" K). In Florida, recommended N rate is not based on soil test and is a blanket total seasonal amount of 150 kg HA^{-1} with 0–50 kg HA^{-1} preplant incorporated in the bed, and the remaining injected weekly through the growing season starting at plant establishment.
We need to apply 34-0-34 N-P_2O_5-K_2O (1:0:1) preplant using a 15-0-15 fertilizer (a 1:0:1 type fertilizer).
How much 15-0-15 needs to be applied?
100 kg of 15-0-15 fertilizer contain 15 kg of N. We will need 227 kg of fertilizer applied to 8333 m of bed (or 227/8333 = 0.03 kg m^{-1}) to apply 34 kg N HA^{-1}.
What happens if 13-4-13 is used instead of 15-0-15?
Based on the label, 100 kg of fertilizer contains 13 kg of N. For 34 kg of N, we need 100 × 34/13 = 262 kg·ha^{-1} of 13-4-13. (or 262 kg of 13-4-13/8333 = 0.03 kg m^{-1} of row)
How much P_2O_5 was applied?
P: 4 × 262/100 = 11 kg·ha^{-1} of P_2O_5 We apply nutrients (here P) that are not needed. Hence, the choice of fertilizer matters!
We need to apply 0.84 kg HA^{-1} $day^{-1}$of N and K_2O (1:0:1) through the drip using liquid 8-0-8 (1:0:1 also) **How much liquid fertilizer is needed for a daily injection? For a weekly injection? How much needs to be ordered for the whole season?**
A daily rate of 0.84 kg N is also 0.84 × 7 = 5.88 kg N $week^{-1}$ (assuming that 1 L = 1 kg)
Volume needed for 1 day: 0.84/0.08 = 10.5 L HA^{-1}
Volume needed for 1 week: 5.88/0.08 = 73.5 L HA^{-1}
So, a 73.5-L weekly injection of 8-0-8 to a 1-HA field provides 5.88 kg of N, no P, and 5.88 kg of K_2O.
For a 23-week-long season, we will need 73.5 × 23 = 1690 L HA^{-1} $season^{-1}$.

micronutrients on these soils. Most of the N and K applied to crops like sweet corn and snap beans through over-head irrigation system reach the ground first, and are actually taken up by the roots.

3.3.12 Practice 8

Reality check: Units for all factors should be clearly known every time application rates are calculated. In the end, "the result must make sense".

4 Conclusion

Fertilizers may be lost through chemical transformations or movement below the root zone of vegetable cops. By placing fertilizer near the seeds, transplants or plants, localized applications of fertilizers are strategies that increase the uptake rate of applied nutrients, thereby reducing the application rates, the fertilization cost and reduce the environmental impact of vegetable production. They are most effective when used together with cover crop, reduced tillage, nitrification and ureases inhibitors, grafting, and irrigation management. Recommended field cultural practices that may increase NUE include soil testing, fertilization plans, irrigation schedules, controller-based real-time irrigation scheduling, low-pressure drip-irrigation, the use of the Soil Phosphorus Storage Capacity Index, controlled-release fertilizers, amendments that increase soil water holding capacity (such as biochar, polymers, or zeolites), or that increase soil organic matter content (such as manures, compost, or cover crops). Further progress in nutrient use efficiency may (and will) be achieved through breeding and molecular biology that target root architecture and transport sites inside the roots. Sap analyses and identification of the mechanisms that govern the gene expression in the scion under the control of compounds produced by the root stock, may help explain the molecular basis for grafting vigor. Further progress may also come from better management in the field (applying smaller quantities of fertilizer more often). Ultimately, the effectiveness of the practices adopted by growers depends on the level of awareness growers have about the risk of nutrient loss, the cost of those practices, and field variability.

Glossary

AMT Ammonium transporter
BMAP Basin management action plan
BMP Best management practices
BS Bed spacing
Ca Calcium
CEC Cation exchange capacity
cHATS Constitutive high-affinity transporting system
cLATS Constitutive low-affinity transporting system
CNR Crop nutritional requirement
CO_2 Carbon dioxide
DCD Dicyandiamide
DMPP 3,4-dimethylepyrazole phosphate
DNA Deoxyribonucleic acid
Ep Evaporation
ET Evapotranspiration
ETc Crop evapotranspiration
ETo Reference evapotranspiration
FDACS Florida Department of Agriculture and Consumer Services
FDEP Florida Department of Environmental Protection
ft Feet
$H_2PO_4^-$ Dihydrogen phosphate ion
HPO_4^{2-} Hydrogen phosphate ion
HA Standard length of row or bed in 1 hectare at standard bed spacing

iHATS Nitrate-inducible high-affinity transporting system
iLATS Nitrate-inducible low-affinity transporting system
K Potassium
K_2O Potassium oxide
lb Pounds
LBF Linear bed feet length
Mg Magnesium
N Nitrogen
NBPT N-(n-butyl) thiophosphoric triamide
NH_4^+ Ammonium ion
NO_3^- Nitrate ion
NOI Notice of intent
NRT Nitrate transporter bn
NUE Nutrient use efficiency
P Phosphorus
P_2O_5 Phosphorus pentoxide
PTR Peptide transporter
RNA Ribonucleic acid
SPAD Soil-plant analysis development
sq-ft Square feet
TMDLs Total maximum daily loads

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