Improving Nitrogen and Phosphorus Fertilizer Use Efficiency for Florida's Horticultural Crops

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SUMMARY. Florida's citrus (*Citrus* spp.), vegetable, and turfgrass industries must improve nitrogen (N) and phosphorus (P) fertilizer use efficiency to remain sustainable in an era of emerging environmental policies designed to protect water quality. Producers have traditionally used water-soluble N and P fertilizers because they are plentiful and economical. Improving nutrient use efficiency (NUE) is being addressed through implementation of best management practices (BMPs) such as nutrient management planning, proper fertilizer material selection, better application timing and placement, and improved irrigation scheduling. Emerging technology that will aid in this effort includes increased use of enhanced efficiency fertilizers (EEFs), organic soil amendments, fertigation, and foliar fertilization. However, any new technology shown to improve NUE must be economically feasible before it can be considered a BMP. Future research in this area will aim to improve the economics of EEFs and precision fertilizer application.

Florida's citrus, vegetable, ornamental, and turf growers walk a fine line as they attempt to maintain economical production while simultaneously protecting the surrounding environment from excessive nutrients. In the face of increased fertilizer cost and stringent environmental regulation, these industries have a critical need to improve nitrogen (N) and phosphorous (P) fertilizer use efficiency to remain sustainable. Plant nutrient management is intensive when producing high-value horticultural crops that demand high fertilizer and irrigation inputs. Producers cannot afford a decrease in crop volume or quality due to nutrient deficiency, especially considering the total capital outlay required to produce a crop [e.g., more than \$25,000/ha for tomato (*Solanum lycopersicum*) production]. When applied nutrients are not taken up by the crop, fertilization efficiency decreases and unused N and P can be lost through leaching or runoff to groundwater or surface water. Total maximum daily load (TMDL) implementation in Florida will limit N and/or P loading in watersheds where horticultural crops are grown. If nutrient management practices within a watershed are not efficient enough to meet prescribed TMDLs, then the industry could face penalties

that would threaten its viability in that watershed.

The objective of this article is to describe general avenues and new directions that Florida's horticultural crop producers can take to improve N and P nutrient use efficiency (NUE), defined as the ratio of the amount of fertilizer nutrient taken up by the target plant to the amount applied. First, common water-soluble fertilizer (WSF) materials that have been used for decades to supply N and P to horticultural crops are characterized, and best management practices (BMPs) that are being implemented to minimize off-site nutrient loss are summarized. Second, alternative fertilizer sources and methods of application that have been shown to improve NUE are explored. Finally, high-priority research topics that will improve our knowledge about how to keep nutrients in the horticultural crop root zone are suggested.

Water-soluble N and P fertilizers

Water-soluble fertilizers dominate in Florida because they are plentiful and cost considerably less than slow or controlled-release fertilizers. A negative aspect about water-soluble N fertilizer is that it readily and rapidly leaches through Florida's sandy soils with excessive rainfall or irrigation. Five materials make up essentially the entire suite of water-soluble N fertilizers used (Table 1). Each material has unique characteristics that make it suitable or unsuitable for particular horticultural applications (Sartain and Kruse, 2001). For example, the acidifying property of ammonium sulfate makes it desirable for application to acid-loving plants such as highbush blueberry (*Vaccinium corymbosum*). On the other hand, urea is not suitable for application to Florida's alkaline soils due to ammonia volatilization hazard.

Phosphorus fertilizers applied in Florida are almost entirely water-soluble materials. An exception occurs when a polymer-coated N-P-K material is used that applies a small amount of P in controlled-release form. The group of water-soluble P fertilizers used in Florida is comprised of four materials that each have unique characteristics (Table 2). They are quite versatile in their horticultural application, but there are a few instances where a particular material should not be used (Sartain and Kruse, 2001). For example, diammonium phosphate should not be applied to an alkaline soil due to volatilization of N and loss of P availability.

The efficiency of WSFs can be enhanced by using appropriate rates, sources, application timing, and placement.

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
2.54	inch(es)	cm	0.3937
0.4536	lb	kg	2.2046
48.8243	lb/1000 ft ²	kg·ha ⁻¹	0.0205
1.1209	lb/acre	kg·ha ⁻¹	0.8922
28.3495	oz	g	0.0353
0.001	ppm	g·L ⁻¹	1000
1	ppm	mg·L ⁻¹	1
2.3385	qt/acre	L·ha ⁻¹	0.4276
2.2417	ton/acre	t·ha ⁻¹	0.4461
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

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Table 1. Properties of water-soluble nitrogen (N) fertilizers used in Florida commercial horticulture production.

Property	Ammonium sulfate	Ammonium nitrate	Urea	Potassium nitrate	Calcium nitrate
Water solubility (g·L ⁻¹) ^z	Moderate (708)	High (1175)	High (780)	Moderate (132)	High (1211)
Ammonia volatilization potential	High ^y	Moderate ^y	High ^x	None	None
Calcium carbonate equivalent [per unit (20 lb) of N] ^z	-5.35	-1.80	-1.80	+1.80	+1.20
Salt index [per unit (20 lb) ^w of N]	3.25	3.06	1.62	5.34	4.19
Horticultural uses					
Turfgrass	X	X	X	X	
Citrus	X	X			X
Vegetables	X	X		X	X
Landscape	X	X	X		
Nursery	X	X			X
Greenhouse	X	X			X
Deciduous/tropical fruit	X	X			
Fertilizer solutions, any crop			X	X	

^z1 g·L⁻¹ = 1000 ppm, 20 lb = 9.1 kg.^yIf soil pH is alkaline.^xAt any soil pH.

Table 2. Properties of water-soluble phosphorus (P) fertilizers used in Florida commercial horticulture production.

Property	Concentrated superphosphate	Monoammonium phosphate	Diammonium phosphate	Ammonium polyphosphate	Phosphoric acid
Water solubility (%)	85–90	100	100	100	100
Reaction	Acidic	Acidic	Initially basic, then acidic	Slightly acidic	Acidic
Salt index [per unit (20 lb) of phosphate (P ₂ O ₅)] ^z	0.21	0.49	0.64	—	—
Horticultural uses					
Turfgrass	X	X	X		
Citrus	X	X	X		
Vegetables	X				
Landscape	X		X		
Nursery	X				
Greenhouse		X	X		
Deciduous/Tropical fruit	X	X	X		
Fertilizer solutions, any crop				X	X

^z20 lb = 9.1 kg.

Specific techniques to improve WSF efficiency in Florida's horticultural production systems are discussed in production guides (Obreza and Morgan, 2008; Olson and Simonne, 2007), and review articles (Hochmuth, 2003; Locascio, 2005), thus they will not be discussed in detail here.

BMPs to improve WSF use efficiency

In Florida, BMPs are defined as “practices based on research, field-testing, and expert review determined to be the most effective and practicable on-location means, including economic and technological considerations, for improving water quality in agricultural and urban discharges.” The formal procedure used to estab-

lish horticultural crop BMPs after the need was identified included: 1) forming a steering committee and technical work groups, 2) producing a draft BMP manual, 3) peer-review and revision, 4) holding public workshops, and 5) adopting the manual in state code. Producers who voluntarily implement BMPs receive a presumption of compliance with water quality standards and are eligible for cost-share funds to improve operations.

Florida Department of Agriculture and Consumer Services (FDACS) has published BMP manuals for sod, container nursery, vegetable, and citrus production (FDACS, 2000, 2002, 2004, 2005, 2006, 2007a, 2007b), while the Florida Department of Environmental Protection (FDEP) has produced BMP manuals for golf

courses and turf/ornamental landscapes (Thomas, 2007, 2008). Most nutrient BMPs are simple, common-sense, “good housekeeping” practices. In abbreviated form, they involve: 1) educating and training field operators about how to manage fertilizer, 2) developing a nutrient management plan, 3) using appropriate fertilizer sources and formulations, 4) using application equipment that applies fertilizer to target sites, 5) properly calibrating and maintaining application equipment, 6) using precision nutrient application where appropriate, 7) avoiding high-risk fertilizer applications (such as during the rainy season), 8) splitting fertilizer applications throughout the growing season, 9) adding organic matter to the soil whenever possible, and

10) using soil moisture sensors to improve irrigation scheduling.

Enhanced efficiency fertilizers (EEFs)

The American Association of Plant Food Control Officials describes EEFs as fertilizer products with characteristics that minimize the potential of nutrient losses to the environment, as compared with “reference soluble” products (Hall, 2006). Enhanced efficiency fertilizers include slow and controlled-release

materials as well as nitrification and urease inhibitors. Agronomic effectiveness of EEFs is not implied in this definition, but it is assumed. In Florida, high-volume use of EEFs in horticultural applications is limited to turfgrass, greenhouse, nursery, and landscape settings due to higher costs compared with WSF. Smaller amounts of EEFs are used in citrus replant situations and other specialty horticulture. For example, vegetable growers sometimes include slow-release N in fertilizer blends applied under plastic mulch.

NUTRIENT RELEASE FROM EEFs. There are several modes by which nutrients are released from EEFs (Table 3). Coated fertilizers contain water-soluble N (alone or in combination with other nutrients) surrounded by an impermeable or semipermeable coating. Nutrients are released by diffusion through the coating or following degradation of the coating. Examples include sulfur-coated urea (SCU), Osmocote® (Scotts, Marysville, OH), Nutricote® (Florikan, Sarasota, FL), and Polyon® (Agrium Advanced Technologies,

Table 3. Properties of enhanced efficiency fertilizers used in Florida commercial horticultural production.

Product	Nutrients	Properties
Synthetic organic compounds		
Ureaformaldehyde reaction products (UF) [e.g., methylene urea (MU)]	38%–40% nitrogen (N)	Low-solubility organic compound; biological N release influenced by soil temperature, pH and moisture; roughly a 90-d release period in Florida.
Isobutylidene diurea (IBDU)	31% N	N released by chemical hydrolysis to urea; release relatively unaffected by temperature; good cool season response; release is affected by particle size (smaller = faster); roughly a 60-d release period in Florida.
Coated materials		
Sulfur-coated urea (SCU)	32%–38% N	N release depends on thickness of sulfur (S) coating, biological activity, temperature, and soil pH; cool season response is erratic; S coating can be fragile, and if it cracks, the slow-release property is lost; roughly a 60-d release period in Florida.
Polymer/sulfur-coated fertilizers (PCU, PCSCU)	41%–43% N	Primary coating of S with a secondary polymer coat; use of S as a coating material decreases cost of production; coating is abrasion resistant; nutrients are released by a combination of diffusion and capillary action; release is less temperature sensitive than straight polymer-coated fertilizers.
Polyon® (Agrium Advanced Technologies, Sylacauga, AL)	41%–44% N	Polyurethane-coated urea; N is released by osmotic diffusion; release rate is influenced by coating thickness and temperature; coating is abrasion-resistant.
Osmocote® (Scotts, Marysville, OH)	Various concentrations of N, phosphorus (P), and potassium (K), plus secondary and micronutrients	Soluble fertilizer core coated with a polymer; nutrient release pattern varies with coating thickness; commercial products are a blend of different coating thicknesses; nutrient release is by diffusion through the coating; release is affected by temperature; designed release rates vary from 150 to 480 d.
Nutricote® (Florikan, Sarasota, FL)	Various concentrations of N, P, and K, plus secondary and micronutrients	Soluble fertilizer coated with polyolefin; nutrient release is controlled by coating composition, not thickness; continuous moisture is necessary for nutrient release; release period varies from 40 to 540 d, depending on coating properties.

Sylacauga, AL). Noncoated EEFs include materials of limited water solubility that release plant-available N as they decompose chemically or microbially. Examples include ureaformaldehyde (UF), methylene urea (MU), and isobutylidene diurea (IBDU). In all cases, moisture and temperature play a significant role in determining how quickly N and other nutrients are released.

It is important for a producer to understand how a particular EEF works and to know its designed release rate before applying it in a horticultural situation. Studies evaluating EEF use in vegetable production have emphasized how a crop can suffer if nutrient release is not fast enough (Csizinszky et al., 1993; Graetz et al., 1987). Simonne and Hutchinson (2005) measured N release rates of 18 EEFs tested for utility in growing potato (*Solanum tuberosum*). Only three materials released N at a rate fast enough for potato production; the rest of the materials were too slow. Figure 1 shows an example of an EEF release curve that is well-matched to plant needs (Medina et al., 2008). Citriblen® fertilizer (Scotts) is formulated for use in mature citrus groves, where recommendations suggest that two-thirds of the N should be released within 110 d after applying in the spring.

TIMING OF EEF APPLICATION. The goal in EEF application timing is to match the release curve with crop nutrient demand during the growing season (Schwab and Murdock, 2005). For example, newly planted citrus trees should be fertilized at

planting, while established trees should receive EEF in late winter or early spring before the first spring vegetative flush and bloom. Turf and ornamental landscapes in southern Florida can receive EEF between April and September, but in northern Florida, it should only be applied between May and July (Sartain, 2007). Vegetables should be fertilized with EEFs preplant, beneath the plastic mulch if applicable (Simonne and Hochmuth, 2007). For greenhouse and nursery crops, EEFs are typically incorporated into the potting media or topdressed after planting.

PLACEMENT OF EEF. Placement (e.g., surface vs. incorporated) is important to improve NUE and decrease leaching. In an EEF placement study, Broschat (2005) measured lower N, P, and K release rates from surface-applied Osmocote® and Nutricote® fertilizers compared with placing them 10 cm deep in the potting substrate. Million et al. (2007a) found that surface application of Osmocote® to sweet viburnum (*Viburnum odoratissimum*) did not affect plant growth compared with incorporation, but N and P leaching losses were reduced 16% and 25%, respectively, when the EEF was surface-applied. In a field study, EEFs undergoing evaluation for long-term use on sweet orange (*Citrus sinensis*) trees were applied to the soil surface even if the manufacturer's instructions stated that the material should be incorporated (Obreza et al., 1999). In all cases, surface application did not detrimentally affect EEF performance, likely because

it was applied within the wetted pattern of the microirrigation system that maintained a continuous moist environment on the grove floor.

TEMPERATURE AND MOISTURE EFFECTS ON EEF. Temperature and moisture can affect EEF release rate (Sartain and Kruse, 2001). In most cases, as temperature increases, nutrient release from an EEF increases. However, the temperature-release curve relationship has not been well defined in a quantitative way for many of the EEFs used in Florida. Surface-applied EEFs release nutrients more slowly than incorporated EEFs due to intermittent wetting and drying. For continuous nutrient release, EEF particles need to be continuously moist, but they do not require complete water immersion.

HORTICULTURAL PERFORMANCE AND N LEACHING. Numerous Florida studies have measured horticultural performance, and in some cases, leaching, of EEFs. Turfgrass has been the most studied crop in the past two decades. In a series of field experiments, polymer-coated ammonium sulfate and polymer-coated urea applied to bermudagrass (*Cynodon dactylon*), perennial ryegrass (*Lolium perenne*), and/or st. augustinegrass (*Stenotaphrum secundatum*) produced equal or better turf growth and quality ratings when compared with a standard fertilization program using WSF (Sartain, 1994c, 1995a; Varshovi and Sartain, 1993, 1996a, 1996b, 1996c). In addition, EEFs reduced N leaching losses by 50% to 75% compared with WSF (Sartain, 1992; Varshovi and Sartain, 1993). However, EEFs have not always performed better than WSF. In a large pot study, Saha et al. (2007) found that even though less N leaching occurred when st. augustinegrass was fertilized with EEF, higher plant quality was observed where WSF was used.

A typical question that a producer considering the use of EEF asks is: "Can I apply a lower fertilizer rate when using an EEF compared with a conventional WSF program and get the same response?" Environmentally enhanced fertilizer evaluation studies have been structured to answer this question by determining the rate by source interaction in full factorial experiments, but a conglomeration of results (Table 4) suggests there is

Fig. 1. Nitrogen (N) release patterns of Citriblen® (Scotts, Marysville, OH) enhanced efficiency fertilizer measured in southwestern and central Florida (Medina et al., 2008).

Table 4. Summary of Florida studies comparing enhanced efficiency fertilizers (EEFs) with water-soluble fertilizer (WSF) where it was possible to determine a rate by source interaction from a full factorial experiment.

Study reference	Crop	EEFs tested vs. WSF ^a	Did a lower rate of EEF perform as well or better than a higher rate of WSF?
Zekri and Koo, 1992	Non-bearing citrus trees	MU, SCU, IBDU, Osmocote® (Scotts, Marysville, OH)	Yes. In a 2-year period, EEFs applied at a 50% rate performed equally well compared with WSF applied at the recommended (100%) rate.
Locascio and Alligood, 1992	Bell pepper	MU, IBDU, Multicote® (Haifa Chemicals, Haifa, Israel), Nutricote® (Florikan, Sarasota, FL)	No. In a single-year study, there was no interaction between fertilizer source and rate with respect to pepper yield.
Sartain, 1993	Bermudagrass, ryegrass	IBDU, coated WSF	In a single-season study, no for turf growth, yes for turf visual quality; same visual quality from half-rate of EEF compared with full rate of WSF.
Csizinszky et al., 1993	Tomato	PCU	No. In a single-year study, the EEF was less effective than WSF.
Alva and Tucker, 1993	Newly planted citrus trees	Resin-coated (Meister®; Chisso-Asahi Fertilizer, Tokyo)	Yes. In a 2-year period, EEFs applied at a 50% rate or less performed equally well compared with WSF applied at the recommended (100%) rate.
Boman, 1993	Mature citrus trees	Osmocote®	Yes. In a 4-year period, the EEF applied at 15% and 25% rates performed equally well compared with WSF applied at the recommended (100%) rate.
Obreza, 1993	Newly planted citrus trees	IBDU, MU	No. In a 4-year period, there was no interaction between fertilizer source and rate with respect to tree growth, fruit yield, or juice quality.
Sartain, 1994a, 1994b	Bermudagrass, ryegrass	IBDU, PCSCU	Single-season study. No for both turf growth and visual quality.
Ferguson and Davies, 1995	Newly planted citrus trees	PCU, IBDU, Osmocote®	Yes. In a 4-year period, all EEFs applied at a 20% rate performed equally well compared with WSF applied at the recommended (100%) rate.
Sartain, 1995b	Warm- and cool-season turfgrasses	UF, MU, IBDU, coated WSF	Single-season study. No for turf growth and visual quality.
Sartain, 1996a	Ryegrass	IBDU, coated WSF	In a single-season study, no for turf growth, yes for turf visual quality; same visual quality from a half-rate of the EEF compared with a full WSF rate.
Sartain, 1996b	Bermudagrass	IBDU, coated ammonium sulfate	In a single-season study, no for turf growth and visual quality.
Alva and Paramasivam, 1998	Mature citrus trees	PCU	No. In a 3-year period, there was no interaction between fertilizer source and rate with respect to sweet orange yield.
Obreza et al., 1999	Newly planted citrus trees	Escote® (Spectrum Brands, Atlanta, GA), Meister®, Osmocote®, Nutricote®, Prokote® (Scotts)	Yes. In a 6-year period, Osmocote® applied at a 50% rate performed equally well compared with WSF applied at the recommended (100%) rate.
Hutchinson et al., 2003	Potato	PCU, PCSCU	Yes. In a single-year study, EEFs applied at 50% and 75% rates performed equally well compared with WSF applied at the recommended (100%) rate.
Obreza and Rouse, 2006	Young-bearing citrus trees	IBDU, MU	No. In a 4-year period, there was no interaction between fertilizer source and rate with respect to total soluble solids yield.

^aMU = methylene urea, SCU = sulfur-coated urea, IBDU = isobutylidene diurea, PCU = polymer-coated urea, PCSCU = polymer-coated sulfur-coated urea, UF = urea formaldehyde.

no definitive answer. Of the 16 experiments summarized, six showed that a lower rate of EEF performed as well or better than a higher rate of WSF, eight showed no rate advantage to EEF, and two showed mixed results depending on the measured response. Of the six “yes” answers, five involved citrus trees and one involved vegetables. Of the eight “no” answers, three involved citrus, three involved turfgrass, and two involved vegetables.

N leaching from field-applied EEFs is assumed to be minimal because, by design, these materials release water-soluble N at a slow rate. Nitrogen not released to the soil remains in an insoluble form or is protected from dissolution by a coating, therefore it cannot leach all at once. Leaching from EEFs has been measured in laboratory simulations with no plants (Table 5), measured in field lysimeters containing turfgrass (Table 6), and estimated in a central Florida citrus grove on deep sandy soil (Table 7). In all cases, N leaching from water-soluble N fertilizer was greater than leaching from EEFs. Nitrogen leaching from containerized plant production has also been measured (Broschat 1995; Table 8). In one experiment, plant growth substrate influenced the relative amount of fertilizer N that leached. Less nitrate leached from EEFs compared with WSF when plants were grown in pine bark–peat–sand media. When the media was sandy field soil, nitrate leaching did not differ between fertilizer types. Phosphorus leaching from EEFs was always significantly lower compared with WSF, regardless of potting substrate type. Plant growth was as good or better with EEFs compared with WSF.

Natural organic soil amendments and fertilizers

This grouping includes less processed materials like animal manure and biosolids that may or may not have a guaranteed nutrient analysis, plus more refined materials like fish and seaweed emulsions that are sold as commercial products with a guaranteed analysis. If an organic material is included as part of a nutrient management plan, the mineralization rate must be considered when determining the rate to apply (Treadwell et al.,

Table 5. Leaching of water-soluble and enhanced efficiency nitrogen (N) fertilizer applied to a sandy Entisol followed by exposure to simulated rainfall events.

Study reference	Fertilizer	N leached (% of N applied) ^z
Wang and Alva, 1996 ^y	Ammonium nitrate	100 a
	Isobutylidene diurea	32 b
	Meister® plastic coated	12 c
	(Chisso-Asahi Fertilizer, Tokyo)	
Paramasivam and Alva, 1997 ^x	Urea	28 a
	Poly-S® (Scotts, Marysville, OH)	12 b
	Meister® plastic coated	6 c
	Osmocote® (Scotts)	5 c

^zWithin each study, values followed by the same letter are not significantly different from each other at $P < 0.05$.

^y102 cm (40.2 inches) of simulated rainfall applied in eight events during a 29-d period.

^x40 cm (15.7 inches) of simulated rainfall applied in eight events during a 42-d period.

Table 6. Leaching of nitrogen (N) from water-soluble and enhanced efficiency fertilizer (EEF) sources 125 d after applying N fertilizer at a rate of 2 lb/1000 ft² (97.6 kg·ha⁻¹) to ryegrass (J.B. Sartain, unpublished data).

Fertilizer type	N source	N leached (% of N applied) ^z
Water-soluble	Ammonium sulfate	12.8 a
Water-soluble	Urea-ammonium nitrate	8.1 b
EEF	CoRon® (Helena Chemical, Collierville, TN)	7.2 b
EEF	Nutralene® methylene urea (Agrium Advanced Technologies, Sylacauga, AL)	2.9 c
EEF	Polygon® (Agrium Advanced Technologies)	2.8 c
EEF	Sulfur-coated urea	2.8 c
EEF	Isobutylidene diurea	1.1 d
EEF	Nitroform® ureaform (Agrium Advanced Technologies)	0.4 c

^zValues followed by the same letter are not significantly different from each other at $P < 0.05$.

Table 7. Estimated annual nitrate-nitrogen (NO₃-N) leached below the root zone of a central Florida citrus grove planted on deep sandy soil and treated with three methods of N fertilization. Data represent the mean of a 2-year period (Paramasivam et al., 2001). Quadratic regressions of annual NO₃-N leached versus N rate for each fertilization method were significant at $P < 0.05$.

N rate (kg·ha ⁻¹) ^z	Dry soluble fertilizer	Fertilization	EEF
	[NO ₃ -N leached (kg·ha ⁻¹ per yr)]		
56	—	—	0.8
112	11.4	17.3	2.2
168	12.4	21.3	5.6
224	13.9	26.9	—
280	22.0	32.2	—

^zkg·ha⁻¹ = 0.8922 lb/acre.

2007). Organic matter decomposes relatively quickly in Florida’s warm and humid climate. For example, Hanselman et al. (2004) showed that roughly half of the N in biosolids and two-thirds of the N in poultry (layer) manure mineralized to plant-available forms during the first year after application at several Florida locations. The N mineralization was front-loaded for poultry manure and bio-

solids (i.e., most of the N became plant-available in the first month after application, followed by a gradual release of the remainder during the subsequent 11 months). A similar release of N from seabird guano, fish powder, feather meal, and blood meal was observed by Hartz and Johnstone (2006). In their study, most of the applied N mineralized within 2 weeks.

Table 8. Container-grown foliage (peace lily) plant size and relative amount of nitrate-nitrogen (NO₃-N) and orthophosphate-phosphorus (PO₄-P) leached 6 months after enhanced efficiency fertilizer (EEF) or water-soluble fertilizer (WSF) application to pine bark-peat-sand media or sandy field soil (Broschat, 1995).

Fertilization method	Plant dry wt (g) ^z		NO ₃ -N leached (% of N applied)		PO ₄ -P leached (% of P applied)	
	Pine bark-peat-sand media ^y	Sandy field soil	Pine bark-peat-sand media	Sandy field soil	Pine bark-peat-sand media	Sandy field soil
Liquid WSF	30 a	22 b	48 b	47 a	28 a	17 b
Dry granular WSF	28 a	18 c	54 a	46 a	23 b	22 a
Lightly-coated EEF	31 a	24 ab	29 d	44 a	12 d	11 c
Heavily-coated EEF	33 a	27 a	35 c	45 a	18 c	16 b

^z1 g = 0.0353 oz.

^yValues followed by the same letter are not significantly different from each other at $P < 0.05$.

Fertigation

Nutrient use efficiency can be increased by substituting fertigation for pre-plant WSF application in vegetable production. When bell pepper (*Capsicum annuum*) yield was used an indicator, N use efficiency increased as the proportion of N applied via fertigation increased [Table 9 (Shaw et al., 1996)]. Increased yield implies more N in the fruit per unit area, hence less potential leaching. Additional benefits of fertigation for vegetable production are summarized by Locascio (2005).

Fertigation frequency for vegetables can vary from daily application to one fertigation per week (Simonne and Hochmuth, 2007). No advantage to daily versus weekly fertigation has been observed with proper irrigation management. Nitrogen fertilizer application is most precise if rates are determined by crop growth and resulting nutrient demand. For example, N rates for tomato and bell pepper begin at 0.5 lb/acre per day during the early part of the season and increase to 2.0 lb/acre per day at peak demand.

Citrus trees do not appear to be sensitive to fertigation application frequency. This characteristic allows wide flexibility when developing a fertigation schedule. For example, the 1-year growth response of newly planted citrus trees in Gainesville, FL, did not differ when fertigated 30, 10, or 5 times at the same total N rate (Willis et al., 1991). Growth observed with fertigation did not differ from that observed with dry granular fertilizer applied five times in 1 year. Fertigation frequency also was not a factor when applied to 6-year-old lysimeter-grown trees in Lake Alfred, FL [Table 10 (Syvertsen and Jifon, 2001)]. Neither

Table 9. Bell pepper marketable yield response to four preplant/fertigation nitrogen (N) fertilizer combinations applied under plastic mulch to a sandy Ultisol (Shaw et al., 1996).

N applied preplant (%)	N applied by fertigation (%)	Total fancy yield (t·ha ⁻¹) ^z	Total marketable yield (t·ha ⁻¹)
0	100	4.2	9.1
30	70	4.4	9.5
70	30	3.8	8.3
100	0	2.9	6.6
P value for treatment effect		0.0531	0.0006

^z1 t·ha⁻¹ = 0.4461 ton/acre.

N uptake efficiency nor the relative amount of applied N that leached was significantly different when comparing about 80 fertigations per year with about 12 per year.

Horticultural plant response to fertigation is as good or better than the response observed with well-managed dry soluble fertilization. In either case, irrigation (and sometimes drainage) water management is critical for success. Nitrogen leaching following fertigation can be minimized if the crop is not over-irrigated. It cannot be overemphasized how important irrigation duration is when fertigating. Although fertigation is sometimes referred to as “spoon feeding,” in this case, the “food” is water-soluble plant nutrients that can easily be driven beneath the plant root zone if too much water follows the fertilizer pulse (Simonne et al., 2003). It is true that fertigation prevents a large mass of nutrients from being leached in a single day (as could occur when heavy rain follows a dry fertilizer application), but leaching can still occur in smaller increments if irrigation management is poor. An interesting result of the study summarized in Table 10 was that even in a lysimeter with carefully controlled irrigation and a confined root system, about half

of the N applied via fertigation leached past the root zone.

Table 7 shows an example that is contrary to the principle outlined above. Irrigation scheduling in the test citrus grove was optimal, yet more N leached in the fertigation treatment compared with dry soluble fertilizer applications. The authors of this study (Paramasivam et al., 2001) explained that more N leaching occurred with fertigation “purely because of unexpected prolonged irrigation or unexpected high rainfall following certain fertigation events in both years.”

Foliar fertilization with N and P

CITRUS. The amount of plant nutrients that can be taken up through the leaves of a citrus tree is very small. However, there are special cases where foliar application of N and/or P is justified. It must be recognized that a positive response may be due to additional effects of the materials on tree physiology beyond simple enhancement of tree nutrition.

Forms of urea are available that can be readily absorbed by citrus leaves. Foliar urea sprays applied during the winter have enhanced the number of flowers and yield of ‘Valencia’ sweet oranges (Albrigo, 1999).

After cool temperatures or drought stress have occurred, applying 50 to 60 lb/acre of urea can enhance flower bud induction and may increase fruit yield. Maximum penetration of urea into citrus leaves occurs within 12 to 24 h after spray application (Orbovic et al., 2001). Optimum conditions for foliar uptake include air temperature between 77 and 88 °F, high relative humidity, and spray solution with a pH between 7 and 8 to prevent urea breakdown. Under favorable environmental conditions, roughly half of foliar-applied urea penetrates the leaves, while most of the other half is lost through volatilization. The rate of foliar-applied N should be considered as part of the total annual N rate applied to the grove. For example, a foliar spray of 50 lb/acre of urea applies 23 lb/acre of N. If the fertilization plan calls for a total of 180 lb/acre per year of N, only 157 lb/acre should be included in the soil-applied fertilizer program. In Florida citrus production areas where groundwater nitrate contamination exists or is seen as a potential problem, urea sprays should be evaluated to provide a portion of the tree N requirements, especially during the summer months when leaching potential is the greatest.

Citrus leaves are extremely impervious to phosphate (PO_4^{3-}) (Lovatt and Mikkelsen, 2006). Conversely, phosphite (PO_3^{3-}) is more readily absorbed into plant tissue, and once inside the plant, it remains stable. Phosphite does not readily convert to phosphate in the plant, therefore the nutritional value of absorbed PO_3^{3-} is uncertain. However, phosphite is officially recognized by FDACS as a source of P for crops. In Florida, a prebloom foliar application of 2.6 qt/acre of 28% P_2O_5 as potassium phosphite (K_3PO_3) to 'Valencia' sweet oranges significantly increased flower number, fruit yield, and total soluble solids yield compared with an untreated control (Albrigo, 1999). These results suggest that the effect of phosphite was not due to the molecule's fungicidal attributes, but to other growth-stimulating properties.

OTHER HORTICULTURAL CROPS. Foliar applications of N and P are not recommended for vegetable production because leaves cannot absorb sufficient quantities to correct a deficiency, and leaf burn is likely if this is attempted (Simonne and Hochmuth,

2007). This principle also applies to ornamental plants and turfgrass.

Example cost comparisons of EEF versus WSF programs

CITRUS. Although coated EEFs performed very well in a 6-year trial comparing them with a standard WSF program (1991–96), they would not have been economically feasible for commercial production. The EEF materials evaluated would have cost three to four times as much to use as WSF, even when the lower application cost was factored in (Obreza et al., 1999; Table 11). Extra yield obtained by using EEF did not nearly make up for the higher fertilizer cost.

VEGETABLES. A potato production study (Simonne and Hutchinson, 2005) determined that the cost of a water-soluble N fertilization program in most years would fall between \$72/ha and \$158/ha. Estimated EEF program cost would be about \$20/ha to \$195/ha more than the most expensive soluble N cost. This extra cost could be offset by reduced application cost and/or providing cost-share for the use of EEF.

How irrigation affects fertilizer use efficiency

Irrigation effects on fertilizer NUE for vegetable production were summarized by Hochmuth (2003) and Locascio (2005), and for citrus production by Obreza and Morgan (2008). Fertilizer use efficiency of container-grown ornamental production was improved by changing the irrigation and/or fertilization methods (Yeager and Henley, 2004). One change involved the conversion of overhead irrigation to microirrigation or capillary mat/wick irrigation. The other change involved the use of EEFs [Osmocote®, Nutricote®, Multicote® (Haifa Chemicals, Haifa, Israel), and Polyon®] with overhead irrigation. During a 4-year period, the growth index of peace lily (*Spathiphyllum* spp.) was about the same regardless of EEF source. However, the nitrate-N concentration in the groundwater 4 ft below the ground surface of the shade-house decreased as a result of EEF use (Fig. 2). In another study involving containerized production of Osmocote®-fertilized sweet viburnum, excessive irrigation (double the required

Table 10. Influence of the number of fertigations applied to 6-year-old sweet orange trees growing in lysimeter tanks on the relative amount of nitrogen (N) leached and on N use efficiency (Syvertsen and Jifon, 2001).

Yr	Fertigation treatment	Fertigations (no./yr)	Applied N that leached (%)	N use efficiency ^z
1999	With every irrigation	76	51	30
	Weekly	36	58	27
	Monthly	11	56	24
2000	With every irrigation	81	46	42
	Weekly	38	62	28
	Monthly	14	53	35

^z(Amount of N taken up by the citrus trees divided by the amount of N applied) × 100.

Table 11. Cost of six fertilizer programs (five enhanced efficiency fertilizers and one water-soluble fertilizer) applied to young 'Valencia' sweet orange trees from 1991 through 1996 compared with cumulative lb soluble solids yield and gross monetary return (Obreza et al., 1999).

Fertilizer	6-yr fertilization cost (\$/tree)	Cumulative yield [total soluble solids (lb/tree)] ^z	Gross return (\$/tree)
Prokote® (Scotts, Marysville, OH)	15.49	27.7	28.90
Sierra® (Scotts)	19.20	27.0	28.25
Nutricote® (Florikan, Sarasota, FL)	19.85	26.5	27.47
Meister® (Chisso-Asahi Fertilizer, Tokyo)	15.81	25.8	26.41
Escote® (Spectrum Brands, Atlanta, GA)	14.90	24.9	25.98
Water-soluble	5.06	24.2	25.40

^z1 lb = 0.4536 kg.

Fig. 2. Effect of nitrogen (N) fertilizer type and application method on groundwater nitrate-N concentration beneath ornamental plant production during a 4-year period (Yeager and Henley, 2004); EEF = enhanced efficiency fertilizer, 1 mg·L⁻¹ = 1 ppm.

rate) decreased plant growth, increased runoff volume from the nursery, increased N loss in runoff by 21% to 34%, and increased P loss in runoff by 28% to 38% (Million et al., 2007b).

Future research needs

Despite numerous improvements in fertilizer use efficiency that have occurred during the past several decades, further advancement is possible if research is undertaken on the following aspects of fertilizer use: 1) develop a short-term procedure to verify the nutrient release period claimed on EEF labels, 2) evaluate nutrient leaching characteristics of EEF materials applied in the field and greenhouse, 3) conduct an economic study of EEF use that determines the value of the environmental benefit, 4) improve irrigation scheduling techniques, and 5) develop new technology for precision nutrient application.

Conclusion

The efficiency of WSF application to Florida's horticultural crops has been enhanced by using appropriate rates, sources, application timing, and placement. Producers who implement contemporary BMPs are improving NUE to a greater extent due to the synergistic effect of commodity-oriented nutrient management practices joined in a holistic program. The next steps for producers to take include greater use of EEFs, wider adoption of fertigation, application of foliar fertilizers where appropriate, and more precise irrigation scheduling. Enhanced efficiency

fertilizers hold great promise to improve NUE even more, but additional research on characterization, plant response, environmental effects, and economics is needed before EEF use can be established as a BMP.

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