

Controlled-release Fertilizers for Vegetable Production in the Era of Best Management Practices: Teaching New Tricks to an Old Dog

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SUMMARY. Best management practices (BMPs) for vegetable crops are under development nationwide and in Florida. One goal of the Florida BMP program is to minimize the possible movement of nitrate-nitrogen from potato (*Solanum tuberosum*) production to surface water in the St. Johns River watershed without negatively impacting potato yields or quality. Current fertilizer BMPs developed for the area focus on fertilizer rate. Controlled-release fertilizers (CRF) have long been a part of nutrient management in greenhouse and nursery crops. However, CRFs have been seldom used in field-vegetable production because of their cost and release characteristics. Nutrient release curves for CRFs are not available for the soil moisture and temperature conditions prevailing in the seepage-irrigated soils of northern Florida. Controlled-leaching studies (pot-in-pot) in 2000 and 2001 have shown that plant-available nitrogen (N) was significantly higher early in the season from ammonium nitrate, calcium nitrate and urea compared to selected CRFs. However, N release from off-the-shelf and experimental CRFs was too slow, resulting in N recoveries ranging from 13% to 51%. Cost increase due to the use of CRFs for potato production ranged from \$71.66 to \$158.14/ha (\$29 to \$64 per acre) based on cost of material and N application rate. This

higher cost may be offset by reduced application cost and cost-share programs. Adoption of CRF programs by the potato (and vegetable) industry in Florida will depend on the accuracy and predictability of N release, state agencies' commitment to cost-share programs, and CRFs manufacturers' marketing strategies. All interested parties would benefit in the development of BMPs for CRFs.

While most nitrogen fertilizers commonly used in horticulture have a high water solubility, controlled-release fertilizers are fertilizer materials that allow for a delayed release of N. The delay in N release may be achieved by two types of strategies. First, N may be slowly released from long-chain alkane derivatives, such as isobutyldiene urea (IBDU) or crotonyldiene urea (CDU), under the action of soil microorganisms (Conner, 1996). Because several soil parameters, such as acidity, redox potential, and moisture, affect hydrolysis rate, release time may not be accurately predicted. In the other strategy, N fertilizer (often urea) is coated with either sulfur [sulfur-coated urea (SCU)], a polymer [polymer-coated urea (PCU)], or a combination of both [polymer-sulfur-coated urea (PSCU)]. The use of SCU in ornamental production in the 1960s was initiated to save labor and time by simplifying fertilization practices. CRFs were developed to replace multiple applications of soluble fertilizers by a single application of a material that could release fertilizer over time. Hence, early CRF research focused on extending release time to up to 36 months and on determining adequate N-P-K ratios in the CRF. As a result, CRFs are widely used today in ornamental production and turf maintenance.

Because at any time only a small fraction of N is in soluble form when CRFs are used, studies in the 1980s and later focused on the possible use of CRFs for environmental protection with all horticultural crops (Bardsley, 1987; Pool and Conover, 1982; Tyler et al., 1996; Yeager and Cashion, 1993). CRFs became tools to reduce the risk for N leaching by excessive irrigation or rain while maintaining productivity. For example, the use of Osmocote (The Scotts Co., Marysville, Ohio) in spathiphyllum (*Spathiphyllum* spp.) and areca palm (*Chrysalidocarp-*

pus lutescens) production significantly reduced leaching compared to soluble fertilizers (Broschat, 1995). Meister (Helena Chemical, Collierville, Tenn.) 100 and SCU produced the highest quality and growth of bermudagrass (*Cynodon dactylon*) (Sartain, 1988). The benefits of using CRFs in citrus production were also investigated in Florida. The growth and foliar N concentration of young 'Hamlin' orange trees (*Citrus sinensis*) were not affected by the use of IBDU as compared to soluble fertilizer (Marler et al., 1987). In another study, resin-coated fertilizer did not reduce foliar nutrient content and growth parameters of young citrus trees as compared to the same rate of dry fertilizer. In addition, the high rate of dry fertilizer [0.154 kg/tree (0.34 lb/tree) N per year] resulted in higher nitrate leaching at 1.5-m (5 ft) depth than all other treatments (Alva and Tucker, 1993). In some cases, citrus yields increased with CRF at rates of 76% of soluble fertilizer (Rouse et al., 1999). Because CRFs were approximately four times more expensive than conventional fertilizers and resulted in only a 15% yield increase, CRFs were not economical for citrus production.

The use of CRFs for vegetable production on sandy soils has long been investigated, with different levels of success. Early research first focused on partially replacing soluble N with a CRF source. Vegetable yields were either lower for potato and muskmelon (*Cucumis melo*) (Lorenz et al., 1972), bell pepper (*Capsicum annuum*) (Everett, 1977), tomato (*Lycopersicon esculentum*) (Csinzinszky, 1989; Csinzinszky et al., 1993; Lorenz et al., 1972; Sweeney et al., 1987), and strawberry (*Fragaria × anasassa*) (Albregts and Chandler, 1993), or similar for pepper (Hochmuth et al., 1994; Locascio and Alligood, 1992), tomato (Csinzinszky et al., 1992), and strawberry (Albregts et al., 1991) compared to those achieved with soluble fertilizer programs. In more recent trials, CRFs significantly increased potato marketable yields while not reducing tuber specific gravity (Hutchinson et al., 2002, 2003; Zvomuya and Rosen, 2001). Most of these studies used off-the-shelf CRFs with release times that tended to be too long to meet the nutritional requirements of fast-growing vegetable crops. Because historical yields could not be consis-

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tently achieved or increased with CRFs and because of higher CRF cost, CRFs have not been used widely in vegetable production.

Legislative changes in the 1990s have increased the importance of CRFs. In response to public awareness of environmental issues, section 303(d) of the Federal Clean Water Act of 1977 (U.S. Congress, 1977) required that states identify impaired bodies of water and establish total maximum daily loads (TMDLs) for pollutants entering these bodies of water. Best management practices were defined as specific cultural practices aimed at reducing the negative environmental impact of agricultural production while maintaining or increasing yield and productivity. In 1987, the Florida legislature passed the Surface Water Improvement and Management Act (SWIM), 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 defined a process for the development of TMDLs. The Florida Department of Agriculture and Consumer Services released *Water Quality/Quantity BMPs for Indian River Area Citrus Groves* in 2000 (Bowman, 2000) and the

Florida Vegetable and Agronomic Crop Water Quality and Quantity BMP Manual in 2003 (Florida Department of Agriculture and Consumer Services, 2003). Both manuals define the BMPs that will apply to these industries in Florida, and identify CRFs as a BMP that has direct impact on water quality (Bowman, 2000; Simonne and Hochmuth, 2003a). While N leaching may be reduced through irrigation scheduling and split nutrient injections for crops grown with drip irrigation, CRFs are particularly needed for reducing N leaching in crops grown on bare ground, with seepage irrigation [seepage irrigation consists of maintaining a water table perched on an impermeable layer; the top of the water table is maintained at the 45.7-cm (18 inches) depth for potato production]. Consequently, the University of Florida, the water management districts, and fertilizer manufacturers are actively cooperating in developing CRF products that are well suited for vegetable production (Table 1). Particularly, the length and pattern of release need to match crop growing period and N uptake pattern. Because N uptake patterns differ considerably among different crop species, it is unlikely that a single formulation

will provide adequate release for all crops (Hauck, 1985).

The testing and characterization of a CRF involves the study of crop yield response to rates and formulation and a knowledge of the release pattern. Crop response must be known before fertilization recommendations can be made. Knowledge of the release pattern is essential in predicting release, and eventually prescribing emergency sidedress applications when release may become too slow. Several obstacles exist in determining the N release pattern of a CRF in the field. First, as PCU CRFs are patented materials, owners of the patents are unlikely to share information on product release. Another obstacle, more fundamental in nature, is the definition of the term "release." The initial chemical form of N inside the prill is usually urea. Urea is first hydrolyzed and then transformed into ammonium and nitrate, which are the two N forms absorbed by plants. Physical release may be defined as the amount of N that exits the prill. Experimentally, physically released N may be quantified by the difference between total N initially in the prill and N left in the prill at the time of analysis. Physical release may also be indirectly determined by measuring

Table 1. Characteristics of and modifications needed to adapt existing controlled-release fertilizers (CRF) to vegetable production.

Attribute	Typical existing CRF ^z	Desirable CRF attributes for vegetable production ^z
Product identification	Coated with different colors based on manufacturers' preferences	CRF blending will be simpler if colors used for different release times are standardized. Color coding will also discourage the resale of CRF to other users at a higher price.
Fertilizer grade	Most existing products supply nitrogen (N), phosphorus (P), and potassium (K).	Because vegetable fertilization is soil test-based, N, P, and K application rates may be different. Single source CRFs (N-0-0, 0-P-0, or 0-0-K) will allow that.
Nitrogen form	Most existing products are urea-coated fertilizers. The availability of nitrate and ammonium for plant growth depends on the activity of soil ureases and of microorganisms (<i>Nitrosomonas</i> and <i>Nitrobacter</i>).	The optimum nitrate:ammonium (NO ₃ -N:NH ₄ -N) ratio for most vegetable crops is 3:1. Excessive NH ₄ -N is toxic for plants and reduces growth and yield.
Time of release	From 3 to 18 months or more	Vegetables are fast-growing crops (1 to 3 months). Thin coatings will speed the release.
Predictability of release	Nutrient release curves are typically proprietary information of the manufacturers. Fertilizer labels provide an expected release time at a constant temperature. No standard protocol exists to develop release curves.	Because moisture and/or temperature conditions may alter nutrient release, predictability of release should be accurate enough to allow for supplemental fertilizer application before tissue testing detects decline in nutrient levels.
Cost	Typical products are priced at \$772 to \$1323/t for a 46N-0P-0K grade; this corresponds to \$1.76/kg to 2.87/kg of N.	An application of 224 kg·ha ⁻¹ of N using urea costs approximately \$124/ha or \$0.55/kg of N. This makes the cost of N three to five times less when soluble sources are used compared to CRF. Who will pay for the difference?

^z 1 t = 1.1 ton; \$1/kg = \$0.454/lb; 1 kg·ha⁻¹ = 0.89 lb/acre.

soil N. The N fractions representing physically released N are urea (soluble and partially hydrolyzed), ammonium, nitrate, and, eventually, some nitrite. Immobilized N, volatilized N, or other sources of N loss are not accounted for. In either case, physical release focuses on the behavior of the CRF, but is not representative of plant-available N. In contrast, immediately plant-available N is represented by the ammonium and nitrate fractions found in the soil, but does not include N in the form of urea. Urea is readily soluble in water, and may be subject to leaching (Benson and Barnette, 1939; Beri et al., 1978). Hence, no single fraction has been used as the standard method for quantifying release.

A third obstacle found in determining N release from a CRF is the assessment of the relative importance of water and temperature in controlling the release rate. While most available commercial literature suggests that release is primarily controlled by temperature (Shoji, 1999), recent studies have shown that a combination of both factors affect release (Hicklenton and Cairns, 1992; Husby et al., 2003). Therefore, the experimental determination of a N release curve must account for these two factors, which may be achieved under laboratory conditions. By incubating CRFs samples at known temperatures, release curves have been determined by treating aliquots with ureases, and quantifying the amount of ammonium present in the aliquot (Shaviv, 1996) or by evaporating soluble salts to dryness and weighing dry salts (Hicklenton and Cairns, 1992). Another method for determining N release curves is to place the CRF into water and quantify released material by refractometry at regular intervals. Indirect determination of N release may be made by monitoring changes in leachate electrical conductivity and pH (Paramasivam and Alva, 1997). All of these methods have the advantage of being simple and require limited equipment. However, release conditions in the laboratory (preset temperature, release in full immersion over the entire release period) are not representative of release conditions in the field. In the field, CRFs are exposed to wetting and drying cycles. Also, in the field soil temperature is likely to fluctuate, especially in hyperthermic course-textured sandy soils. These methods need to be modified when

plant-available N release needs to be determined. It is possible to determine CRF nutrient release from pot-in-pot experiments with pots buried in the field and watered regularly. In this situation, fluctuations in temperature in the pots are similar to those in the soil. The outer pot allows for fast and easy leachate recovery.

With an acreage of approximately 13,760 ha (34,000 acres) and a value of \$150 million, potato is one of the major vegetable crops grown in Florida with seepage irrigation. The development of CRF for potato production at a competitive price has the potential to create a win-win situation for growers and regulatory agencies (Livingston-Way, 2000). As a first step, this research investigates release curves of off-the-shelf and first-generation experimental CRF formulations to be used alone or in blends for potato grown with seepage irrigation. The objectives of this work were to 1) define the ideal attributes of a CRF for potato production, 2) determine the nutrient release pattern of selected CRFs, and 3) assess the economic feasibility of using CRF for potato production.

Materials and methods

NUTRIENT RELEASE PATTERN FOR CRFs. Pot-in-pot trials were conducted at the University of Florida's Plant Science Research and Education Unit Yelvington Farm in Hastings, Fla., in 2001 and 2002. Experimental procedures used were similar for both years unless otherwise specified. Two 20.3-cm-diameter (8 inches) plastic pots were nested within each other and separated by 1.9-cm (3/4 inch) spacers. The inner pot was filled with an Ellzey fine sand (sandy, siliceous, hyperthermic, Arenic Ochraqualf) collected from the top 30.5-cm (12 inches) zone of a nearby potato field. Selected fertilizers (Table 2) were mixed with the soil in each pot at N rates of 6.18 and 4.80 g/pot (0.218 and 0.169 oz/pot) in 2001 and 2002, respectively. The 2001 rate corresponded to 224.2 kg·ha⁻¹ (200 lb/acre) which is the University of Florida/Institute of Food and Agricultural Sciences (UF/IFAS) recommended rate of N for potato production (Hochmuth et al., 2003) and the BMP rate for potato production in northern Florida (Livingston-Way, 2000). The rate was reduced in 2002 to minimize errors due to the dilution of leachate samples needed to match

the calibration range of the analytical equipment used for nitrate (NO₃-N) and ammonium (NH₄-N) analyses. Once filled with the soil/fertilizer mixture, the double pots were buried in the field in hills used for potato production on 26 Mar. 2001 and 3 Mar. 2002 (day after start, DAS = 0) so that the top of the lower pot was 2.5 cm (1 inch) above the top of a potato hill. Screened wholes in the bottom of the inside pot allowed for water drainage and contained soil particles in the upper pot. A removable plastic cover was placed on top of each double pot to isolate the pots from rainfall and reduce evaporative losses. Pots were buried 61.0 cm (24 inches) apart.

Approximately every 7 d, 400 mL (13.5 fl oz) of deionized water were added to the top of each pot and allowed to drain into the lower pot for 24 h. A 400-mL volume applied to these pots was equivalent to a 1.194-cm (0.47 inch) rainfall event. UF/IFAS definition of a leaching rain is 7.6 cm (3 inches) of rain in 3 d or 10.2 cm (4 inches) in 7 d (Simonne and Hochmuth, 2003b). The next day, the volume of water collected in the lower pot was recorded. Leachate aliquots were collected and frozen before being shipped to the University of Florida's Analytical Research Laboratory in Gainesville, where NO₃-N and NH₄-N concentrations were determined colorimetrically by EPA methods 353.2 and 350.1, respectively (U.S. Environmental Protection Agency, 1983a, 1983b). The amounts of NO₃-N and NH₄-N leached on each sampling date were calculated by multiplying leachate volume by leachate concentration. Immediately plant-available N recovered on each date was calculated as the sum of NO₃-N and NH₄-N recovered on that date, and cumulated.

The experiments were arranged in a randomized complete-block design with three replications. Data were analyzed with Proc GLM (SAS, 2001) and means were compared using Duncan's multiple range test (5%). Coefficients of variation were calculated as 100 times the ratio between the standard deviation and the mean.

Daily average soil temperature data at the 10-cm (3.9 inches) depth were downloaded from the Florida Agricultural Weather Network (FAWN) web site (UF/IFAS, 2003). The sum of soil temperature between each sampling date was calculated by cumulating

Table 2. Selected fertilizer sources for the pot-in-pot studies in 2001 and 2002 at the University of Florida's Plant Science Research and Education Unit Yelvington Farm in Hastings, Fla., on an Ellzey fine sand.

Treatment	Manufacturer ^z	Grade (N-P-K)	Type ^y	Nitrate-N (%)	Ammonium-N (%)	Urea-N (%)
2001						
Ammonium nitrate + urea	Gator Fertilizer	34-0-0 + 46-0-0	Soluble Soluble	25	25	50
Urea	Gator Fertilizer	46-0-0	Soluble	0	0	100
Calcium nitrate	Hydro	15-0-0	Soluble	100	0	0
Ammonium nitrate	Gator Fertilizer	34-0-0	Soluble	50	50	0
Polymer-sulfur-coated urea (PSCU) 3 + polymer-coated (PCU) ^y (50:50 by weight)	Scott	35-0-0 + 43-0-0	CRF	0	0	100
Scott's PCU ^y	Scott	43-0-0	CRF	0	0	100
Mid-size isobutyldiene urea (IBDU)	Scott	31-0-0	CRF	0	0	100
PCU Coating 1 ^y	Scott	38-0-0	CRF	0	0	100
PCU Coating 2 ^y	Scott	37-0-0	CRF	0	0	100
PCU Coating 3 ^y	Scott	35-0-0	CRF	0	0	100
Osmocote	Scott	11-4.8-9.11	CRF	0	11	89
Osmocote Plus	Scott	15-3.9-10	CRF	8	7	85
2002						
Control		None		0	0	0
Ammonium nitrate	Gator Fertilizer	34-0-0	Soluble	50	50	0
S-8909	Scott	37-0-0	CRF	0	0	100
Extend	Scott	43-0-0	CRF	0	0	100
S-9593	Scott	11-4.7-9.1	CRF	0	0	100
CRF-01 ^x	X ^s	38-0-0	CRF	0	0	100
Type 10	Meister	40-0-0	CRF	0	0	100
Type 20	Meister	40-0-0	CRF	0	0	100
Multicote	Haifa Chemicals	40-0-0	CRF	0	0	100
CRF-04 ^x	X	41.1-0-0	CRF	0	0	100
CRF-05 ^x	X	40.3-0-0	CRF	0	0	100
CRF-06 ^x	X	41.8-0-0	CRF	0	0	100

^zGator fertilizer, Hastings, Fla.; Hydro North America, Holland, Mich.; The Scott Company, Marysville, Ohio; Haifa Chemicals, Haifa Bay, Israel.

^yCRF = Controlled-release fertilizer.

^sNames withheld in accordance to active secrecy agreements between the University of Florida and manufacturers.

the mean daily soil temperature and was used to assess similarities in temperature regimes during both years.

For each fertilizer material, the number of days needed to recover 25%, 50%, 75%, and 90% of the total N applied to each pot were determined. Plant-available N recovery was calculated by dividing the cumulated plant-available N recovered on the last sampling date (67 and 78 DAS in 2001 and 2002, respectively) by 6.18 and 4.80 mg/pot in 2001 and 2002, respectively, which were the amounts of N placed in each pot. Because small amount of residual N are likely to reduce off-season N leaching, a CRF suitable for potato production should release 80% to 90% of N over the cropping season.

ECONOMIC FEASIBILITY. The goal of the economic analysis was to evaluate different pricing strategies

and determine the corresponding amount of cost-share needed to offset the additional production cost due to the use of a CRF. Currently, potato growers in northern Florida use a urea-ammonium nitrate (UAN) blend (32N-0P-0K). A cost-share scale exists for growers who voluntarily reduce their N rates; highest cost-share level is provided for the BMP rate (Table 3). The additional cost was calculated as the difference between the cost of using the UAN blend and a CRF. The cost of the UAN program was determined for a range of N rates and a range of UAN prices. The range of N fertilizer rates used was 168.1 to 336.2 kg·ha⁻¹ (150 to 300 lb/acre), which includes the 280.2 kg·ha⁻¹ (250 lb/acre) average industry rate and the BMP rate. Selected UAN blend price range was \$143 to \$187/t (\$130 to \$170 per ton). The cost of the CRF program was

Table 3. Cost-share program used for nitrogen rates on potato production sponsored by the St. Johns River Water Management District, Palatka, Fla.^z

Nitrogen (N) fertilizer rate (kg·ha ⁻¹ of N) ^y	Cost-share rate (\$/ha) ^y
281+	0
281-253	25
253-225	49
225 ^x -196	74
196-168 ^w	None currently

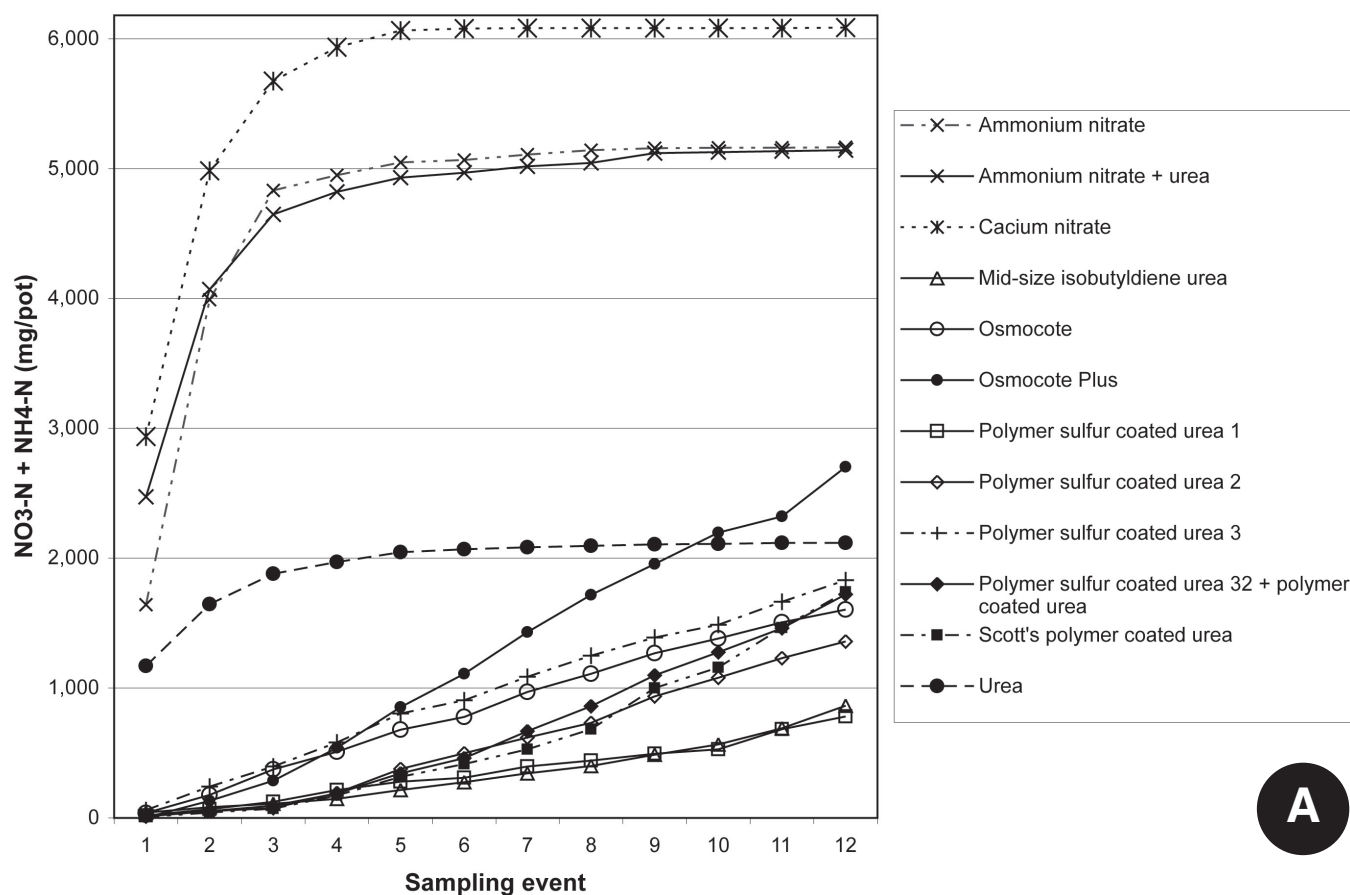
^zFrom Livingston-Way, 2000.

^y1 kg·ha⁻¹ = 0.89 lb/acre, \$1/ha = \$0.40/acre.

^xUniversity of Florida/Institute of Food and Agricultural Sciences N recommended rate for potato production (Hochmuth et al., 2003).

^wPossible rate range for controlled-release fertilizers.

determined for an N application rate range of 140.1 to 252.2 kg·ha⁻¹ (125 to 225 lb/acre). Selected CRF price range was \$331 to \$1213/t (\$300 to \$1100 per ton).



A

Fig. 1. Cumulative immediately plant-available nitrogen (nitrate + ammonium) (A, above), ammonium-nitrogen (B, next page, top), and nitrate-nitrogen (C, next page, bottom) recovered in leachate of selected fertilizer in a pot-in-pot study conducted at the University of Florida's Plant Science Research and Education Unit Yelvington Farm in Hastings, Fla., in 2001 on an Ellzey fine sand [total nitrogen applied was 6.18 g/pot (0.218 oz/pot)]. See Table 2 for complete information on fertilizer sources. Sampling dates 1 to 12 occurred on 1, 4, 5, 11, 18, 26, 33, 39, 47, 53, 60, and 67 d after initial leaching, respectively.

Differences in application costs for soluble and CRF fertilizer programs were not included because they were numerically small compared to the cost of the fertilizer themselves. Current fertilizer recommendations are to split sidedress fertilizer in one or two applications (Hochmuth et al., 2003) while CRFs are entirely applied preplant. Hence, when the estimated cost of fertilizer application is \$7.41/ha (\$3/acre) (Hutchinson and Simonne, 2003), the savings on fertilizer application by using CRF would be \$14.83/ha (\$6/acre) [\$7.41 vs. \$22.24/ha (\$3 vs. \$9/acre)].

Results and discussion

EXPERIMENTAL CONDITIONS. Leachate was collected on 12 sampling dates each year, between 1 and 67 DAS in 2001, and 2 and 78 DAS in 2002. Because pots were covered with a lid, rainfall pattern had no effect on the test

and was unlikely to affect release pattern. The cumulative soil temperatures were 18, 70, 89, 210, 372, 552, 704, 833, 1013, 1162, 1343, and 1552 °C (64.4, 158.0, 192.2, 410.0, 701.6, 1025.6, 1299.2, 1531.4, 1855.4, 2123.6, 2449.4, and 2825.6 °F) in 2001, and 30, 73, 326, 473, 634, 784, 947, 1124, 1307, 1497, 1668, and 1852 °C (86.0, 163.4, 618.8, 883.4, 1173.2, 1443.2, 1736.6, 2055.2, 2384.6, 2726.6, 3034.4, and 3365.6 °F) in 2002, for sampling dates 1 to 12, respectively. Temperature accumulation was representative of typical temperature regimes in the spring in the area and was similar in both years. For example, early in the season, accumulated temperatures were 552 °C on 26 DAS in 2001 compared with 634 °C on 29 DAS in 2002. Later in the season, cumulative temperatures were 1552 °C on 67 DAS in 2001 compared to 1668 °C on 71 DAS in 2002. Yet,

because tested materials were different in both years and the lengths of the sampling periods were different, data were analyzed by year.

POT-IN-POT. For both years and each sampling date, significant differences were observed in $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, and immediately plant-available N recovered (all $P < 0.01$; R^2 ranged from 0.77 to 0.95; Figs. 1, 2). Coefficients of variation tended to be higher in 2002 than in 2001. In 2001, cv ranged from 62% to 71% and from 115% to 151% for cumulative $\text{NO}_3\text{-N}$ recovered, from 36% to 90% and from 23% to 178% for cumulative $\text{NH}_4\text{-N}$ recovered, and from 45% to 69% and 33% to 116% for cumulative immediately plant-available N for 2001 and 2002, respectively. Higher cv values for cumulative $\text{NO}_3\text{-N}$ recovered than for cumulative $\text{NH}_4\text{-N}$ recovered were attributed to the additional chemical transformation needed to obtain NO_3

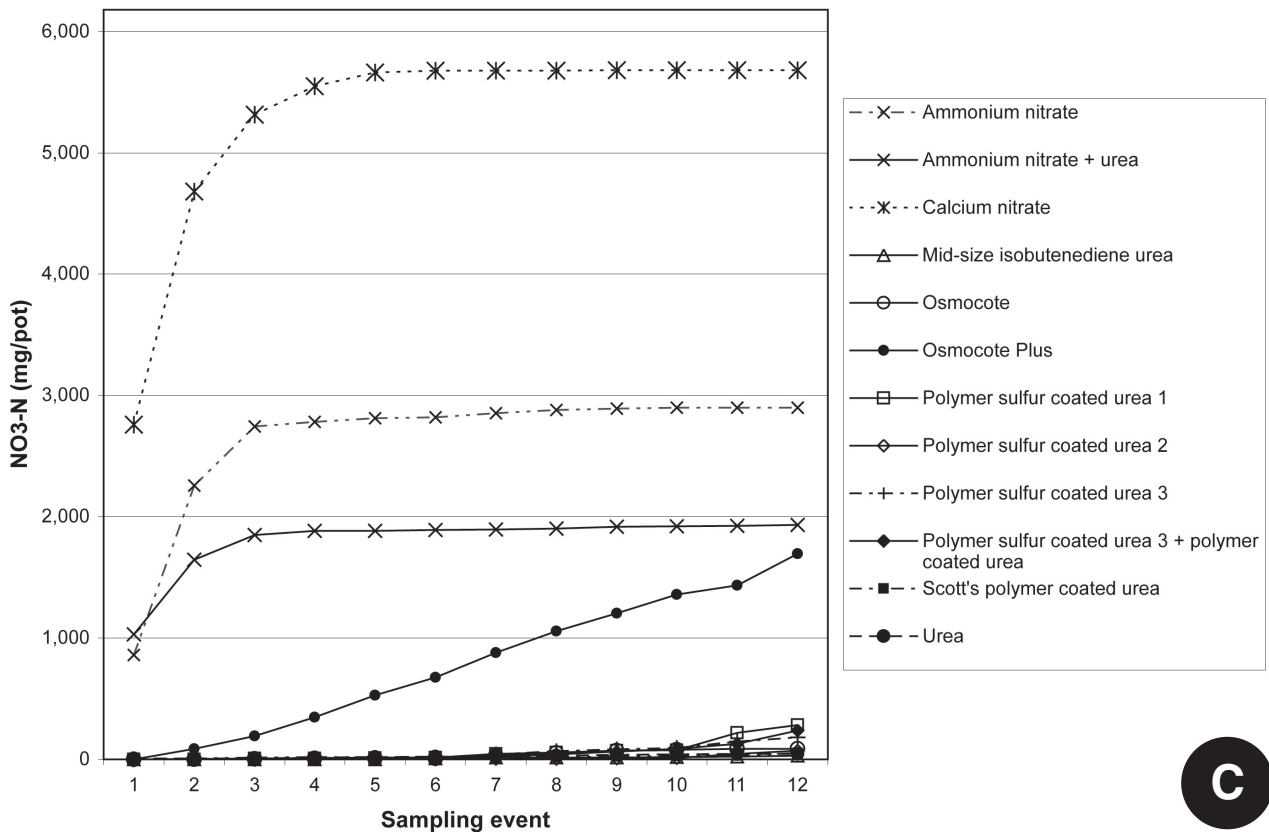
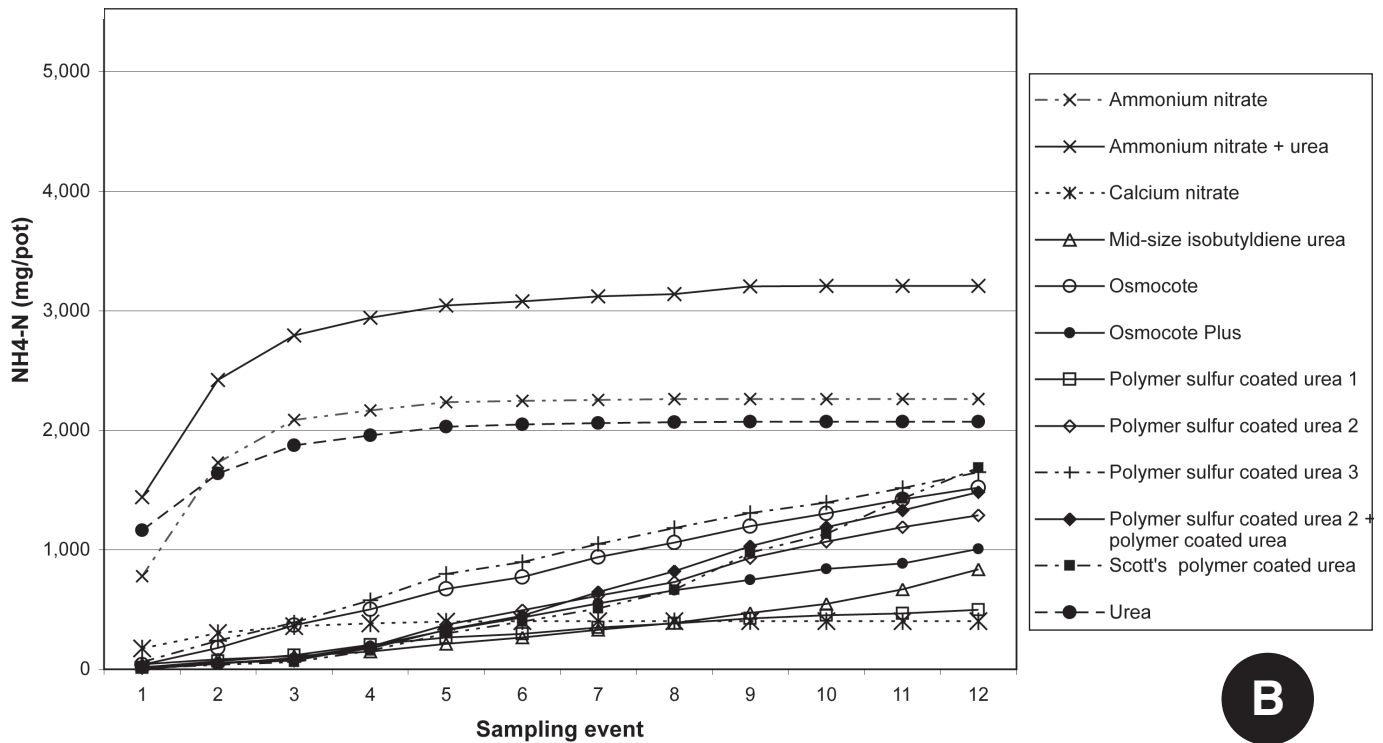


Fig. 1 (continued from previous page). Cumulative immediately plant-available nitrogen (nitrate + ammonium) (A, previous page), ammonium-nitrogen (B, this page, top), and nitrate-nitrogen (C, this page, bottom) recovered in leachate of selected fertilizer in a pot-in-pot study conducted at the University of Florida's Plant Science Research and Education Unit Yelvington Farm in Hastings, Fla., in 2001 on an Ellzey fine sand [total nitrogen applied was 6.18 g/pot (0.218 oz/pot)]. See Table 2 for complete information on fertilizer sources. Sampling dates 1 to 12 occurred on 1, 4, 5, 11, 18, 26, 33, 39, 47, 53, 60, and 67 d after initial leaching, respectively.

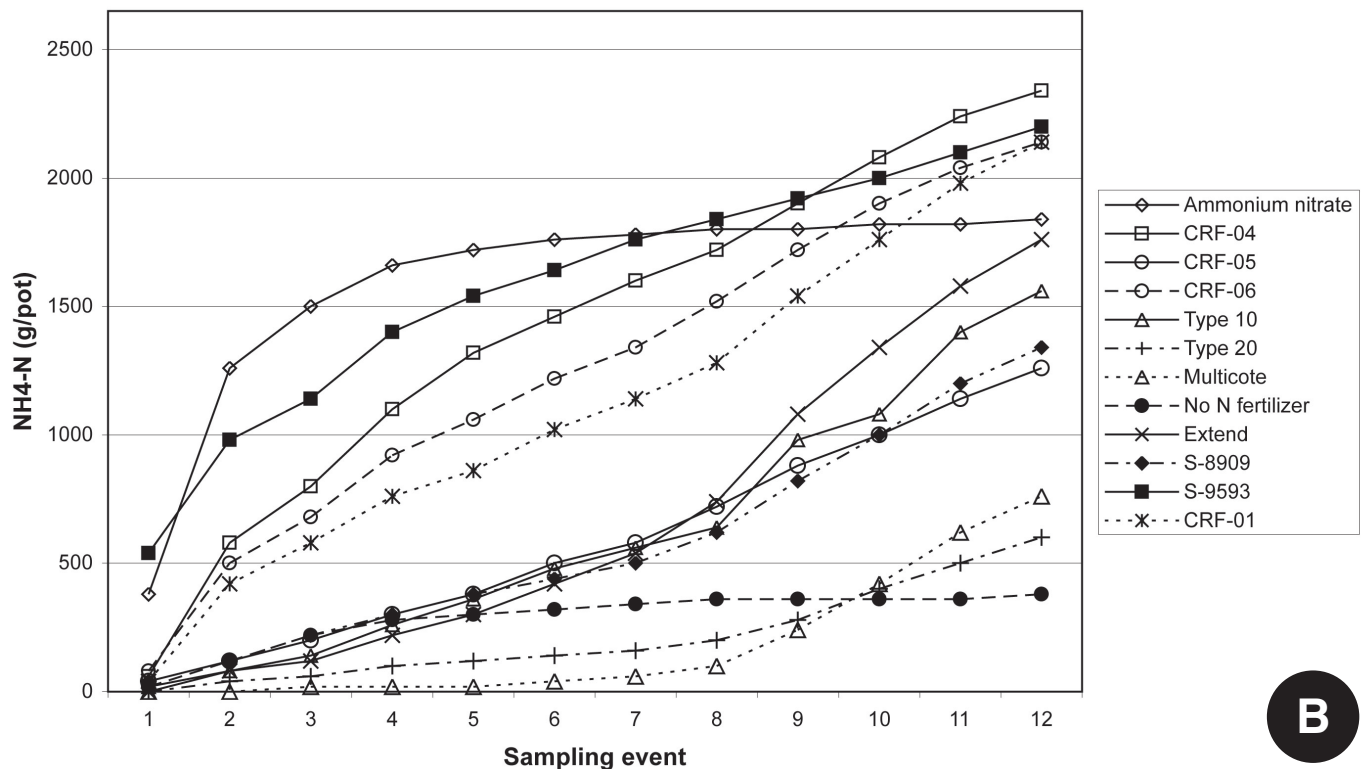
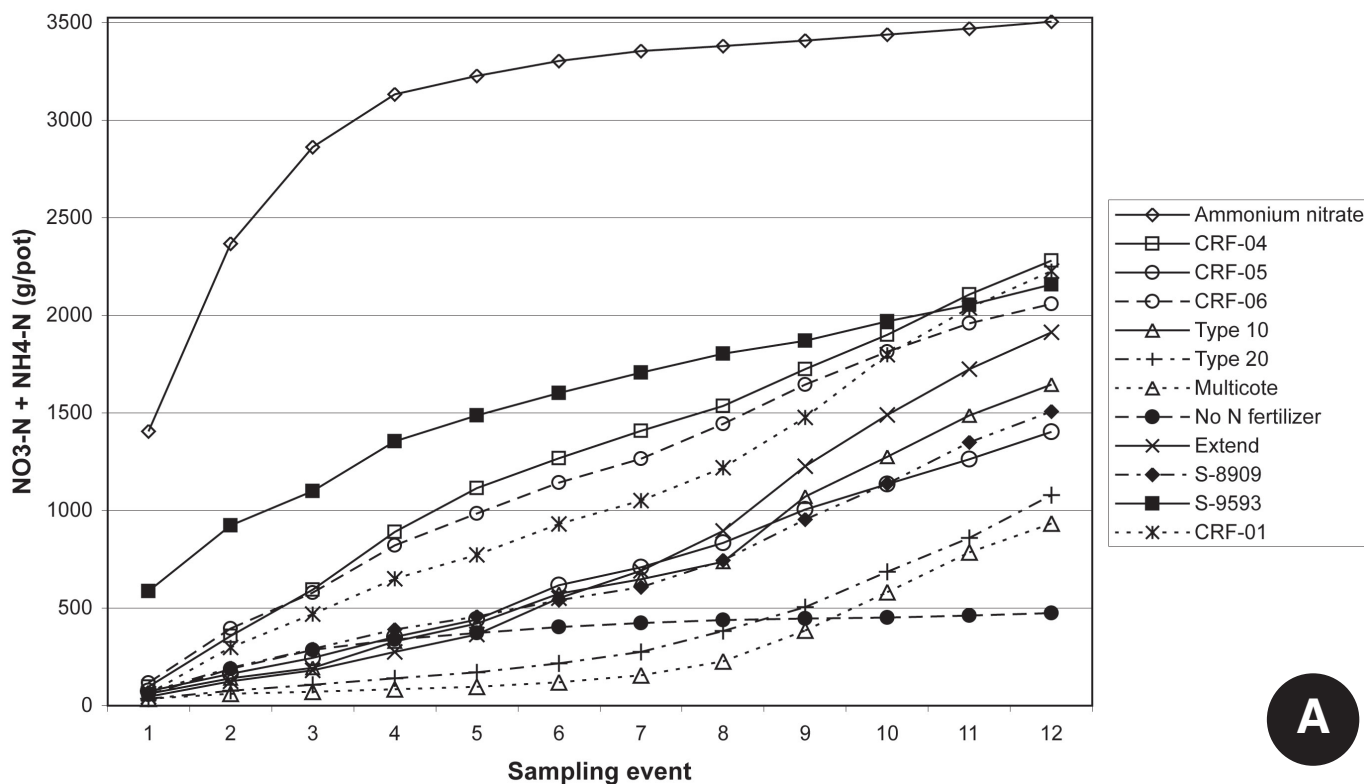


Fig. 2. Cumulative immediately plant-available nitrogen (nitrate + ammonium) (A, top), ammonium-nitrogen (B, bottom), and nitrate-nitrogen (C, next page, top) recovered in leachate of selected fertilizer in a pot-in-pot study conducted at the University of Florida's Plant Science Research and Education Unit Yelvington Farm in Hastings, Fla., in 2002 on an Ellzey fine sand [total nitrogen applied was 4.80 g/pot (0.169 oz/pot)]. See Table 2 for complete information on fertilizer sources. Sampling dates 1 to 12 occurred on 2, 8, 15, 22, 29, 36, 43, 50, 57, 64, 71, and 78 d after initial leaching, respectively.

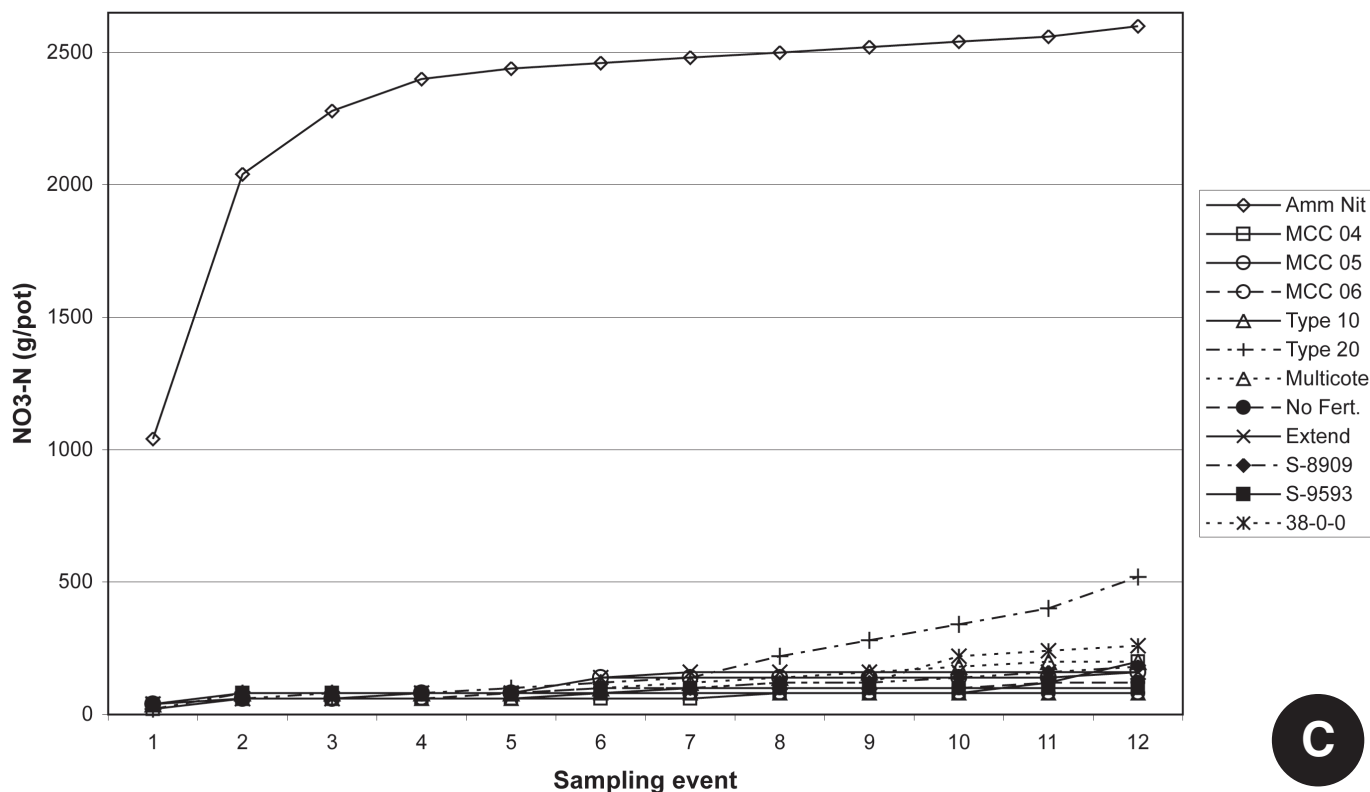


Fig. 2 (continued from previous page). Cumulative immediately plant-available nitrogen (nitrate + ammonium) (A, previous page, top), ammonium-nitrogen (B, previous page, bottom), and nitrate-nitrogen (C, this page, top) recovered in leachate of selected fertilizer in a pot-in-pot study conducted at the University of Florida's Plant Science Research and Education Unit Yelvington Farm in Hastings, Fla., in 2002 on an Ellzey fine sand [total nitrogen applied was 4.80 g/pot (0.169 oz/pot)]. See Table 2 for complete information on fertilizer sources. Sampling dates 1 to 12 occurred on 2, 8, 15, 22, 29, 36, 43, 50, 57, 64, 71, and 78 d after initial leaching, respectively.

from urea. High cvs were not of experimental importance in these tests. However, if these high cvs represent an heterogeneity in N release, crop uniformity with CRFs may be affected. Also, high cv may reflect a less predictable N release.

In 2001, N from soluble N sources was recovered in the leachate rapidly (during the first four sampling dates) compared to the CRFs (Fig. 1A). Significantly higher N recoveries occurred on the first sampling date for the soluble N sources compared to the CRFs. These results illustrate how fast N sources may leach in field condition when soluble sources of N are used.

The typical phases of the release curve of a CRF are induction phase, steady release rate phase, and declining release rate phase (Shoji, 1999). In both years, observed release patterns for selected CRFs were not similar to the typical release pattern. Release patterns for plant-available N tended to be linear (Figs. 1A, 2A). During the sampling period, recovery of plant-available N ranged between 13% for

PSCU1 and 38% for Osmocote Plus in 2001, and 22% for Multicote and 49% for CRF-4 in 2002. In contrast, recovery for plant-available N from soluble sources were 83%, 84%, and 98% for urea-ammonium nitrate, ammonium nitrate, and calcium nitrate in 2001, and 82% for ammonium nitrate in 2002. These results show that the off-the-shelf CRFs tested in 2001 and the experimental CRFs tested in 2002 did not release N rapidly enough to supply adequate N to a potato crop. CRF-4 had numerically the highest seasonal plant-available N recovery, but cumulative release of S-9593 was greater than that of CRF-4 for the first 10 sampling dates. While recovery rate was increased with the experimental CRFs, further thinning of the coating was needed to accelerate the release.

It is not uncommon to observe a burst of release shortly after the application of CRFs to the soil from the poorly coated or physically damaged granules as observed by Hanafi et al. (2002). In our study, this was not observed during either year (Figs. 1A, 2A)

for CRFs except for Osmocote Plus in 2001 and S-9593 in 2002. For these two CRFs, approximately 10% of the total plant-available N release occurred on the first sampling date. Early release is not necessary for potato production since the emerging potato plants obtain their nutrients from the seed piece during the first few days. In contrast, early release may represent an added environmental risk of N leaching.

CRFs may not release 100% of the coated N as the thickness of some prills may permanently prevent N release. The fraction of N "never" released is termed "locked-up N." Because of the limited release observed in these tests, lock-up could not be estimated.

A no-fertilizer treatment was tested in 2002. Total plant-available N over the 78 d was less than 500 mg/pot (0.0176 oz/pot; less than 10% of the total applied to the other treatments). Nitrogen recovered in this treatment was likely to come from soluble residual N (ammonium or nitrate) and mineralized organic matter. Based on the size of the pots, a 500-mg/pot N



Table 4. Cost of soluble fertilizer program (\$/ha) based on cost of material (\$/t) and rates of nitrogen fertilizer (kg·ha⁻¹).^z

Nitrogen rate [kg·ha ⁻¹ (lb/acre)]	Cost of soluble fertilizer (\$/t) ^y				
	143	154	165	176	187
168.1 (150)	77	82	87	94	99
196.1 (175)	89	94	101	109	116
224.2 (200)	101	109	116	124	131
252.2 (225)	114	121	131	138	148
280.2 (250)	124	136	146	156	163
308.2 (275)	138	148	158	171	180
336.2 (300)	151	163	173	193	198

^zUrea-ammonium nitrate mix: 32N-0P-0K.

^yCurrent typical cost; \$1/t = \$0.907/ton.

^xUniversity of Florida/Institute of Foods and Agricultural Sciences' recommended rate and St. Johns River Water Management District best management practice.

^wAverage rate used by the industry.

recovery corresponds to 25 kg·ha⁻¹ (22.3 lb/acre).

Since the dominant N source in selected CRFs was urea, most of the N recovered was in the ammonium form (Figs. 1B, 2B) and ammonium release patterns were similar to those of plant-available N (Figs. 1A, 2A). Ammonium recovery was 69% for urea-ammonium nitrate and 73% for ammonium nitrate in 2001, and 82% for ammonium nitrate in 2002. Approximately 200 mg/pot (0.007 oz/pot) were recovered over the entire test in 2001 from calcium nitrate. This value is close to the recovery observed in 2002 for the no-N control and was attributed to residual N. Ammonium release pattern in 2002 confirmed that CRF-04, CRF-06, and CRF-01 showed a significantly faster release rate throughout the test period starting on the second sampling date (Fig. 2B). This confirms that the release of these three CRFs is the closest to desirable release for potato production. Ammonium release from Type 10 and Type 20 was not significantly higher than that of the no-N control. These two materials missed the window of release and are not suitable for potato production.

Once released in the pot, NH₄⁺ may be transformed into nitrate by soil microorganisms. Because pots were watered approximately once weekly, soil in the pot was well aerated. This condition was expected to be conducive to nitrification. This was not the case, as very little NO₃⁻ was found in the leachate of most CRFs (Figs. 1C, 2C). The NO₃⁻-N recovered was observed with the CRF that had nitrate in its formulation (Osmocote Plus in 2001). Nitrate recoveries from the soluble

fertilizers were 92% for calcium nitrate, 94% for ammonium nitrate, and 125% for UAN in 2001, and 62% for ammonium nitrate in 2002. These results may suggest that nitrification rates in this type of soil is relatively low under the temperatures found in early spring. This supports the current use of a blend of soluble N sources (ammonium nitrate) in fertilization programs used for potato, even if this may increase the risk of nitrate leaching, especially at the beginning of the season.

ECONOMIC ANALYSIS. The cost of a fertilizer program for potato depends on the rate and price of the N fertilizer used. For N rates ranging from 224.2 to 336.2 kg·ha⁻¹ and fertilizer costs ranging from \$143 to \$187/t, the current cost of N fertilization for potato ranges between \$108.72 and \$192.74/ha (\$44 and \$78 per acre) (Table 4). When soluble N sources are used, N fertilization represents between 2.1% and 3.5% of the total production cost for potato. Similarly, the cost of a CRF program also depends on the rate used and the price of the material. While the range of N rates needed to produce potato economically has been well documented for soluble N sources (Hochmuth et al., 2003), limited research data are available to determine the corresponding range of CRF application rate that will result in yields comparable to those obtained with current fertilizer recommendations. Current data suggest that N rates could

be reduced between 140.1 and 196.1 kg·ha⁻¹ (125 and 175 lb/acre) of N when a CRF is used (Hutchinson et al., 2002, 2003). However, these data need confirmation before a N recommendation may be made when CRFs are used. It is unlikely that the recommended rate for soluble (224.2 kg·ha⁻¹) and CRF N-sources will be the same as CRFs increase fertilizer efficiency. No information on CRF prices is currently available since there is no market for CRF on potato. For 9713 ha (24,000 acres) fertilized with a N rate of 196.1 kg·ha⁻¹ and using a 43N-0P-0K CRF, the potato industry in northern Florida would need approximately 3629 t (4000 tons) of CRF each year. From discussion with manufacturers, it is likely that the CRF prices will range from \$551 to \$1213/t (\$500 to \$1100 per ton), based on the pricing strategy of the manufacturer. This upper value represents current prices for CRFs sold for the ornamental and turf industries. It is likely that this upper value would be reduced should a large demand arise from the development of suitable CRFs for potato production. For N rates ranging from 112.1 to 224.2 kg·ha⁻¹ (100 to 200 lb/acre) when CRFs are used with costs of \$551 to \$1213/t, the corresponding CRF program costs ranged between \$86.48 and \$632.57/ha (\$35 and \$256 per acre) (Table 5). This represents 3.9% to 7.8% of the potato production cost.

CRFs are more expensive than soluble fertilizers on a per unit N basis. However, Florida citizens and growers would benefit if CRF costs were shared by all parties that have a stake in improving water quality in the St. Johns River watershed. In this simple model, the cost of a soluble N fertilizer program in most years falls between \$93.90 to \$155.67/ha (\$38 to \$63 per

Table 5. Cost of controlled-release fertilizer (CRF) program (\$/ha) based on cost of material (\$/t) and rates of N fertilizer (kg·ha⁻¹).^z

Nitrogen rate [kg·ha ⁻¹] (lb/acre)]	Cost of CRF (\$/t) ^y								
	331	441	551	661	772	882	992	1102	1213
	----- Cost of CRF program (\$/ha) ^x -----								
112.1 (100)	87	116	143	173	200	230	260	287	316
140.1 (125)	109	146	180	218	250	287	324	358	395
168.1 (150)	131	176	215	260	302	346	390	430	474
196.1 (175)	151	203	252	304	351	403	455	502	554
224.1 (200)	173	232	287	346	400	460	519	573	633

^zCRF assumed to be 43N-0P-0K.

^y\$1/t = \$0.907/ton.

^x\$1/ha = \$0.405/acre.

acre). Estimated CRF program costs would be approximately \$19.77 to \$195.21/ha (\$8 to \$79 per acre) more than the most expensive soluble N cost (\$155.67/ha). If this cost difference was supported 100% by local, state, or national regulatory agency funds, the cost-share program would require \$144,000 to \$1,422,000 annually to be fully funded. The northeast Florida potato crop is valued at approximately \$60 to 75 million. The cost-share program costs would be a relatively small cost to keep this thriving northeast Florida industry.

In conclusion, from being labor-saving tools in the 1960s, CRFs have now become an important management tool to reduce the environmental impact of horticultural production while maintaining or increasing productivity. As such, CRFs are recognized as one of the few BMPs that have a direct impact on off-site nutrient movement and water quality. Plant-available N release pattern of off-the shelf and first-generation experimental CRFs was not rapid enough to ensure an 80% release within the 100-d growth period of a potato crop. Economic analysis has shown that replacing a soluble N fertilization program with one based on CRF would result in a cost increase of \$71.66 to \$158.14/ha. The extra-cost could be offset by reduced application costs and/or providing an increasing the level of cost-share for the use of CRFs. Further development in CRFs for vegetable crops should focus on further reducing release time and increasing the predictability of the release. It is likely that the importance of CRF research for vegetable production will increase in the near future.

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