Effects of Controlled-release Fertilizer Nitrogen Rate, Placement, Source, and Release Duration on Tomato Grown with Seepage Irrigation in Florida

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Abstract. Controlled-release fertilizer (CRF) use is a best management practice that may reduce nitrogen (N) loss to the environment. Several factors affect CRF nutrient release; therefore, including CRF in a fertilization program may have challenges. Thus, the study objective was to evaluate the effects of CRF N rate, source, release duration, and placement on seepage-irrigated marketable tomato (*Solanum lycopersicum* L.) yield, leaf tissue N (LTN) concentration, post-season soil N content, and postharvest fruit firmness and color. There were two soluble fertilizer (SF) controls [University of Florida/Institute of Food and Agriculture Sciences (UF/IFAS) (224 kg·ha⁻¹) and grower standard (280 kg·ha⁻¹)] and six and seven CRF treatments (alone or in combination with SF) in Fall 2011 and 2012, respectively. Cumulative rainfall totaled 31.4 and 37.4 cm during the 2011 and 2012 seasons with average air temperatures of 22.4 and 22.1 °C, respectively. Soil temperatures ranged from 14.2 to 40.6 °C in 2011 and 11.1 to 36.6 °C in 2012 with a strong correlation ($r = 0.95$) to air temperature. Controlled-release urea resulted in 7.5% to 17.9% plant mortality in 2011 and reduced yields in 2012 compared with CRF N–phosphorus–potassium (NPK) at a similar N rate. LTN concentrations were above or within the sufficiency range for all treatments. In 2011, using CRF-urea at 190 kg·ha⁻¹ N produced similar marketable tomato yield in all fruit categories except season total large tomatoes, which produced significantly fewer marketable tomatoes with 13.5 Mg·ha⁻¹ compared with UF/IFAS and grower standard with 17.9 and 14.2 Mg·ha⁻¹, respectively. In 2012, CRF-NPK (168 kg·ha⁻¹ N) significantly reduced first and second harvest combined large and season total large and total marketable yields compared with the UF/IFAS rate and grower standard treatments. Marketable yield was not significantly affected by CRF (urea or NPK) release duration, but CRF-NPK 180-day release duration significantly increased residual soil N in 2012 compared with CRF-NPK 120-day release with 74.2 and 34.3 kg·ha⁻¹ N, respectively. Rototilling CRF-urea into the bed, which was only evaluated in 2011, significantly increased total season yields compared with CRF-urea broadcast in row before bedding (BIR) with 43.0 and 46.5 Mg·ha⁻¹, respectively. There were no significant yield differences when 50% or 75% of the total N was CRF placed in the hybrid fertilizer system, which is a system with CRF placed BIR with the remaining N as SF-N banded on the bed shoulders. No significant differences among treatments were found for total residual soil N in 2011; however, higher soil N remained in CRF (NPK and urea) treatments compared with SF treatments in 2012, except for Treatment 9. No significant differences were found among treatments for fruit firmness or color in 2011 or 2012. CRF-NPK at 190 to 224 kg·ha⁻¹ N with a 120-day release may be recommended as a result of similar or greater first harvest and total season marketable yields compared with IFAS-recommended rates and low residual soil N. Further research must be conducted to explore CRF placement and percentage urea composition, although use of the hybrid system or rototilling may be recommended.

Fresh-market tomato comprised 16% of the harvested vegetable area and 23% of Florida vegetable production with 11,700 ha

harvested and a market value of \$268 million in 2012 [U.S. Department of Agriculture (USDA), 2013]. The Federal Clean Water Act of 1972 and the Florida Restoration Act of 1999 codified the maintenance and improvement of water quality for human consumption, wildlife habitat, crop irrigation, etc. (Bartnick et al., 2005). To improve polluted water bodies, the Florida Department of

Agriculture and Consumer Services adopted a series of best management practices, which includes the use of CRF (Bartnick et al., 2005). Controlled-release fertilizers are SFs occluded in a polymer, resin, sulfur, or a polymer covering a sulfur-coated urea that protect nutrients against leaching from the root zone to become an environmental pollutant (Slater, 2010; Trenkel, 2010).

Approximately 40% of the Florida fresh-market tomato industry uses seepage irrigation as a result of low operating costs and straightforward use (E.J. McAvoy, personal communication; Zotarelli et al., 2013). In seepage irrigation, ground or surface water pumped into a series of canals creates a water table perched on a slowly permeable layer (agrillic or textural). Growers maintain the top of the water table at 0.4 to 0.6 m below the bed surface to irrigate the crop by capillarity (Smajstrla and Muñoz-Carpena, 2011). Oscillation in the water table causes nutrient leaching, primarily nitrate-nitrogen (NO₃⁻-N) and potassium (K⁺); thus, a stable water table must be sustained (Sato et al., 2009).

Producers of seepage-irrigated tomato use raised beds covered with polyethylene mulch and the gradient fertilizer system, in which fertilizers are applied BIR before bed formation and banded on the bed shoulders (BBS) after bed formation (Geraldson, 1980; Liu et al., 2012). The UF/IFAS recommends that 100% of the P and micronutrients and 10% to 20% of the N and K⁺ be BIR. The remaining 80% to 90% of the N and K⁺ should be placed BBS. The UF/IFAS-recommended fertilizer rates for tomato production are 224 kg·ha⁻¹ N and P and K fertilization based on calibrated soil test results (Olson et al., 2012). Additional N fertilizer applications are recommended as a result of leaching rainfall, defined as 76 mm of rainfall in 3 d or 102 mm of rainfall in 7 d, extended harvest season, or low LTN or petiole sap NO₃⁻-N concentrations (Olson et al., 2012).

When polymer-coated urea (PCU) was placed as the only N source BIR or BBS in plasticulture tomato production, similar or lower total marketable tomato yields, respectively, were found compared with SFs at a similar N rate in two single-year studies (Ozores-Hampton et al., 2009). The reduced yields were likely the result of low PCU N release when BBS. To increase soil NO₃⁻-N content, Ozores-Hampton et al. (2009) placed PCU and SF N (80% CRF:20% SF N ratio) BIR at 168 kg·ha⁻¹ N, which resulted in similar tomato yields compared with the UF/IFAS SF recommendation during a winter production season. However, high plant mortality and reduced plant biomass were associated with high NH₄⁺-N soil concentration from the PCU (Ozores-Hampton et al., 2009). To overcome the NH₄⁺-N toxicity, a “hybrid fertilizer system” was created that contains 50% to 80% of the N as CRF placed BIR with the remaining N as SF BBS. Use of this system, in a single-year study, resulted in similar marketable tomato yields when CRF KNO₃ was applied at equal or 25% reduced N rates compared with SF (Ozores-Hampton

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et al., 2009). A recent study, Carson et al. (2014), confirmed these results in a 2-year study. However, CRF KNO₃ is more costly compared with CRF-urea (E. Ellison, personal communication). Because microbial activity increases with temperature (Frederick, 1956), perhaps detoxification of ammonium released from CRF-urea may be accelerate during the fall season compared with the winter, which may allow for use of CRF-urea.

Soil fumigation and staggered plantings extend the time CRFs are in the ground releasing nutrients before planting. For instance, a soil fumigant application requires a 2- to 3-week period between bed formation (and fumigation) and planting, and staggered plantings allowing for continual harvest may increase the production season by 3 weeks (Noling et al., 2012). Therefore, the extended production season must be considered in selection of CRF release duration (Carson and Ozores-Hampton, 2013). However, soil temperatures higher or lower than the CRF manufacturer's nutrient release determining temperature will decrease or increase the release duration, respectively (Carson and Ozores-Hampton, 2013). For instance, Carson et al. (2013) found that the release duration of 90-, 120-, and 180-d release CRFs was shortened by 46% to 69% as a result of high soil temperatures that averaged 25.1 °C in white polyethylene mulch raised beds during a fall season. Thus, the objective of this research was to evaluate the effects of CRF N rate, source [mixed N (54% NH₄⁺, 46% NO₃⁻) compared with urea-N], release duration, and bed placement on marketable tomato yield, LTN content, post-season soil N content, and post-harvest fruit firmness and color during the fall.

Materials and Methods

A CRF study was conducted during Fall 2011 and Fall 2012 on a commercial tomato

farm near Immokalee, FL (lat. 26°14'5" N, long. 81°28'55" W) on Basinger fine sand (hyperthermic Spodic Psammaquents) (Table 1) using seepage irrigation (Natural Resources Conservation Service, 2012). Each trial was arranged in a randomized complete block design with four replications and placed between a set of irrigation ditches spaced 15 m apart, which contained three beds, a drive road, and another three beds (Fig. 1). On 6 Sept. 2011 and 3 Sept. 2012, tomato 'BHN726' transplants at the three- to five-true leaf stage, grown in 128-cell trays (Speedling, Sun City, FL), were planted 51 cm apart on raised beds. The beds measured 76 cm wide and 20 cm high with 1.8 m between row centers. Pest and disease control followed UF/IFAS recommendations (Olson et al., 2012).

In 2011 and 2012, 2.2 Mg·ha⁻¹ dolomite and gypsum, respectively, were added to adjust pH and supply calcium before bed formation. On 15 Aug. 2011 and 17 Aug. 2012, beds were fertilized, formed, fumigated with methyl bromide/chloropicrin (50:50) at 84 kg·ha⁻¹ (ICL-IP, South Charleston, WV), and covered with white virtually impermeable film (0.038 mm; Berry Plastic, Evansville, IN).

Two SF treatments and six and seven CRF treatments containing PCU and polymer-coated compound N (54% NH₄⁺, 46% NO₃⁻), P, and K⁺ fertilizer from Agrium Advanced Technology (Loveland, CO) were used in Fall 2011 and Fall 2012, respectively (Table 2). Two treatments were replicated over years (T1 and T2). The fertilizer gradient system was used in T1 and T2 at 224 and 280 kg·ha⁻¹ SF-N, respectively (Geraldson, 1980). The CRFs were placed BIR as the only N source for T3 to T7 and T3 to T5 in 2011 and 2012, respectively. Treatment 3 was similar between years, although the treatment received an additional 90 kg·ha⁻¹ K⁺ in 2011 compared with 2012 (Table 2). Ozores-Hampton et al. (2012b) obtained maximum yield between 338 and 348 kg·ha⁻¹ K as calculated using a quadratic plateau model; thus, with 490 and 400 kg·ha⁻¹ K in 2011 and 2012, respectively, the additional K supplied as K₂SO₄ should not

affect yields. In T8 (PCU120T) of 2011, fertilizers typically placed BIR were roto-tilled into the false bed before bed formation. The roto-tilling placement was removed as a treatment in 2012. In 2012, fertilizer placement for T6 to T8 used the hybrid fertilizer system, and all N was applied BIR for T9 [75% CRF:25% SF as Ca(NO₃)₂ and KNO₃]. In both years, soluble P was applied as triple superphosphate BIR. Soluble K⁺ BIR was supplied as potassium magnesium sulfate except in T9 in 2012, where K⁺ and Mg²⁺ were supplied from KNO₃ and MgSO₄. All treatments received 68 kg·ha⁻¹ Mg²⁺ from potassium magnesium sulfate and kieserite (MgSO₄·H₂O). Potassium or N fertilizer BBS was applied as soluble K₂SO₄ or NH₄NO₃.

Soil temperature data were collected every 30 min at 10 cm below the bed surface using a Watchdog data logger (Model B100; Spectrum Technologies Inc., Plainfield IL). The water table depth was recorded seven (2011) and 15 (2012) times from monitoring wells in each replicate as described by Smajstrla and Muñoz-Carpena (2011).

Plant mortality data were collected as number of dead plants from each row of the three-bed plot on 7 Oct. 2011. Beginning at first flower appearance (26 Sept. 2011 and 24 Sept. 2012), six most recently matured whole leaves were collected in each plot at 15-d intervals for seven collection dates. The leaves were placed in an oven at 50 °C until dry and milled to pass through a 60-mesh sieve. LTN concentration was measured by combustion using a NA2500 C/N Analyzer (Thermo Quest-CE Instruments, Waltham, MA).

Treatments were applied to plots that were 9.1 m long (17 to 18 plants) and three beds wide. Fruit yield data were collected from 5.1 m or 10 plants in the center bed of the plot. Fruits ranging from marketable mature green to ripe were harvested three times (23 Nov., 7 Dec., and 21 Dec. 2011; and 11 Nov., 7 Dec., and 21 Dec. 2012) and graded into size categories extra-large (greater than 7.00 cm), large (6.35 to 7.06 cm), medium (5.72 to 6.43 cm), and unmarketable fruit according to USDA grade standards (USDA,

Table 1. Soil chemical properties and nutrient status before soil fertilization.

Parameter ²	2011	2012
Organic matter (%)	1.8	2.3
pH	7.1	6.5
CEC (meq/100 g)	2.2	1.7
	----- (mg·kg ⁻¹)-----	
Phosphorus ³	111 VH ^x	107 VH
Potassium ^x	9 VL	9 VL
Magnesium	18 VL	19 VL
Calcium	392 VH	279 VH
Sodium	5 L	3 L
Sulfur	51 M	11 L
Zinc	10.4 VH	11.8 VH
Manganese	13 M	14 M
Iron	13 H	39 H
Copper	19.3 VH	19.2 VH
Boron	0.7 M	1.3 H

²The soil nitrogen content is assumed to be zero in the sandy, low cation exchange capacity (CEC) soils of Florida; therefore, laboratories in Florida do not test for soil nitrogen content.

³Bray P1 was used to extract phosphorus, and Melich 3 was used to extract the other nutrients.

^xVL, L, M, H, and VH = very low, low, medium, high, and very high, respectively.

Fig. 1. This photograph, taken on 3 Oct. 2012, shows the research trial arrangement. The trial is flanked to each side by an irrigation ditch. Replicates one and two were in the left three rows and replicates three and four were in the right three rows. The center bed on each side was harvested for yield determination.

1991) and weighed. In 2011, yield data were corrected for plant mortality by dividing plot yield by the number of harvested plants in the plot and then multiplying plant yield by

10,722 plants per hectare. Plants directly next to an empty plant hole were excluded from data collection to avoid yield inflation as a result of improper competition.

In 2011, a subsample of 10 mature green fruit was collected from each plot at first harvest (FH), washed with chlorinated water (150 ppm free chlorine), surface-dried at room temperature, transported to a commercial packing facility in Immokalee, FL, and ripened with 150 ppm ethylene at 20 °C and 85% to 90% relative humidity to simulate commercial handling (Sargent et al., 2005). After 13 d, tomatoes were at the red ripe stage and were transported to the UF/IFAS Southwest Florida Research and Education Center (SWFREC) Vegetable Horticulture Laboratory (VegLab) in Immokalee, FL. Fruit firmness was measured as fruit deformation after 5 s using a deformation meter equipped with a 1-kg weight and 16-mm probe (Model C125EB; Mitutoyo Corp., Aurora, IL); fruit were rated for external color using the official USDA grade standards, a 1 to 6 scale (1 = green; 6 = red) (USDA, 1991). In 2012, to reduce variability resulting from maturity differences, the subsample size was increased to 20 mature green fruit, which were collected and ripened as described for 2011. However, tomato fruit were removed from the ripening room at the first sign of breaker stage (3 d) and transported to the UF/IFAS SWFREC VegLab. Ten fruit from each plot, at breaker stage of development, were selected and ripened at room temperature until red ripe, which occurred at 10 d after harvest. Fruit firmness and color were measured and rated as described for 2011.

On 22 Dec. 2011 and 2 Jan. 2013, post-season soil samples were collected using a soil slicer as described by Muñoz-Arboleda et al.

Fig. 2. Changes in leaf tissue nitrogen (N) concentration for tomato grown with soluble fertilizer and controlled-release fertilizer programs in Immokalee, FL, during Fall 2011 and 2012 with University of Florida/Institute of Food and Agriculture Sciences (UF/IFAS) sufficiency ranges. PCU120 = polymer-coated (PC) urea 120-d release (43N-0P-0K); PCU180 = PC urea 180 d release (43N-0P-0K); PCU120/180 = PCU120 and PCU180 in a 2:1 mix; PCF120 = PC compound nitrogen (N), phosphorus (P), and potassium (K) fertilizer with 120-d release (19N-6P-13K); PCU120T = PCU120 applied on top of the false bed, rototilled in before bedding; PCF180 = PC NPK with 180-d release (18N-6P-12K). NS, *, *** = Nonsignificant or significant at $P \leq 0.05$ or ≤ 0.001 , respectively.

Table 2. Nutrient rates and bed placement used in testing soluble fertilizer (SF)/controlled-release fertilizer (CRF) fertility programs on tomato in southwest Florida during Fall 2011 and Fall 2012.

Treatment ^z	Placement ^y	BIR						BBS		Total									
		N		P		K		N	K	N			P			K			
		SF	CRF	SF	CRF	SF	CRF	SF	SF	SF	CRF	T	SF	CRF	T	SF	CRF	T	
		kg·ha ⁻¹																	
2011																			
T1: grower standard	Gradient	24	11 ^x	49	0	37	0	245	363	269	11	280	49	0	49	400	0	400	
T2: UF/IFAS ^w	Gradient	24	11	49	0	37	0	189	363	213	11	224	49	0	49	400	0	400	
T3: PCF120	BIR	0	224	18	31	0	127	0	363	0	224	224	18	31	49	363	127	490	
T4: PCU120	BIR	0	190	49	0	37	0	0	363	0	190	190	49	0	49	400	0	400	
T5: PCU120	BIR	0	224	49	0	37	0	0	363	0	224	224	49	0	49	400	0	400	
T6: PCU120	BIR	0	280	49	0	37	0	0	363	0	280	280	49	0	49	400	0	400	
T7: PCU120/180	BIR	0	224	49	0	37	0	0	363	0	224	224	49	0	49	400	0	400	
T8: PCU120T	Rototilled	0	224	49	0	37	0	0	363	0	224	224	49	0	49	400	0	400	
2012																			
T1: grower standard	Gradient	24	11	49	0	37	0	245	363	269	11	280	49	0	49	400	0	400	
T2: UF/IFAS	Gradient	24	11	49	0	37	0	189	363	213	11	224	49	0	49	400	0	400	
T3: PCF120	BIR	0	224	18	31	37	127	0	235	0	224	224	18	31	49	272	127	400	
T4: PCF180	BIR	0	224	18	31	37	117	0	245	0	224	224	18	31	49	283	117	400	
T5: PCF180	BIR	0	168	26	23	37	88	0	274	0	168	168	26	23	49	311	88	400	
T6: PCF180	Hybrid—75% CRF	0	168	26	23	37	88	56	274	56	168	224	26	23	49	311	88	400	
T7: PCF180	Hybrid—50% CRF	0	112	33	16	37	59	112	304	112	112	224	33	16	49	341	59	400	
T8: PCU180	Hybrid—50% CRF	0	112	49	0	37	0	112	363	112	112	224	49	0	49	400	0	400	
T9: PCU180	Hybrid—75% CRF	56	168	49	0	37	0	0	363	56	168	224	49	0	49	400	0	400	

^aUF/IFAS = University of Florida/Institute of Food and Agriculture Sciences; PCU120 = polymer-coated (PC) urea 120-d release (43N-0P-0K); PCU180 = PC urea 180-d release (43N-0P-0K); PCU120/180 = PCU120 and PCU180 in a 2:1 mix; PCF120 = PC compound nitrogen (N), phosphorus (P), and potassium (K) fertilizer with 120-d release (19N-6P-13K); PCU120T = PCU120 applied on top of the false bed, rototilled in before bedding; PCF180 = PC NPK with 180-d release (18N-6P-12K).

^bBIR = broadcast in row before bed formation; Hybrid = hybrid fertilizer system with CRF BIR and SF-N placed on the bed shoulders; BBS = banded on the bed shoulders after bed formation.

^wThe grower and UF/IFAS treatments contain 11 kg·ha⁻¹ from methylene urea.

^xAfter a leaching rain event on 28 Oct. 2011, 34 kg·ha⁻¹ N SF was added.

(2006). A 9-cm slice of soil was taken perpendicular to the bed at the center of each plot. The slice of soil was divided into three vertical sections, which were homogenized and subsampled. The subsamples were placed on ice and stored below 4 °C in the laboratory until analysis. In each replicate of the trial, bulk density of the raised bed and soil moisture content were measured to calculate nutrient concentration on a dry soil weight basis (Blake, 1965). Before analysis, soil samples were sieved, and CRF prills were collected, weighed, crushed, and extracted separately. Urea-N, $\text{NH}_4^+\text{-N}$, and $\text{NO}_3^-\text{-N}$ were extracted from a 4.5-g moist soil sample and from CRF prills collected from each soil sample using 40 mL of 2 M KCl containing $14.8 \mu\text{mol}\cdot\text{L}^{-1}$ phenyl mercuric acetate (Mulvaney and Bremner, 1979; Sato and Morgan, 2008). A flow analyzer (QuikChem 8500; Lachat Co., Loveland, CO) using the salicylate-hypochlorite, cadmium reduction method measured $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ concentrations in soil and fertilizer extracts at 660 nm and 520 nm, respectively. Urea-N concentrations in the extracts were measured by the modified diacetyl monoxime method using a DR/4000U Spectrophotometer (Hach Co., Loveland, CO) at 527 nm (Sato et al., 2009; Sato and Morgan, 2008). Soil and CRF prill $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, and urea-N concentrations were converted to $\text{kg}\cdot\text{ha}^{-1}$ N using the sample size (for soil) or weight of the moist soil subsample (for CRF prills), extractant volume, soil moisture content, soil bulk density, and the volume of the raised bed.

Because the treatment makeup was different in each year, data were analyzed separately by year using analysis of variance (ANOVA) (SAS Version 9.3, SAS Institute Inc., Cary, NC). Plant mortality data were normalized using arcsin transformation before ANOVA. Linear regression was used to analyze plant mortality by N rate. Single df orthogonal contrasts were used to compare treatments means for yield, post-season soil N contents, and plant mortality. Duncan's multiple range test, 5% level, was used to compare LTN concentrations.

Results and Discussion

Weather conditions. Overall, average temperatures during the 2011 and 2012 seasons were similar, 0.2 °C higher and 0.3 °C lower, respectively, compared with the previous 10-year average fall temperature (September through December) [Florida Automated Weather Network (FAWN), 2013]. Air temperatures from transplant to third harvest were similar between seasons with a minimum, mean, and maximum of 9.3 and 9.4 °C, 22.4 and 22.1 °C, and 33.4 and 33.3 °C for 2011 and 2012, respectively (FAWN, 2013). The cumulative season rainfall was 3.8 (2011) and 9.3 cm (2012) higher than the previous 10-year average (FAWN, 2013). Total cumulative rainfall was 31.4 (2011) and 37.4 cm (2012) with a leaching rainfall (7.6 cm of rainfall in 3 d) on 28 Oct. 2011. Thus, following

UF/IFAS recommendations, $34 \text{ kg}\cdot\text{ha}^{-1}$ N as NH_4NO_3 was added to the UF/IFAS (T2) treatment by hand punching holes in the mulch and applying dry granular fertilizer (Olson et al., 2012). No additional N was added in 2012 because there were no leaching rain events. The manufacturer of the CRF used in the study determines nutrient release at a constant 20 °C. Because mean air temperatures were above 20 °C for 13 (2011) and 12 (2012) weeks, the CRF nutrient release rate would be expected to increase with a compressed nutrient release period (Carson and Ozores-Hampton, 2013).

Soil temperature. Season average minimum, mean, and maximum soil temperatures 10 cm below the bed surface during the fall seasons were 20.4 and 20.2 °C, 25.1 and 24.7 °C, and 31.1 and 30.7 °C in 2011 and 2012, respectively. Daily air and soil temperatures were strongly correlated ($r=0.95$). Similarly, Zheng et al. (1993) reported that air and soil temperatures were highly correlated ($r=0.85$ to 0.96) in bare soil and sod and that air temperature may be used as a soil temperature prediction tool. Because the manufacturer of the CRFs used in the study determined nutrient release at a constant 20 °C and weekly mean field soil temperatures were greater than 20 °C until 22 Dec. 2011 (the entire season) and 13 Nov. 2012 (greater than half the season), an increase of the CRF nutrient release rate and shorter nutrient release durations would be expected. Carson et al. (2013) reported that the periods of nutrient release of four polymer-coated fertilizers were reduced by 46% to 69% under white polyethylene mulch during the Fall 2011 tomato season with a mean temperature of 23.4 °C. Thus, the appropriate CRF N release duration must be determined for use in the fall, winter, and spring seasons.

Water table depth. Water table depths below the bed surface fluctuated between 0.39 and 0.67 m in 2011 and 0.36 to 0.55 m in 2012, which were comparable to water table levels found in studies near Immokalee, FL (Carson et al., 2012; Ozores-Hampton et al., 2012a). Intervals between readings were 15 (2011) and 7 d (2012) or longer. However, back-to-back measurements between 6 Dec. and 7 Dec. 2012 indicated a 7-cm increase in the water table as a result of the grower pumping water for irrigation. Thus, some daily water table fluctuations may not have been detected during the season with these reading intervals.

Plant mortality. The mortality rates (%) observed in 2011 for T1 to T8 were 1.7, 0.0, 2.5, 7.5, 8.8, 9.6, 7.1, and 17.9, respectively. The standard deviations (percent mortality) (based on untransformed data) for T1 to T8 calculated among the replicated blocks were 3.3, 0.1, 2.2, 4.4, 5.5, 5.8, 5.2, and 14.8, respectively. No interaction between bed location (beside the ditch, middle, or beside the drive road) and fertilizer treatment was found in 2011 ($P=0.83$). Therefore, plant mortality was likely related to fertilizer treatment. For instance, CRF-urea (T4 to T8) treatments resulted in greater mortality when

contrasted ($P=0.0001$) with SF (T1 and T2) and CRF-NPK (T3; 54% NH_4^+ , 46% NO_3^-) treatments. The linear regression between plant mortality and N rates was nonsignificant; therefore, plant mortality did not linearly increase with N rate. Tomatoes mortality decreased ($P=0.047$) when grown with equal N rates and mixed CRF-urea release durations (T7, 120/180-d release mix) compared with T5 (CRF-urea, 120-d release). Plant mortality increased when CRF-urea was rototilled into the bed ($P=0.0062$) compared with CRF-urea BIR. No plant mortality was observed in 2012.

In 2011, CRF-urea provided 100% of the total N for T4 to T8, whereas in 2012, ammoniacal N sources provided 75% of the total N for T8 (50% CRF-urea and 50% NH_4NO_3 BBS) and T9 (75% CRF-urea and 25% $\text{NO}_3^-\text{-N}$ BIR). The N supplied by SF ($\text{NO}_3^-\text{-N}$) in 2012 minimized plant mortality in the CRF-urea treatments. Barker and Mills (1980) indicated that accumulation of NH_4^+ and volatilization of NH_3 , the end products of enzymatic urea degradation, may cause damage to tomato plants under the correct environmental field conditions. In a winter season tomato study by Ozores-Hampton et al. (2009), 29% to 54% plant mortality occurred as a result of NH_4^+ toxicity when using PCU with seepage irrigation. In a spring tomato study in central Florida, total marketable yields decreased linearly when PCU was included as an increasing percentage of the total N (0% to 100%) (Csizinszky et al., 1993). Soil microbial activity and CRF-urea nutrient release increases with temperature (Frederick, 1956; Huett and Gogel, 2000). Thus, fall seasons should have an accelerated microbial nitrification and detoxification of the urea and NH_4^+ compared with the winter and early spring season. High plant mortality from the CRF-urea occurred, which was probably the result of the use of soil fumigation that limited nitrifying bacteria in the soil (Ivors, 2010). CRF-urea may be included in a tomato fertility program as a result of higher N content and low cost per unit, although more research will be needed to determine the percentage of the total N that may be applied as urea without crop injury or reduced yields.

Plant nutritional status. LTN concentration decreased from first buds to third harvest for all treatments in 2011 and 2012 (Fig. 2). In 2011, no differences among treatments were found in LTN concentration for any sample date and all samples were within or greater than the sufficiency range. In 2012, there were differences among treatments at 67, 85, and 95 d after transplant (DAT); however, all LTN concentrations were above the sufficiency range. At 85 DAT, plants in all treatments had a greater LTN concentration than T5. At 95 DAT, T1, T7, T8, and T9 resulted in the greatest LTN concentration. Treatment 5 led to the lowest LTN concentration from 67 DAT through 95 DAT and showed visible symptoms of N deficiency.

Monitoring LTN concentration allows growers to maximize yield potential and fertilizer management efficiency with the

goal of determining if supplemental N may be necessary during the crop cycle (Hochmuth et al., 2010). LTN concentrations greater than or within the sufficiency range suggest that N was not a limiting factor for yield during 2011 or 2012; however, visible symptoms of N deficiency at LTN concentrations above the upper sufficiency range were found, indicating N was a limiting factor in one treatment. Furthermore, these deficiency symptoms suggest that the sufficiency ranges may not discriminate between crop N adequacy and deficiency, which warrants further investigation.

Yield responses to controlled-release fertilizer nitrogen rates. In 2011 and 2012, contrasts between SF [grower standard (T1) and UF/IFAS (T2)] were nonsignificant, except FH large tomato yield in 2012 (Tables 3 and 4). Thus, T1 and T2 were used in contrasts when comparing SF and CRF treatments, except for FH large tomato yield in 2012 where only T2 was used for comparisons. When SF was compared with CRF-urea (T4, T5, or T6), SF led to a greater total season large tomato yield compared with CRF-urea at 190 kg·ha⁻¹ N. In 2012, at 168 kg·ha⁻¹ N, CRF-NPK (T5) led to lower first and second harvests combined (FSHC) large, total season large, and total marketable yields compared with CRF-NPK at 224 kg·ha⁻¹ (T3 and T4). In contrast, compared with SF, CRF-NPK at 224 kg·ha⁻¹ (T3 and T4) increased extra-large and total marketable FH yields. The majority of treatment effects on yield, which were not mentioned, were nonsignificant.

Compared with UF/IFAS N rate, a N rate reduction of 15% using CRF-urea and 25% using CRF-NPK resulted in similar and lower season total marketable yields, respectively. Therefore, a 0% to 15% N rate reduction may be acceptable using CRF, especially when a grower's third harvest will be dependent on market conditions (Ozores-Hampton et al., 2012a); however, a 25% reduction in N rate should not be recommended. In contrast, Carson et al. (2014) recommended a 0% to 25% N rate reduction during the fall season when using CRFs (100-, 140-, and 180-d release mix), from Florikan ESA (Sarasota, FL), in the hybrid fertilizer system.

Yield responses to controlled-release fertilizer nitrogen source. There were no marketable yield differences between CRF-NPK (T3) and CRF-urea (T5, T7, and T8) at 224 kg·ha⁻¹ N in 2011. In 2012, use of CRF-NPK (T6 and T7) in the hybrid fertilizer system resulted in greater season total large and total marketable yields compared with the CRF-urea treatments (T8 and T9).

In 2011 and 2012, urea-N and NH₄⁺-N sources were 100% and 75% of the TN in treatments containing CRF-urea, respectively, which probably caused the high plant mortality in 2011. When tomato yield was corrected for plant mortality in 2011, there were no yield differences between CRF-urea or CRF-NPK. However in 2012 (without mortality), CRF-NPK resulted in greater season total marketable tomato yields than CRF-urea. Csiszinsky et al. (1993) found that FH extra-large and total season marketable

Table 3. Fruit yield by size categories for first harvest, first and second harvest combined, and season total harvest (three harvests combined) for two soluble fertilizer (SF) and six controlled-release fertilizer (CRF) tomato fertility programs used to grow tomato in Immokalee, FL, during Fall 2011.

Treatment ^z	N rate (SF/CRF)	First harvest				First and second harvest				Season total harvest				
		Xlg ^y	Lrg	Med	Total	Xlg	Lrg	Med	Total	Xlg	Lrg	Med	Total	Cull
		(Mg·ha ⁻¹ ± sd)												
T1: grower standard	269/11	9.1 ± 0.6	4.6 ± 0.3	2.9 ± 1.6	16.5 ± 2.1	14.9 ± 1.4	11.5 ± 1.7	10.0 ± 1.1	36.4 ± 2.7	15.5 ± 1.5	14.2 ± 2.9	16.0 ± 1.9	45.6 ± 6.0	12.4 ± 2.7
T2: UF/IFAS ^x	247/11	8.9 ± 1.3	4.9 ± 1.7	2.8 ± 0.6	16.6 ± 2.1	14.9 ± 2.6	15.1 ± 2.0	16.2 ± 2.3	46.2 ± 3.5	15.6 ± 2.5	17.9 ± 1.2	24.6 ± 3.0	58.1 ± 4.9	10.7 ± 2.3
T3: PCF120	0/224	9.2 ± 0.5	5.9 ± 1.1	3.8 ± 1.1	18.9 ± 2.3	14.9 ± 3.0	14.2 ± 3.8	11.7 ± 2.8	40.7 ± 7.6	15.7 ± 3.7	17.7 ± 4.5	20.2 ± 3.6	53.6 ± 10.5	11.2 ± 3.1
T4: PCU120	0/190	9.5 ± 2.3	4.8 ± 1.2	4.3 ± 1.0	18.7 ± 2.1	14.6 ± 2.7	11.3 ± 2.5	12.7 ± 0.8	38.7 ± 2.7	14.9 ± 2.8	13.5 ± 2.8	18.9 ± 2.9	47.3 ± 4.9	10.7 ± 1.7
T5: PCU120	0/224	7.6 ± 2.2	4.4 ± 0.4	4.1 ± 0.5	16.1 ± 2.1	12.9 ± 4.4	10.5 ± 0.9	10.9 ± 1.6	34.4 ± 5.4	13.7 ± 4.5	12.9 ± 0.7	16.4 ± 2.2	43.0 ± 5.6	10.0 ± 1.1
T6: PCU120	0/280	8.3 ± 3.4	3.8 ± 1.9	3.2 ± 2.0	15.3 ± 6.9	11.4 ± 3.5	10.4 ± 4.3	10.6 ± 3.6	32.3 ± 10.3	11.8 ± 3.6	12.3 ± 4.2	16.3 ± 3.7	40.4 ± 10.4	9.9 ± 2.3
T7: PCU120/ 180	0/224	7.4 ± 0.9	4.5 ± 1.3	3.5 ± 0.9	15.4 ± 2.4	12.2 ± 1.6	10.7 ± 2.1	12.0 ± 0.9	34.9 ± 2.9	13.0 ± 1.8	12.9 ± 2.8	18.2 ± 1.8	44.1 ± 5.7	10.6 ± 2.2
T8: PCU120T	0/224	10.0 ± 2.8	5.8 ± 1.3	5.3 ± 2.6	21.1 ± 4.9	13.6 ± 2.4	12.1 ± 2.3	12.2 ± 2.9	37.9 ± 1.8	13.7 ± 2.4	14.5 ± 3.5	18.3 ± 4.2	46.5 ± 4.4	9.6 ± 2.1
P value	—	0.51	0.35	0.28	0.31	0.17	0.11	0.02	0.02	0.22	0.06	0.01	0.01	0.68
Significance ^w	—	NS	NS	NS	NS	NS	NS	*	*	NS	NS	*	*	NS

P value														
Single df contrast														
T1 vs. T2	0.12	0.79	0.43	0.22	0.13	0.72	0.64	0.30	0.22	0.75	0.77	0.48	0.92	0.92
T3 vs. T5, 7, 8	0.13	0.35	0.58	0.35	0.23	0.12	0.16	0.06	0.32	0.12	0.08	0.07	0.49	0.49
T1, 2 vs. T4	0.53	0.14	0.86	0.42	0.28	0.052	0.62	0.21	0.21	0.014	0.38	0.053	0.66	0.66
T1, 2 vs. T5	0.21	0.16	0.15	0.08	0.90	0.49	0.91	0.72	0.95	0.43	0.88	0.80	0.45	0.45
T1, 2 vs. T6	0.89	0.29	0.41	0.43	0.14	0.69	0.20	0.17	0.13	0.61	0.23	0.19	0.57	0.57
T5 vs. T7	0.50	0.19	0.028	0.09	0.38	0.74	0.18	0.69	0.32	0.85	0.30	0.81	0.08	0.08
T5 vs. T8	0.45	0.33	0.024	0.10	0.37	0.11	0.021	0.03	0.28	0.10	0.007	0.018	0.50	0.50

^zUF/IFAS = University of Florida/Institute of Food and Agriculture Sciences; PCU120 = polymer-coated urea 120-d release (43N-0P-0K); PCU120/180 = PCU120 and a polymer-coated urea 180-d release (43N-0P-0K) in a 2:1 mix; PCF120 = polymer-coated compound nitrogen (N), phosphorus (P), and potassium (K) fertilizer with 120-d release; PCU120T = PCU120 applied on top of the false bed, retolled in before bedding.

^yXlg = extra-large (greater than 7.00 cm); Lrg = large (6.35 to 7.06 cm); Med = medium (5.72 to 6.43 cm).

^wTotal N rate includes 224 kg·ha⁻¹ N applied at bedding and 34 kg·ha⁻¹ fertilizer applied after a leaching rain event on 28 Oct. 2011.

^xNS, *, ** = Nonsignificant or significant at P ≤ 0.05 or ≤ 0.01, respectively.

Table 4. Fruit yield by size categories for first harvest, first and second harvest combined, and season total harvest (three harvests combined) for two soluble fertilizer (SF) and seven controlled-release fertilizer (CRF) tomato fertility programs used to grow tomato in Immokalee, FL, during Fall 2012.

Treatment ^z	N rate (SF/CRF)	First harvest			First and second harvest			Season total harvest						
		Xlg ^y	Lrg	Med	Total	Xlg	Lrg	Med	Total	Cull				
(Mg·ha ⁻¹ ± sd)														
T1: grower standard	269/11	19.3 ± 7.2	1.4 ± 1.0	— ^x	20.7 ± 18.1	27.3 ± 6.7	14.8 ± 1.5	3.5 ± 1.9	45.5 ± 6.1	30.8 ± 7.0	27.9 ± 1.4	9.7 ± 3.3	68.4 ± 4.2	9.1 ± 1.5
T2: UF/IFAS	213/11	17.7 ± 3.7	2.5 ± 0.9	0.1 ± 0.07	20.3 ± 4.4	28.5 ± 5.7	14.9 ± 1.8	4.5 ± 1.8	47.8 ± 7.7	32.5 ± 7.3	27.2 ± 1.2	12.5 ± 3.1	72.2 ± 5.4	7.3 ± 2.9
T3: PCF120	0/224	24.9 ± 2.6	2.5 ± 1.2	—	27.3 ± 2.6	31.8 ± 2.2	13.5 ± 1.9	3.9 ± 2.1	49.2 ± 4.5	36.2 ± 3.5	27.1 ± 1.8	10.8 ± 3.8	74.2 ± 7.3	10.5 ± 3.4
T4: PCF180	0/224	22.2 ± 4.3	3.0 ± 1.1	—	25.2 ± 5.0	30.6 ± 4.0	15.0 ± 3.3	3.2 ± 1.5	48.9 ± 3.3	33.1 ± 4.9	27.8 ± 3.8	10.1 ± 1.9	71.0 ± 3.7	9.2 ± 0.7
T5: PCF180	0/168	22.8 ± 3.6	3.4 ± 1.1	0.1 ± 0.12	26.3 ± 4.3	28.5 ± 2.7	12.1 ± 1.8	3.3 ± 0.5	43.9 ± 2.5	29.9 ± 2.7	20.5 ± 3.8	9.8 ± 3.1	60.1 ± 4.8	7.6 ± 0.7
T6: PCF180	56/168	25.0 ± 3.0	3.0 ± 0.5	—	27.9 ± 3.3	33.3 ± 3.8	14.3 ± 2.5	4.7 ± 2.3	52.3 ± 4.6	35.5 ± 4.3	26.7 ± 1.0	13.7 ± 3.5	75.8 ± 2.2	8.0 ± 2.7
T7: PCF180	112/112	20.5 ± 4.0	2.4 ± 1.0	0.1 ± 0.07	23.0 ± 5.0	28.5 ± 2.8	14.9 ± 1.8	3.8 ± 1.3	47.2 ± 5.8	31.1 ± 2.0	28.6 ± 1.8	12.0 ± 0.8	71.7 ± 3.2	8.7 ± 1.4
T8: PCU180	112/112	20.8 ± 5.5	2.6 ± 0.9	—	23.5 ± 5.6	30.4 ± 4.8	13.4 ± 1.7	4.1 ± 1.5	47.9 ± 3.1	33.0 ± 4.8	22.1 ± 3.2	11.0 ± 2.8	66.2 ± 4.6	8.0 ± 1.9
T9: PCU180	56/168	19.0 ± 3.5	2.3 ± 0.4	—	21.3 ± 3.7	26.0 ± 2.8	14.9 ± 0.9	3.7 ± 1.5	44.6 ± 4.4	28.9 ± 2.8	27.8 ± 2.6	11.0 ± 2.8	67.8 ± 3.3	8.6 ± 2.7
P value	—	0.25	0.025	0.066	0.19	0.30	0.27	0.72	0.19	0.33	0.0004	0.50	0.0005	0.33
Significance ^w	—	NS	*	NS	NS	NS	NS	NS	NS	NS	***	NS	***	NS

Single df contrast

P value													
T1 vs. T2	SF rate	0.60	0.029	0.08	0.89	0.68	0.94	0.25	0.43	0.59	0.71	0.17	0.19
T3 vs. T4	Duration	0.40	0.31	—	0.52	0.69	0.21	0.46	0.93	0.33	0.72	0.70	0.26
T3, 4 vs. T5	CRF rate	0.78	0.10	0.005	0.99	0.28	0.049	0.73	0.052	0.09	0.0001	0.68	0.0001
T1, 2 vs. T3, 4	SF vs. CRF	0.029	0.66 ^y	0.22	0.020	0.11	0.53	0.49	0.26	0.18	0.93	0.63	0.28
T1, 2 vs. T5	SF vs. low CRF rate	0.12	0.07 ^y	0.048	0.052	0.80	0.016	0.37	0.28	0.51	0.0001	0.43	0.0003
T8 vs. T9	Urea vs. urea + nitrate	0.56	0.41	0.38	0.50	0.14	0.22	0.71	0.28	0.20	0.0026	0.97	0.58
T6, 7 vs. T8, 9	Hybrid NPK vs. Urea	0.20	0.47	0.53	0.19	0.19	0.64	0.57	0.11	0.30	0.036	0.19	0.0024
T6, 9 vs. T7, 8	50% CRF vs. 75% CRF	0.55	0.79	0.07	0.56	0.92	0.59	0.67	0.65	0.95	0.13	0.55	0.17

^zUF/IFAS = University of Florida/Institute of Food and Agriculture Sciences; PCU180 = polymer-coated (PC) urea 180-d release (43N-0P-0K); PCF120 = PC compound nitrogen (N), phosphorus (P), and potassium (K) fertilizer with 120-d release (19N-6P-13K); PCF180 = PC NPK with 180-d release (18N-6P-12K).

^yXlg = extra-large (greater than 7.00 cm); Lrg = large (6.35 to 7.06 cm); Med = medium (5.72 to 6.43 cm).

^wMedium fruit were not harvested in all treatments during first harvest.

^xNS, *, **, *** = Nonsignificant or significant at $P \leq 0.05$, ≤ 0.01 , or ≤ 0.001 , respectively.

^yOnly T2 was used in comparisons as a result of a significant contrast between T1 and T2.

tomato yields decreased linearly as CRF-urea increased from 0% to 100% of the TN. In a similar study, Csizinszky et al. (1992) reported a quadratic response to methylene urea with a maximum FH extra-large and total, and season total extra-large marketable tomato yields when methylene urea provided 50% of the TN. Thus, as a result of mortality and lower total season marketable yields, CRF-urea and $\text{NH}_4^+\text{-N}$ should not contribute greater than 50% of the TN. Although Carson et al. (2013) reported that high soil temperatures decreased fertilizer release duration under white polyethylene mulch during Fall 2011, only FH medium tomato yields were negatively affected by CRF-urea release duration when corrected for mortality. Some yields may be adjusted lower by 7.5% to 17.9% to take into consideration plant mortality.

Yield responses to controlled-release fertilizer nitrogen duration. In 2011, 120-d release CRF-urea (T5) resulted in greater FH medium tomato yield compared with the CRF-urea release duration mix (T7). In 2012, no differences in yield were found between CRF-NPK 120- and 180-d release at 224 kg·ha⁻¹ (T3 and T4).

Increased CRF-N release rates and shorter CRF N release durations resulting from soil temperatures greater than the temperature at which manufacturers determine CRF release duration are well documented in the literature (Carson and Ozores-Hampton, 2013). In a single-year study, Carson et al. (2013) documented similar N release durations between 120- and 180-d release CRF-urea in the fall season under white polyethylene mulch. Thus, few differences in tomato yield resulting from CRF release duration may be expected.

Yield responses to controlled-release fertilizer nitrogen placement. In 2011, rototilling CRF-urea (T8) into the bed increased FH medium, FSHC medium and total, and season total medium and total marketable tomato yields compared with CRF-urea (T5) as the only N source BIR. In 2012, T9, CRF-urea and soluble $\text{NO}_3^-\text{-N}$ BIR resulted in greater total season large marketable tomato yield compared with CRF-urea in the hybrid system (T8). No yield differences were found when CRF (NPK or urea) comprised 50% (T7 and T8) compared with 75% (T6 and T9) of the total N in the hybrid fertilizer system.

Rototilling CRF-urea into the bed increased marketable tomato yields compared CRF-urea BIR. Similarly, Hochmuth (1998) rototilled CRF-NPK into the bed resulting in increased drip-irrigated marketable tomato yields compared with CRF-NPK banded on the bed surface. During 2012, when CRF-NPK and CRF-urea were placed in the hybrid fertilizer system with 25% and 50% soluble N (T6 and T7), no yield differences were found compared with 100% CRF-NPK BIR (T3 and T4) ($P > 0.05$, contrast not shown). No research studies have directly compared the hybrid fertilizer system, rototilling, and BIR placements for seepage-irrigated tomato production. However, Ozores-Hampton et al. (2009) found that CRF-urea and SF BIR and

CRF-NPK in the hybrid fertilizer system produced increased and similar marketable tomato yields compared with SF, respectively.

Post-season soil samples. In 2011, TN remaining post-season (1 d after the last harvest) ranged from 37.9 to 80.4 kg·ha⁻¹ (Table 5). The grower standard treatment (T1) resulted in higher residual NH₄⁺-N concentrations compared with UF/IFAS treatment (T2). However, the TN content remaining post-season was similar. Lower residual soil urea-N and higher CRF prill NH₄⁺-N and NO₃⁻-N contents remained for soils with CRF-NPK (T3) compared with CRF-urea (T5, T7, and T8), but no differences were found in residual TN. Greater NO₃⁻-N content but lower urea-N content remained in the soil with SF treatments compared with CRF-urea (T4, T5, and T6) at any rate. No differences were found in the amount of N remaining in the soil resulting from CRF-urea release duration or use of CRF-urea BIR compared with rototilling incorporated.

In 2012, TN remaining post-season (12 d after last harvest) ranged from 7.6 to 74.2 kg·ha⁻¹ (Table 6). No differences were found in residual N between grower standard and UF/IFAS treatments. CRF-NPK of 180-d release (T4) resulted in greater residual TN content as a result of greater NH₄⁺-N and NO₃⁻-N contents in the CRF prills than CRF-NPK of 120-d release (T2). Greater NO₃⁻-N remained in CRF-NPK fertilizer prills at 224 kg·ha⁻¹ (T4) compared with 168 kg·ha⁻¹ (T5), but similar TN contents remained post-season. CRF-NPK at 168 and 224 kg·ha⁻¹ (T3, T4, and T5) resulted in a greater residual

soil NH₄⁺-N and TN contents remaining post-season than SF treatments. Soils of T8 (CRF-urea in the hybrid fertilizer system) had higher NO₃⁻-N, CRF prill urea-N and residual TN contents post-season compared with T9 (CRF-urea with SF BIR). However, T9 had similar NO₃⁻-N contents, more CRF, and similar TN rates applied at the beginning of the season. When comparing CRF-NPK (T6 and T7) with CRF-urea (T8 and T9) in the hybrid fertilizer system, no differences were found in residual TN. However, CRF-urea resulted in higher residual soil urea-N but lower NO₃⁻-N and NH₄⁺-N CRF prill contents. When 50% of the TN applied was CRF (NPK or urea), higher residual NO₃⁻-N in the soil and TN was found compared with treatments containing 75% of the N as CRF (NPK or urea). This difference was probably the result of the lower residual N content in the prills of CRF-urea compared with CRF-NPK and the lower soil N content of T9 that was likely resulting from leaching of SF-N BIR.

Similar to this study, Hendricks and Shukla (2011) reported 40 to 49 kg·ha⁻¹ N remaining at the UF/IFAS SF N rate in the fall tomato season. Overall in 2011, CRF rate, placement, duration, and source had no effect on TN remaining post-season. However, CRF-urea resulted in the highest urea-N content in the soil and CRF-urea prills. In 2012, CRF-NPK and SF rates did not affect TN remaining or N species distribution. However, a CRF 180-d release had greater N remaining in the CRF-NPK prills compared with a CRF-NPK 120-d release resulting in higher TN. Differences in N release would not be

expected because soil temperatures were similar between years and Carson et al. (2013) reported similar nutrient release durations for CRF-urea with 120- and 180-d release duration when used in plasticulture tomato production during Fall 2011. However, higher residual TN was found with CRF (NPK and urea) in 2012 compared with SF at similar N rates as a result of higher soil NO₃⁻-N contents and higher residual CRF prill N contents. Treatment 9 resulted in low residual soil TN, but the residual soil N contents are similar to T6 with a similar pre-season SF-to-CRF distribution and the CRF prill N contents are similar to T8, the other CRF-urea treatment. Overall, when T6 and T7 were used to compare 50% to 75% CRF in the hybrid fertilizer system, there were no differences in residual TN post-season; however, the distribution of the N is different (contrast not shown). When T8 and T9 are included in the analysis of 50% and 75% CRF N in the hybrid fertilizer system, results become less clear as a result of high and low residual N in T8 and T9, respectively.

Post-harvest quality. No differences were found in tomato firmness at the red ripe stage ($P = 0.15$ and 0.06) with 3.4 and 2.2 mm deformation and external tomato color ($P = 0.15$ and 0.25) with USDA color scores of 5.6 and 5.9 at the red ripe stage in 2011 and 2012, respectively (data not shown). Therefore, N source, CRF release duration, N rate, and placement had no practical commercial significance for post-harvest quality. Similarly, external color of field-grown processing tomato grown at N rates ranging from 0 to

Table 5. Residual soil ammonium–nitrogen (NH₄⁺-N), nitrate-N (NO₃⁻-N), urea-N, and total N from two soluble fertilizer (SF) and six controlled-release fertilizer (CRF) programs used to grow tomato in Immokalee, FL, during Fall 2011.

Treatments ^z	N rate (SF/CRF)	Soil			CRF prills			Total	N release ^y (%)
		NH ₄ ⁺ -N	NO ₃ ⁻ -N	Urea-N	NH ₄ ⁺ -N	NO ₃ ⁻ -N	Urea-N		
		kg·ha ⁻¹							
T1: grower standard	269/11	23.4	57.0	0.0	— ^x	—	—	80.4	—
T2: UF/IFAS ^w	247/11	11.9	47.4	0.3	—	—	—	59.6	—
T3: PCF120	0/224	21.4	22.0	1.9	0.3	0.2	1.5	47.3	99.1
T4: PCU120	0/190	13.1	15.7	12.8	0.2	0.0	3.1	44.8	98.3
T5: PCU120	0/224	14.3	24.9	9.0	0.2	0.0	1.9	50.3	99.1
T6: PCU120	0/280	24.3	33.8	9.8	0.2	0.0	2.5	70.6	99.0
T7: PCU120/180	0/224	12.9	14.6	8.3	0.1	0.0	1.9	37.9	99.1
T8: PCU120T	0/224	16.3	16.4	10.8	0.1	0.0	2.1	46.0	99.0
P value	—	0.08	0.002	0.002	0.61	0.0004	0.73	0.15	
Significance ^v	—	NS	**	**	NS	***	NS	NS	

Single df contrast

		P value						
T1 vs. T2	SF rate	0.02	0.34	0.93	—	—	—	0.19
T3 vs. T5, 7, 8	Source	0.10	0.68	0.009	0.008	0.0001	0.52	0.84
T1, 2 vs. T4	Rate	0.28	0.0004	0.0001	—	—	—	0.07
T1, 2 vs. T5	Rate	0.43	0.005	0.004	—	—	—	0.16
T1, 2 vs. T6	Rate	0.13	0.04	0.002	—	—	—	0.97
T5 vs. T7	Duration	0.78	0.31	0.83	0.22	0.38	0.96	0.43
T5 vs. T8	Placement	0.67	0.40	0.58	0.082	0.70	0.79	0.78

^aUF/IFAS = University of Florida/Institute of Food and Agriculture Sciences; PCU120 = polymer-coated (PC) urea 120-d release (43N-0P-0K); PCU120/180 = PCU120 and PC urea 180-d release in a 2:1 mix; PCF120 = PC compound nitrogen (N), phosphorus (P), and potassium (K) fertilizer with 120-d release (19N-6P-13K); PCU120T = PCU120 applied on top of the false bed, rototilled in before bedding.

^bN release = (total CRF N applied N remaining in CRF prills)/total CRF N applied.

^vNo CRF were used in the grower (T1) and UF/IFAS (T2) treatments; thus, there were no CRF prills collected and analysis of variance was carried among CRF treatments for these columns.

^wTotal N rate includes 224 kg·ha⁻¹ N applied at bedding and 34 kg·ha⁻¹ fertilizer applied after a leaching rain event on 28 Oct. 2011.

^xNS, *, **, *** = Nonsignificant or significant at $P \leq 0.05$, ≤ 0.01 , or ≤ 0.001 , respectively.

Table 6. Residual soil ammonium–nitrogen (NH₄⁺-N), nitrate-N (NO₃⁻-N), urea-N, and total N from two soluble fertilizer (SF) and six controlled-release fertilizer (CRF) programs used to grow tomato in Immokalee, FL, during Fall 2012.

Treatments ^z	N rate (soluble/CRF)	Soil			CRF prills			Total	N release ^y (%)
		NH ₄ ⁺ -N	NO ₃ ⁻ -N	Urea-N	NH ₄ ⁺ -N	NO ₃ ⁻ -N	Urea-N		
		kg·ha ⁻¹							
T1: grower standard	269/11	7.9	7.9	0.0	— ^x	—	—	15.8	—
T2: UF/IFAS	213/11	5.9	1.5	0.2	—	—	—	7.6	—
T3: PCF120	0/224	12.5	5.1	0.1	10.0	6.6	0.0	34.3	92.5
T4: PCF180	0/224	12.9	6.4	0.2	31.3	23.5	0.0	74.2	75.5
T5: PCF180	0/168	9.7	5.9	0.0	23.3	16.0	0.0	55.0	76.6
T6: PCF180	56/168	7.6	5.3	0.0	15.2	10.5	0.0	38.5	84.7
T7: PCF180	112/112	5.8	19.0	0.0	8.4	6.0	0.1	39.1	87.1
T8: PCU180	112/112	5.8	39.9	4.0	0.2	0.2	0.2	50.3	99.5
T9: PCU180	56/168	4.7	3.0	3.1	0.1	0.0	1.7	12.7	98.9
<i>P</i> value	—	0.0007	0.0002	0.0001	0.0001	0.0001	0.34	0.0003	—
Significance ^w	—	***	***	***	***	***	NS	***	—

Single df contrast								
<i>P</i> value								
T1 vs. T2	SF rate	0.28	0.36	0.81	—	—	—	0.52
T3 vs. T4	Duration	0.83	0.86	0.89	0.0002	0.0001	0.99	0.004
T4 vs. T5	Rate	0.10	0.95	0.83	0.12	0.048	0.99	0.14
T1, 2 vs. T3, 4	SF vs. CRF	0.0002	0.83	0.93	—	—	—	0.0001
T1, 2 vs. T5	SF vs. low CRF rate	0.09	0.84	0.92	—	—	—	0.0005
T8 vs. T9	Urea vs. urea + nitrate	0.56	0.0001	0.27	0.99	0.97	0.04	0.006
T6, 7 vs. T8, 9	Hybrid NPK vs. urea	0.29	0.07	0.0001	0.002	0.004	0.08	0.41
T6, 9 vs. T7, 8	50% CRF vs. 75% CRF	0.79	0.0001	0.43	0.37	0.40	0.16	0.04

^zUF/IFAS = University of Florida/Institute of Food and Agriculture Sciences; PCU180 = polymer-coated (PC) urea 180-d release (43N-0P-0K); PCF120 = PC compound nitrogen (N), phosphorus (P), and potassium (K) fertilizer with 120-d release (19N-6P-13K); PCF180 = PC NPK with 180-d release (18N-6P-12K).

^yN release = (total CRF N applied N remaining in CRF prills)/total CRF N applied.

^zNo CRF were used in the grower (T1) and UF/IFAS (T2) treatments; thus, there were no CRF prills collected and analysis of variance was carried out on only CRF treatments for these columns.

^wNS, *, **, *** = Nonsignificant or significant at *P* ≤ 0.05, ≤ 0.01, or ≤ 0.001, respectively.

250 kg·ha⁻¹ was unaffected by N rate (Warner et al., 2004).

In conclusion, the high soil temperatures potentially decreased the duration of CRF (urea and NPK) N release compared with manufacturer-predicted release period. Although there were no detrimental effects on plant health when CRF-NPK nutrient release was accelerated, the accelerated N release from CRF-urea may have caused plant mortality and toxicity resulting from reduced nitrification of NH₄⁺. Based on two single-year trials, a CRF-NPK N rate ranging from 190 to 224 kg·ha⁻¹ may be recommended because similar FH marketable yields and total season marketable yields were produced during fall weather conditions, which is a 0% to 15% reduced N rate compared with UF/IFAS-recommended rates. The CRF (urea and NPK) release durations of 120 and 180 d had similar effects on tomato marketable yields. Further research must be conducted to explore the percentage urea composition usable in a tomato fertility program, although we suggest NH₄⁺-N sources be limited to 50% of the TN resulting from potential plant toxicity and reduced marketable tomato yields. Placement of CRF (NPK and urea) BIR with or without SF and tilling CRFs into the bed performed similar to SF in the seepage-irrigated gradient fertilizer system. CRF N rate, source, release duration, and bed placement did not affect post-harvest tomato quality.

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