Nitrogen Release Properties of Controlled-release Fertilizers during Tomato Production

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Additional index words. *Solanum lycopersicum*, enhanced-efficiency, slow-release, BMP, pouch method, release duration

Abstract. Determination of nutrient release duration from controlled-release fertilizers (CRFs) or soluble fertilizers encapsulated in polymer, resin, or sulfur covered fertilizer coated with a polymer differs among manufacturers, but may be determined as 75% to 80% nitrogen (N) release at a constant temperature (e.g., 20 to 25 °C). Increases or decreases in temperature compared with the manufacturer release determination temperature increase or decrease CRF N release; thus, coated fertilizer may release more rapidly than stated during the fall season when soil temperatures in seepage-irrigated tomato (*Solanum lycopersicum*) production can reach 40.1 °C. The objectives of this study were to evaluate N release duration of CRFs by measuring N release from CRFs incubated in pouches under polyethylene mulch-covered raised beds and to determine the CRF duration suitable for incorporation into a fall tomato fertility program. In 2011 and 2013, 12 and 14 CRFs from Agrium Advanced Technologies, Everris, Florikan, and Chisso-Asahi Fertilizer were sealed in fiberglass mesh pouches (12.7 × 14 cm) that were buried 10 cm below the bed surface in a tomato crop grown using commercial production practices. A data logger collected soil temperature 10 cm below the bed surface. Pouches were collected and N content was measured eight times through two fall seasons. A nonlinear regression model was fit to the data to determine N release rate. During the 2011 and 2013 seasons, minimum, average, and maximum soil temperatures were 21.2 and 19.2, 25.7 and 23.5, and 32.2 and 27.7 °C, respectively. Seasonal total CRF N release was between 77.6% and 93.8% during 2011 and 58.3% and 94.3% in 2013. In 2011, PCU90 and in 2013, PCU90 and PCNPK120 had the highest seasonal total percentage N release (PNR) and FL180 had the lowest in both years. A nonlinear regression fit N release from CRF with $R^2 = 0.85$ to 0.99 during 2011 and 0.49 to 0.99 during 2013. Nitrogen release from all CRFs was faster than the manufacturer's stated release, probably as a result of high fall bed temperatures. A CRF or CRF mixture containing CRFs of 120- to 180-day release duration may be recommended, but the CRFs must release greater than 75% N during the season.

A series of best management practices, including use of CRF, has been implemented for vegetable and agronomic crops by the Florida Department of Agriculture and Consumer Services in response to the Federal Clean Water Act of 1972 and the Florida Restoration Act of 1999 (Bartnick et al., 2005). Controlled-release fertilizers are soluble fertilizer (SF) coated in polymer, resin, or sulfur-coated urea in a polymer coating (Trenkel, 2010).

Field measurements of CRF N release have been made by researchers using the field pouch method, which consists of a known mass of CRF (e.g., 3.5 g N) sealed inside fiberglass mesh pouches that may be buried inside a polyethylene mulched or open bed vegetable systems and removed at prearranged dates (Carson

and Ozores-Hampton, 2012). After collection, the N content remaining in the CRF prills is measured to determine the amount of N remaining and the N release rate. The mesh pouch allows for soil to CRF prill contact, which may affect CRF N release rate. For instance, pouches with 1.2-mm² openings had greater N release compared with a weed-block material with 0.07-mm² openings (Wilson et al., 2009).

Several factors influence nutrient release from CRFs including soil temperature, moisture content, osmotic potential (ψ_s), nutrient composition, coating thickness, and prill diameter (Carson and Ozores-Hampton, 2013). Manufacturers of CRF manipulate the nutrient release duration of resin-coated fertilizer, polymer-coated fertilizer (PCF), and polymer sulfur-coated urea (PSCU) by adjusting coating thickness and composition with thicker coatings having longer release durations (Carson and Ozores-Hampton, 2013). However, in irrigated vegetable production, soil temperature may be considered

the most influential factor (Carson and Ozores-Hampton, 2013). Under laboratory conditions, Lamont et al. (1987) measured N release at nine temperatures from 5 to 45 °C and found a quadratic release response with temperature and time. In a similar study, Gandeza et al. (1991) demonstrated a doubling of the percentage N release (PNR) with each 10 °C rise in temperature from 10 to 30 °C. Thus, a CRF release duration will increase or decrease inversely with soil temperatures that differ from CRF manufacturer label specification. Controlled-release fertilizer manufacturers determine nutrient release duration in water at a constant 20.0, 21.1, and 25.0 °C, respectively (Agrium Advanced Technologies, 2010; Everris, 2013; Florikan ESA, 2012a, 2012b). However, the average daily soil temperatures under a polyethylene mulch-covered, raised vegetable bed in south Florida were greater than 23.9 °C for 8 weeks after bedding and were as high as 40.1 °C during the daytime in a fall tomato (*Solanum lycopersicum*) season (Carson et al., 2012a, 2013). Thus, high soil temperatures during the fall will affect CRF release duration used in tomato production. Therefore, selection of a CRF with too low of a nutrient release duration may result in slow nutrient release causing plant nutrient deficiencies, low plant growth, and reduced yield. In contrast, selection of a CRF with too high of a high nutrient release rate may result in increased soil electrical conductivity, plant toxicity and injury, and the loss of CRF benefits (Shaviv, 1996). Because CRF N release durations, independent of manufacturers' labeling, have not been published for fall production in Florida, the objectives of this study were to evaluate N release duration of CRFs by measuring N release from 90- to 180-d release CRFs incubated in pouches under polyethylene mulch-covered raised beds and to determine the CRF duration suitable for incorporation into a fall tomato fertility program.

Material and Methods

Two concurrent CRF field studies were conducted during each Fall 2011 and 2013 on a commercial tomato farm near Immokalee, FL (lat. 26°14'5" N, long. 81°28'55" W). The soil at the study location was Basinger fine sand (hyperthermic Spodic Psammaquents), which permitted seepage irrigation. The field configuration, bed preparation and fertilization, and fresh market tomato production practices are described in Carson et al. (2014a, 2014b), and dates relevant to these trials are in Table 1.

The two concurrent CRF studies each contained six and seven CRFs in 2011 and 2013, respectively, for a total of 12 CRFs in 2011 and 14 CRFs in 2013 (Table 2). The CRF fall mixes (M112, M168, and M224) are CRF, SF, and filler mixes that when applied at 1493 kg·ha⁻¹ supply 112, 168, and 224 kg·ha⁻¹ CRF N; however, different SF and filler amounts in the pouch may have affected the PNR in 2011. Therefore, a CRF mix (FLmix)

Received for publication 26 Aug. 2014. Accepted for publication 15 Oct. 2014.

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Table 1. Collection dates and days after placement (DAP) for pouches containing controlled-release fertilizer incubated in white polyethylene mulch-covered raised tomato beds during Fall 2011 and 2013 in Immokalee, FL.

Yr/ study	Bedding date	Planting date	Pouch placement	Collection date (DAP)							
				1	2	3	4	5	6	7	8
2011/1	3 Aug.	29 Aug.	3 Aug.	10 Aug. (7)	17 Aug. (14)	30 Aug. (27)	13 Sept. (41)	3 Oct. (61)	1 Nov. (90)	1 Dec. (120)	22 Dec. (139)
2011/2	15 Aug.	3 Sept.	15 Aug.	22 Aug. (7)	30 Aug. (15)	13 Sept. (29)	26 Sept. (42)	14 Oct. (60)	14 Nov. (91)	13 Dec. (120)	22 Dec. (129)
2013/1 and 2	20 Sept.	8 Oct.	24 Sept.	1 Oct. (7)	8 Oct. (14)	21 Oct. (27)	6 Nov. (43)	21 Nov. (58)	23 Dec. (90)	21 Jan. (119)	23 Jan. (121)

Table 2. Controlled-release fertilizers (CRFs) placed in pouches and incubated in white polyethylene mulch-covered raised tomato beds during Fall 2011 and 2013 in Immokalee, FL.

Study	CRF ^z	Abbreviation	Release duration	Grade ^y	Manufacturer ^x
1	PCU	PCU90	90	44-0-0	AAT
1	PCU	PCU120	120	43-0-0	AAT
1	PCNPK	PCNPK120	120	19-2.6-10.8	AAT
1	PCU	PCU180	180	43-0-0	AAT
1 ^w	PCNPK	PCNPK180	180	18-2.6-10	AAT
1	PSCU	PSCU	180	37-0-0	Everris NA
1	RCNPK	RCNPK	120	19-2.6-10	Everris NA
2	PCN	FL100	100	28-0-0	CAFC
2	PCN	FL140	140	28-0-0	CAFC
2	PCKN	FL180	180	12-0-33.2	Florikan ESA
2 ^w	PCM	FLmix	100 to 180	19.2-0-11.3	Florikan ESA
2	Fall Mix 112	M112	100 to 180	7.5-3.6-10.3	Florikan ESA
2	Fall Mix 168	M168	100 to 180	12.3-3.6-10.3	Florikan ESA
2	Fall Mix 224	M224	100 to 180	15-3.6-10.3	Florikan ESA

^zPCU = polymer-coated urea; PCNPK = polymer-coated compound nitrogen (N), phosphorus (P), and potassium (K) fertilizer; PSCU = polymer sulfur-coated urea; RCNPK = resin-coated compound N, P, and K fertilizer; PCN = polymer-coated N; PCNK = polymer-coated potassium nitrate; PCM = polymer-coated mix containing FL100, FL140, and FL180; M112, M168, and M224 are mixes of CRF and SF that when applied at 1493 kg·ha⁻¹ supply 112, 168, and 224 kg·ha⁻¹ CRF N.

^yFertilizer grade = (%N-%P-%K).

^xAgrium Advanced Technology (AAT), Loveland, CO; Everris NA, Inc., Dublin, OH; Florikan ESA, LLC., Sarasota, FL; Chisso-Asahi Fertilizer Co. Ltd. (CAFC), Tokyo, Japan.

^wPCU180NPK and FLmix were included in 2013; all other CRFs were tested in both years.

Table 3. Minimum, mean, and maximum air temperature and soil temperatures at 10 cm below the bed surface during Fall 2011 and 2013 in Immokalee, FL.

Week ending ^z	Air temp						Soil temp					
	Minimum		Mean		Maximum		Minimum		Mean		Maximum	
	2011	2013	2011	2013	2011	2013	2011	2013	2011	2013	2011	2013
9 Aug.	22.1	—	27.6	—	38.3	—	25.7	—	30.3	—	40.1	—
16 Aug.	21.9	—	27.4	—	36.7	—	25.2	—	30.3	—	39.6	—
23 Aug.	22.4	—	26.9	—	37.3	—	24.7	—	29.7	—	40.1	—
30 Aug.	22.8	—	27.1	—	35.0	—	25.0	—	29.3	—	37.6	—
6 Sept.	21.7	—	26.5	—	36.2	—	24.5	—	28.5	—	36.7	—
13 Sept.	22.0	—	27.4	—	37.4	—	24.7	—	30.6	—	39.1	—
20 Sept.	18.4	—	26.9	—	35.3	—	25.0	—	30.3	—	38.1	—
27 Sept.	21.1	21.7	26.3	25.7	35.8	31.7	24.0	25.2	28.3	28.1	36.0	33.9
4 Oct.	15.0	20.3	25.3	26.3	35.7	33.2	22.5	24.7	28.6	28.4	36.0	34.4
11 Oct.	15.9	17.6	24.2	25.1	33.1	34.3	22.2	23.7	26.4	27.8	32.7	33.2
18 Oct.	20.3	17.8	24.3	24.6	33.5	33.3	23.5	23.4	26.0	27.5	32.7	32.2
25 Oct.	10.2	14.7	20.0	24.3	28.4	35.6	18.2	21.2	23.1	27.3	28.2	33.2
1 Nov.	14.0	14.1	22.5	22.3	30.8	32.2	20.2	20.7	24.0	24.6	28.0	29.4
8 Nov.	10.1	13.3	20.1	22.5	29.7	31.2	17.2	20.2	22.4	24.5	27.7	29.7
15 Nov.	9.7	11.7	20.0	21.9	32.0	30.6	16.5	18.9	21.7	23.6	26.7	26.9
22 Nov.	16.1	16.7	23.3	23.5	33.7	32.7	21.2	21.9	24.3	24.7	28.7	27.4
29 Nov.	9.3	4.2	20.0	19.9	30.0	30.1	19.0	16.9	22.5	22.5	27.7	26.2
6 Dec.	6.4	13.1	17.9	20.1	29.2	30.6	14.7	17.9	20.0	21.5	25.0	24.9
13 Dec.	9.5	10.1	20.0	21.1	28.9	31.9	17.5	18.4	21.3	22.7	26.0	25.4
20 Dec.	9.8	6.4	19.2	18.7	29.0	30.1	15.7	16.7	20.7	20.6	24.2	23.9
27 Dec.	11.9	13.4	20.0	21.5	29.4	31.8	17.2	19.4	20.5	22.0	24.2	24.9
3 Jan.	—	7.8	—	20.4	—	30.8	—	16.9	—	21.9	—	23.7
10 Jan.	—	6.8	—	17.4	—	30.1	—	14.7	—	18.6	—	23.7
17 Jan.	—	-0.3	—	17.2	—	29.6	—	13.2	—	20.0	—	24.4
24 Jan.	—	-1.9	—	13.1	—	26.7	—	11.9	—	16.2	—	20.4
Average	15.7	11.5	23.4	21.6	33.1	31.5	21.2	19.2	25.7	23.5	32.2	27.7

^zCollection dates began on 3 Aug. 2011 and 24 Sept. 2013 and ended on 22 Dec. 2011 and 23 Jan. 2014.

was added in 2013, which contained CRFs in a ratio equivalent to the fall mixes that were composed of FL100, FL140, and FL180. Fiber-glass window screen (18 × 14-mesh or 39 pores/cm²) rectangles (15.2 × 30.5 cm) were folded in half and sealed on two sides using

a clothes iron (Model F210; Black & Decker, New Britain, CT). Controlled-release fertilizer samples containing 3.5 g N were placed inside the pouches and the last side was sealed, which resulted in internal dimensions of ≈12.7 × 14.0 cm (Carson et al., 2013). At bed formation in

2011 and 5 d after bedding in 2013 (to reduce personal protective equipment requirements), the pouches were placed level, 10 cm below the bed surface, in the center bed of a three-bed, 1.5-m-long plots. The studies were randomized complete block design with

four replications and eight collection dates. Pouches in the experimental unit, e.g., a set of six or seven pouches representing each CRF, were placed randomly in the plot. After pouches were collected (Table 1), pouch contents were dried in beakers at ambient temperature and stored until analysis (Carson et al., 2012b). In preparation for CRF N analysis, the pouch contents were ground in a blender (Model 36BL23; Waring Commercial, New Hartford, CT) with 300 mL deionized (DI) water to destroy the CRF coating and dissolve the SF. Samples were diluted to 500 mL using DI water, filtered using Whatman no. 42 filter paper, and frozen until N analysis. The solution was analyzed for total soluble N by pyrolysis and chemiluminescence using an Antek 9000 N analyzer (Pac. Co., Houston, TX) in 2011. In 2013, nitrate-N and ammonium-N were measured by salicylate-hypochlorite, cadmium reduction using a Flow Analyzer (QuikChem 8500; Lachat Co., Loveland, CO) at 660 nm and 520 nm, respectively, and urea-N was measured by modified diacetyl monoxime methods using a DR/4000U Spectrophotometer (Hach Co., Loveland, CO) at 527 nm (Sato et al., 2009; Sato and Morgan, 2008). The results for nitrate-N, ammonium-N, and urea-N were summed to determine total CRF N remaining in the prill. The N release results were expressed in cumulative PNR.

Weather data were obtained through the Florida Automated Weather Network (FAWN) and a Watchdog data logger (Model B100;

Spectrum Technologies Inc., Plainfield, IL) collected soil temperature hourly 10 cm below the bed surface through the tomato season.

Analysis of variance and orthogonal contrasts were performed on PNR data by collection date using the general linear model procedure in SAS (Version 9.3; SAS Institute Inc., Cary, NC). Year and CRF were considered main effects and year $\times$ CRF was an interaction effect. The non-linear regression procedure in SAS was used to determine the N release rate by fitting a CRF N release curve, which was also used to calculate the days to 75% N release (Medina et al., 2008; Sartain et al., 2004a, 2004b). The non-linear regression model was:

$$\text{PNR} = a - (a - b) \times e^{-ct}$$

where a = the maximum PNR, b = the intercept or value when time (t) = 0, and c = the rate of increase (Medina, 2011; Sartain et al., 2004a, 2004b). Because $t = 0$ data theoretically equals zero, intercept data were not included in the model, but intercept values were determined. An R^2 statistic for the non-linear regression was calculated, and a Student's t test was used to compare non-linear regression coefficients between years for each CRF.

Results and Discussion

Weather conditions. The minimum, average, and maximum air temperatures from

placement until last collection were 6.4, 23.4, and 38.3 °C and -1.9, 21.6, and 35.6 °C during 2011 and 2013, respectively. The 2011 and 2013 average air temperatures during the incubation period were similar to the moving 10-year average temperatures for the same period, which averaged 23.1 and 21.0 °C, respectively (FAWN, 2013). Total rainfall during the incubation period was greater in 2011 than 2013 with 46.4 and 12.6 cm, respectively. However, 40.3-cm rainfall accumulated during August and September, which delayed trial initiation in 2013. Both 2011 and 2013 accumulated lower than average rainfall during the incubation period compared with the 10-year average of 49.0 and 31.5 cm. The average daily air temperatures first went lower than Agrium Advanced Technologies Inc., Everris Intl., and Florikan ESA LLC. and Chisso-Asahi Fertilizer Co. specifications of 20.0, 20.1, and 25.0 after 10, 10, and 8 weeks in 2011 and 9, 9, and 1 week in 2013, respectively. Because CRF prills directly contact the soil, they are highly affected by soil temperature; however, because air temperature and soil temperature highly correlate, air temperature may reliably indicate temperatures effect on CRF (Carson et al., 2014a, 2014b).

Soil temperature. The minimum, average, and maximum soil temperature 10 cm below the bed surface decreased during the seasons ranging from 25.7 to 14.7 °C, 30.6 to 20.0 °C, and 40.1 to 24.2 °C in 2011 and 25.2 to

Table 4. Percentage nitrogen (N) release from controlled-release fertilizers (CRFs) incubated in pouches 10 cm below the surface of a white polyethylene mulch-covered raised bed during Fall 2011 and 2013 tomato production seasons in Immokalee, FL.

		Collection date DAP (2011–13) ^c							
		1 (7/7)	2 (15/14)	3 (28/27)	4 (42/43)	5 (61/58)	6 (91/90)	7 (120/119)	8 (134/121)
CRF ^y	Yr	----- N release (%) -----							
PCU90	2011	22.9	37.9	64.3	77.8	82.4	89.2	92.6	93.8
	2013	16.0	35.7	62.4	65.3	70.3	87.6	94.3	90.0
PCU120	2011	19.5	33.0	48.6	70.6	77.3	84.5	88.3	91.1
	2013	41.2	44.5	59.4	55.9	68.6	81.9	79.9	76.0
PCNPK120	2011	27.7	37.0	51.7	71.4	79.2	83.3	86.7	90.2
	2013	47.5	61.6	71.1	79.7	85.0	94.8	94.3	94.0
PCU180	2011	23.0	24.4	52.1	69.0	81.8	85.6	88.7	91.5
	2013	29.5	38.6	64.4	51.6	73.0	80.6	83.8	82.3
PCNPK180	2011	—	—	—	—	—	—	—	—
	2013	36.5	34.4	42.6	51.9	61.6	78.3	83.4	85.9
PSCU	2011	31.9	33.6	36.2	45.9	60.6	69.5	77.6	78.2
	2013	41.5	40.8	44.6	43.3	35.8	60.8	63.4	64.0
RCNPK	2011	29.3	42.6	52.3	69.3	76.8	85.5	87.6	90.2
	2013	50.5	60.3	65.6	70.7	78.7	92.4	93.9	91.6
FL100	2011	57.5	69.4	80.0	88.2	92.0	86.0	87.2	91.5
	2013	60.1	65.0	77.3	81.2	87.4	90.1	94.0	92.7
FL140	2011	52.1	68.8	87.0	88.5	94.3	86.9	89.0	91.3
	2013	65.5	65.6	75.4	78.0	82.9	86.3	87.4	88.0
FL180	2011	6.6	10.0	63.3	61.3	87.5	62.5	75.1	77.6
	2013	19.0	19.1	43.0	44.4	41.1	50.1	59.4	58.3
FLmix	2011	—	—	—	—	—	—	—	—
	2013	64.3	61.5	66.4	74.5	69.1	79.4	81.9	77.4
M112	2011	14.2	34.5	47.9	54.5	61.1	78.2	81.4	82.5
	2013	47.2	49.8	49.8	68.0	64.5	77.1	84.9	80.5
M168	2011	38.4	50.3	68.1	71.1	75.8	81.9	84.5	88.0
	2013	57.2	64.3	62.6	72.3	77.3	81.6	88.8	87.6
M224	2011	45.9	57.2	70.8	80.2	80.8	83.2	84.6	86.8
	2013	48.5	58.5	69.7	74.9	79.0	87.3	85.9	86.2

^yThe 2011 d after placement (DAP) number is an average between the DAP for the two studies rounded to the nearest whole number of days.

^zPCU90 = polymer-coated (PC) urea, 90-d release (DR); PCU120 = PC urea, 120 DR; PCNPK120 = PC nitrogen, phosphorus, and potassium (NPK), 120 DR; PCU180 = PC urea, 180 DR; PSCU = polymer sulfur-coated urea, 180 DR; RCNPK = resin-coated NPK, 120 DR; FL100 = PC urea, ammonium nitrate, 100 DR; FL140 = PC urea and ammonium nitrate, 140 DR; FL180 = PC potassium nitrate, 180 DR; FLmix = mix of FL100, FL140, and FL 180; M112, M168, and M224 = mixes of CRF and SF that when applied at 1493 kg·ha⁻¹ supply 112, 168, and 224 kg·ha⁻¹ CRF N.

Table 5. Contrasts of controlled-release fertilizers by collection date and coating technology from pouches incubated in white polyethylene mulch-covered raised tomato beds during Fall 2011 and 2013 in Immokalee, FL.

		Collection date DAP (2011–13) ^z							
		1 (7/7)	2 (15/14)	3 (28/27)	4 (42/43)	5 (61/58)	6 (91/90)	7 (120/119)	8 (134/121)
Contrasts	Yr	----- <i>P</i> value -----							
PCU120 vs. PCU180 ^y	2011	0.15	0.56	0.094	0.29	0.29	0.66	0.34	0.13
	2013	0.0001	0.09	0.21	0.54	0.01	0.0001	0.0011	0.0001
PCNPK120 vs. PCNPK180	2011	—	—	—	—	—	—	—	—
	2013	0.714	0.84	0.91	0.61	0.03	0.0002	0.008	0.0001
PCU120 vs. PCNPK120	2011	0.071	0.057	0.35	0.52	0.0001	0.014	0.0001	0.005
	2013	0.0001	0.0003	0.62	0.46	0.049	0.014	0.91	0.57
PCU180 vs. PCNPK180	2011	—	—	—	—	—	—	—	—
	2013	0.027	0.067	0.016	0.38	0.27	0.47	0.49	0.3227
RCNPK vs. PCNPK120	2011	0.013	0.079	0.004	0.087	0.15	0.022	0.33	0.94
	2013	0.37	0.52	0.65	0.83	0.74	0.0015	0.24	0.16
PCU90 vs. FL100	2011	0.045	0.91	0.011	0.27	0.030	0.79	0.0008	0.004
	2013	0.13	0.30	0.25	0.40	0.049	0.37	0.07	0.03
PSCU vs. PCU180	2011	0.23	0.60	0.0003	0.0003	0.0002	0.025	0.007	0.0001
	2013	0.45	0.16	0.43	0.002	0.0001	0.0001	0.0001	0.0001
PCU180 vs. FL180	2011	0.063	0.002	0.83	0.055	0.35	0.003	0.002	0.0001
	2013	0.007	0.0001	0.31	0.003	0.0001	0.0001	0.0001	0.0001
FL180 vs. PSCU	2011	0.004	0.006	0.0006	0.047	0.0001	0.41	0.63	0.82
	2013	0.04	0.0005	0.81	0.89	0.21	0.002	0.36	0.052
M112, M168, M224 (regression)	2011	0.61	0.36	0.49	0.82	0.40	0.89	0.84	0.89
	2013	0.12	0.35	0.45	0.57	0.29	0.66	0.36	0.03
FLmix vs. M112, M168, M224	2011	—	—	—	—	—	—	—	—
	2013	0.64	0.01	0.0002	0.08	0.0002	0.006	0.46	0.45
FL100, FL140, FL180 (regression)	2011	0.0001	0.0001	0.073	0.001	0.007	0.002	0.77	0.0001
	2013	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
PCU90, PCU120, PCU180 (regression)	2011	0.0001	0.0001	0.41	0.45	0.010	0.58	0.0001	0.0009
	2013	0.45	0.47	0.004	0.46	0.002	0.001	0.48	0.02

^zThe 2011 d after placement (DAP) number is an average between the DAP for the two studies rounded to the nearest whole number of days.

^yPCU90 = polymer-coated (PC) urea, 90-d release (DR); PCU120 = PC urea, 120 DR; PCNPK120 = PC nitrogen, phosphorus, and potassium (NPK), 120 DR; PCU180 = PC urea, 180 DR; PSCU = polymer sulfur-coated urea, 180 DR; RCNPK = resin-coated NPK, 120 DR; FL100 = PC urea, ammonium nitrate, 100 DR; FL140 = PC urea and ammonium nitrate, 140 DR; FL180 = PC potassium nitrate, 180 DR; FLmix = mix of FL100, FL140, and FL 180; M112, M168, and M224 = mixes of CRF and SF that when applied at 1493 kg-ha⁻¹ supply 112, 168, and 224 kg-ha⁻¹ CRF N.

11.9 °C, 29.3 to 14.8 °C, and 34.4 to 20.4 °C in 2013, respectively (Table 3). The average daily soil temperatures were first recorded below the Agrium Advanced Technologies Inc., Everris Intl., and Florikan ESA LLC. and Chisso-Asahi Fertilizer Co. specification of 20.0, 21.1, and 25.0 °C on 12 Nov., 5 Nov., and 17 Oct. in 2011 and 28 Nov., 28 Nov., and 24 Oct. in 2013, respectively. The average daily soil temperature was greater than the CRF manufacturer specification for more than half of the season at all temperatures in 2011 and for 20.0 and 21.1 °C in 2013. Also, the average soil temperature was greater than the 25 °C CRF manufacturer specification in 2013 for 25% of the season. Because high soil temperatures that were above the CRF manufacturer specifications during the first 25% to 50% of the season potentially increased N release rate, nutrient release duration may be expected to decrease (Carson et al., 2013; Carson and Ozores-Hampton, 2013; Gandeza et al., 1991; Huett and Gogel, 2000).

Measured nitrogen release from CRFs incubated the field pouch method. When data were analyzed without the two treatments added in 2013, there were interactions ($P < 0.05$) between CRF and year in six of eight collection dates. The main effects, CRF and year, were significant ($P < 0.05$) in eight and four collection dates, respectively. Therefore, PNR results were presented by year. The PNR at the first collection date ranged from 6.6% to 57.5% in 2011 and 16.0% to 65.5% in 2013 (Table 4). At the end of the season, PNR

ranged from 77.6% to 93.8% during 2011 and 58.3% to 94.0% in 2013. In 2011, PCU90 and in 2013, PCU90 and PCNPK120 had the highest season total PNR, whereas FL180 had the lowest PNR during both seasons. The PNR from PCU120 and PCU180 was not different at any collection date during 2011 but was significantly different at collection dates one and five through eight in 2013 (Table 5). Similarly, PCNPK120 and PCNPK180 had a different PNR at collection dates five through eight in 2013. Perhaps, the high soil temperatures during the early fall accelerated the N release rate of 180-d release PCFs for a similar PNR compared with 120-d release PCFs. The PNR from PCU120 and PCNPK120 was similar during collection dates one through four and three, four, seven, and eight in 2011 and 2013, respectively. With the exception of collection dates one and three, no PNR differences were found for PCU180 and PCNPK180 in 2013. At three nonadjacent and one collection date during the 2011 and 2013 seasons, RCNPK and PCNPK120 were significantly different. Nitrogen release from PCU90 and FL100 were significantly different in 2011 but not in 2013, although numerically the N release was different. Overall, the CRF technology had a greater impact on PNR from the 180-d release CRFs (PSCU, PCU180, and FL180) compared with the impact of constituent SF within 180-d CRF technologies (PCU180 and PCNPK180). The fall season mixes (M112, M168, and M224) were not linearly related, and PNR from the fall mixes were different from FLmix at

four collection dates. At six and eight collection dates in 2011 and 2013, respectively, PNR from the components of the fall mix (FL100, FL140, and FL180) were linearly related; thus, CRF PNR decreased with increasing release duration in 2011 and 2013. Similarly, PNR from PCU90, PCU120, and PCU180 were linearly related at the five and four collection dates in 2011 and 2013, respectively.

The soil temperature during these seasons averaged 2.2 °C lower in 2013 compared with 2011, which was the result of the delayed trial start date in 2013. The lower average soil temperatures in 2013 probably caused the lower PNR found among CRFs when compared with 2011 (Carson and Ozores-Hampton, 2013). Diverse coating technologies released N differently among the 180-d CRF products suggesting that technologies responded differently to increases in temperature during the tomato season. However, the 120-d release CRFs, especially RCNPK and PCNPK120, were similar at more collection dates than different; thus, perhaps the increased temperature affected these coating technologies similarly. The resemblance among N release from PCU90 and FL100 in 2013 was probably related to underlying variability rather than differences in PNR. In 2013, a numerically greater PNR was found with FLmix than M112, M168, and M224 at collections one through six, one and two, and one and two, respectively. Perhaps the SFs and fillers reduced the osmotic potential and N release during the early season in M112, with

Table 6. Nonlinear regression analysis of nitrogen (N) release from controlled-release fertilizers (CRFs) incubated in pouches 10 cm below the surface of a white polyethylene mulch covered raised tomato bed during Fall 2011 and 2013 in Immokalee, FL.

CRF ^z	Yr						75% N release ^x (DAP)	<i>t</i> test		
		a ^y	b	c	<i>R</i> ²	<i>P</i> value		a	b	c
		----- (%) -----		%/d				----- (<i>P</i> value) -----		
PCU90	2011	93.3	−1.4	0.040	0.98	0.0001	42	0.87	0.73	0.28
	2013	92.5	1.6	0.031	0.86	0.0001	52			
PCU120	2011	92.1	1.7	0.029	0.95	0.0001	57	0.36	0.0001	0.26
	2013	84.9	34.3	0.019	0.75	0.0001	92			
PCNPK120	2011	90.8	11.1	0.029	0.97	0.0001	56	0.10	0.0001	0.70
	2013	95.9	38.1	0.031	0.90	0.0001	32			
PCU180	2011	93.5	0.0	0.029	0.97	0.0001	56	0.25	0.018	0.64
	2013	86.2	20.6	0.025	0.78	0.0001	70			
PCNPK180	2011	—	—	—	—	—	—	—	—	—
	2013	100.0	24.6	0.012	0.99	0.0001	90			
PSCU	2011	100.0 ^w	22.7	0.0099	0.99	0.0001	114	— ^v	0.007	0.015
	2013	100.0 ^w	1.6	0.031	0.86	0.0001	> 121 ^v			
RCNPK	2011	92.4	16.9	0.026	0.97	0.0001	57	0.0008	0.0001	0.008
	2013	100.0 ^w	45.6	0.017	0.99	0.0001	44			
FL100	2011	89.4	36.9	0.070	0.92	0.0001	19	0.017	0.017	0.001
	2013	94.1	51.7	0.030	0.92	0.0001	26			
FL140	2011	90.5	14.4	0.096	0.95	0.0001	17	0.63	0.0001	0.0001
	2013	89.5	59.4	0.024	0.88	0.0001	30			
FL180	2011	72.2	−39.3	0.059	0.85	0.0001	> 139 ^v	0.84	0.002	0.01
	2013	68.7	16.9	0.013	0.57	0.0001	> 121 ^v			
FLmix	2011	—	—	—	—	—	—	—	—	—
	2013	87.0	60.3	0.011	0.49	0.0001	68			
M112	2011	84.8	6.9	0.024	0.94	0.0001	86	0.0001	0.0001	0.0009
	2013	100.0 ^w	41.6	0.010	0.98	0.0001	83			
M168	2011	85.5	26.5	0.036	0.96	0.0001	48	0.0001	0.0001	0.0001
	2013	100.0 ^w	54.8	0.011	0.99	0.0001	51			
M224	2011	85.1	31.8	0.045	0.93	0.0001	37	0.34	0.20	0.22
	2013	87.2	39.2	0.034	0.89	0.0001	39			

^zPCU = polymer-coated urea; PCNPK = polymer-coated compound nitrogen (N), phosphorus (P), and potassium (K) fertilizer; PSCU = polymer sulfur-coated urea; RCNPK = resin-coated compound N, P, and K fertilizer; PCN = polymer-coated N, PCNK = polymer-coated potassium nitrate; PCM = polymer-coated mix containing FL100, FL140, and FL180; M112, M168, and M224 are mixes of CRF and SF that when applied at 1493 kg-ha⁻¹ supply 112, 168, and 224 kg-ha⁻¹ N.

^yPercentage N release = $a - (a - b) * e^{-ct}$ where a = maximum N release, b = N release when time (t) = 0, and c = rate of N release.

^xDAP = days after placement.

^wThe a regression coefficient was restrained to 100% N release.

^vExtrapolation beyond the season length is not valid.

the greatest SF and filler amounts, compared with M168 and M224 (Carson and Ozores-Hampton, 2013).

Similar to many fertilizers in this study, a CRF study reported that RCNPK and PCNPK release higher N in the first week of laboratory incubation than any subsequent week and that PNR increased with increasing temperatures from 5 to 45 °C (Lamont et al., 1987). However, 70-d release polyolefin CRF released ≈20% and 60% N in 50 to 150 d during a potato (*Solanum tuberosum*) season, which was slower than the current study as a result of the temperature differences between spring in Minnesota and fall in Florida (Zvomuya et al., 2003). Comparatively, a 70-d release polyolefin CRF released 18% to 20% and 75% to 80% of the N in 30 and 120 d in Japan, which was lower compared with the PNR found at a similar day after placement (DAP) in this study (Gandeza et al., 1991). Thus, when using CRF in seasons with higher temperatures such as those in Florida and the subtropics, a release duration longer than the season may be necessary to obtain a release pattern similar to crop N uptake.

Non-linear regression analysis of nitrogen release. As a result of interactions between year and CRF, the CRF nonlinear regression models were presented by year and were highly significant for all CRFs (Table 6). The nonlinear regression model fit the

pouch-incubated CRF PNR with $R^2 = 0.85$ to 0.99 during 2011 and 0.49 to 0.99 during 2013. The total season PNR (“a” value) was not different between years for seven of 12 replicated CRFs. The “a” values for the fitted regression model differed from the measured total season PNR less than 3% for six and four CRFs and lower than 5% for 10 and six CRFs in 2011 and 2013, respectively. Six of the CRFs that had a 5% or greater PNR difference, which ranged from 8.4% to 21.8%, were bound to 100% N release by the regression model as a result of a relatively linear N release as a result of a high initial release or failure to reach the decay stage of release (Tables 4 and 6). The “b” values were variable with 10 of 12 replicated CRFs having significantly different “b” values between years; however, extrapolation to less than 7 DAP would be invalid, because $t = 0$ data were not used to fit the nonlinear regression model. The “b” or intercept values do not reflect immediately available N, because all N used in this study was encapsulated. The “c” values ranged from 0.0099 to 0.96%/d and 0.010 to 0.034%/d during 2011 and 2013, respectively. The N release rate (“c” value) was similar between years for five of 12 CRFs and significantly lower in six of 12 replicated CRFs in 2013 compared with 2011, which was the result of the lower soil temperature in 2013.

Similar to the pouch-incubated CRF N release results in this study, an exponential-growth nonlinear regression model fit CRF PNR data with a $R^2 \geq 0.98$ when CRFs were incubated in pouches under orange (*Citrus sinensis*) trees (Medina, 2006). Zvomuya et al. (2003) instead used quadratic regression to model N release from pouch-incubated PCU placed in a potato field with a DAP model and a growing-degree day model and found R^2 of 0.96 and 0.91, respectively. However, Medina (2006) obtained PNR greater than 90% during the 360-d trial, but Zvomuya et al. (2003) found PNR of 60% during the 150-d trial. The CRF used by Zvomuya et al. (2003) did not reach the decay stage of release, which is the stage of release where the ψ_s begin to equilibrate and release slows; therefore, linear release results may be expected. As a result of the high PNR during the tomato season in the current study, the exponential-growth nonlinear regression was used to model the data.

Days to 75% nitrogen release. Release of 75% N was obtained in 17 to greater than 139 DAP and 26 to greater than 121 DAP in 2011 and 2013, respectively; thus, all CRFs released with a shorter duration in 2011 than 2013 except RCNPK, PCNPK120, and M112 (Table 6). Furthermore, in all cases, 75% N release was accelerated compared with the CRF manufacturer’s stated release duration.

Fig. 1. Measured and fitted nitrogen (N) release from four representative controlled-release fertilizers (CRFs) [polymer-coated urea 120-d release (A) and polymer-coated urea 180-d release (B) from Agrium Advanced Technologies (Loveland, CO), and polymer-coated N 100-d release (C) and polymer-coated potassium nitrate 180-d release (D) from Florikan ESA (Sarasota, FL)]. The forward and backward sloping shaded areas represent the planting and first harvest windows reported by Carson et al. (2014a, 2014b). The solid and dashed vertical lines cross the day after planting axis (DAP) at 75% N release in 2011 and 2013, respectively. Tomato N uptake was measured in Immokalee, FL (Scholberg, 1996).

At the manufacturer incubation temperature (20.0 °C), PCU180 has a 60- and 90-d longer release duration compared with PCU120 and PCU90; although as a result of higher soil temperatures, 75% N release for PCU180 was 1 and 22 d shorter compared with PCU120 and 14 and 18 d longer compared with PCU90 in 2011 and 2013, respectively. In contrast, PCNPK180, which has a 60-d longer release duration compared with PCNPK120 at CRF manufacturer incubation temperature, had a 58-d longer release duration compared with PCNPK120 in 2013. Compared with FL100, FL140 had a 40-d longer release duration at CRF manufacturer temperatures; however, in the fall season, FL140 obtained 75% N release 2 d before and 4 d after FL100 in 2011 and 2013, respectively. The fall mixes (M112, M160, and M224) obtained 75% N release with a difference of 3 d or lower between years but a 49- and 44-d difference in 75% N release was found among the fall mixes and FLmix in 2011 and 2013, respectively. The CRFs composition in the fall mixes and FLmix were equivalent; thus, the included SF and fillers may have affected the osmotic potential and CRF release duration.

Figure 1 shows four CRFs compared with the tomato growing season, which includes an 18- to 26-d lag period between bedding

and tomato transplanting as a result of fumigation requirements and a 20-d first harvest window as found in Carson et al. (2014a, 2014b). During a 26-d lag period, FL100 and FL140 in 2011 and FL100 in 2013 released 75% of the N before tomatoes were transplanted. Tomato uptake was 10% and 30% of the total season N in the first 30 and 46 d after transplant (Scholberg, 1996). Therefore, two and four CRFs in 2011 and one and five CRFs in 2013 released greater than 75% of the N before tomatoes uptake 10% and 30% season total N, respectively. Furthermore, greater than 50% of the 2011 season and 3 weeks of the 2013 season included the high rainfall season that ends in mid-October in southwest Florida (Rosencrans, 2012). Thus, between 62.8% and 90.3% N in 2011 and 27.1% and 71.6% N in 2013 was released during the high rainfall season in which N will be subject to leaching as a result of water table fluctuations (Sato et al., 2009, 2012). The 90- and 100-d release CRFs released the majority of the N during the rainy season and should not be recommended for tomato production during the fall season. Controlled-release fertilizers of 180-d release duration released between 58.3% and 91.5% of the N during the season, but a thicker coating results in a greater cost compared with CRF of lower release

durations. Furthermore, 180-d CRFs did not consistently maintain low early-season PNR and high total season PNR compared with CRF of 120-d release. Therefore, CRFs or CRF mixes of 120 to 180 d may be recommended, although the CRFs and mixes must consistently release a high portion of the total N to the intended crop.

In conclusion, under the conditions of this study, the PNR from pouch-incubated CRFs in the tomato field was accelerated during the fall season compared with the manufacturer's stated release, which was the result of high soil temperatures that caused coating technology-dependent N release. A CRF or CRF mixture containing CRFs of 120- to 180-d release duration may be recommended for growing conditions in south Florida, but the CRFs must release greater than 75% N during the season.

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