Prediction of Controlled-release Fertilizer Nitrogen Release Using the Pouch Field and Accelerated Temperature-controlled Incubation Methods in Sand Soils

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Abstract. Controlled-release fertilizers (CRFs), a vegetable production best management practice in Florida, are soluble fertilizers (SFs) coated with a polymer, resin, or a hybrid of polymer coating sulfur-coated urea. In 1994, a Controlled Release Fertilizer Taskforce developed an accelerated temperature-controlled incubation method (ATCIM) to predict column-incubated CRF nitrogen (N) release for regulatory purposes. Determination of CRF field N release uses a field method such as a pouch field study, which requires multiple samples and high costs for laboratory N analysis. If the ATCIM may be used to predict CRF N release in the field, then vegetables growers will have a faster and lower-cost method to determine N release compared with the pouch field method. Therefore, the objective of this study was to evaluate the correlation of the ATCIM and the pouch field method as a predictor of N release from CRFs in tomato production in Florida. In 2011 and 2013, 12 and 14 CRFs, respectively, were incubated in pouches placed in polyethylene mulched raised beds in Immokalee, FL, and extracted in the ATCIM during 2013. The ATCIM CRF results were used individually and grouped by release duration to create predicted N release curves in a two-step correlation process. The two-step processes predicted the percentage N release of individual CRF with R^2 of 0.95 to 0.99 and 0.61 to 0.99 and CRFs grouped by release duration with R^2 of –0.64 to 0.99 and –0.38 to 0.95 in 2011 and 2013, respectively. Modeling CRF N release grouped by release duration would not be recommended for CRF 180-d release (DR), because coating technologies behaviors differ in response to high fall soil temperature in polyethylene mulched beds. However, with further model calibration, grouping CRFs of 90 to 140 DR to simulate the CRF N release profile may allow the ATCIM to predict CRF N release without performing the pouch field method, which currently negated the usefulness of the ATCIM in a tomato production system.

The majority of fresh-market tomato in south Florida is grown using subsurface or seepage irrigation as a result of low costs and simple operation (E.J. McAvoy, personal communication; Zotarelli et al., 2013). Seepage irrigation consists of managing a perched water table on a slowly permeable agrillic or spodic soil layer (Pitts et al., 2002). In seepage-irrigated fresh-market tomato (*Solanum lycopersicum* L.) production using soluble fertilizer sources, all the phosphorus and micronutrients plus 10% to 20% of the N and potassium (K) are applied broadcast in-row before bedding and the remainder of the N and K is applied

after bed formation in two bands on the bed shoulders before plants are transplanted in the field (Carson and Ozores-Hampton, 2013). Repeated water table fluctuations, resulting from inadequate water table management or intense rainfall, may result in N leaching losses from 35% to 43% in tomato production in south Florida (Sato et al., 2012). Therefore, vegetable growers should maintain a steady water table to reduce N leaching during the crop season.

In response to the Federal Clean Water Act of 1972 and the Florida Restoration Act of 1999, a series of agronomic and vegetable best management practices (BMPs) have been adopted by the Florida Department of Agriculture and Consumer Services (Bartnick et al., 2005). One BMP can be the use of CRFs, which are SFs encapsulated in a polymer, resin, or a hybrid of sulfur-coated urea occluded in a polymer coating (Bartnick et al., 2005; Trenkel,

2010). By definition, CRFs may increase N use efficiency compared with SF by protecting N against leaching below the root zone and becoming an environmental pollutant (Slater, 2010).

Over the past 50 years, several CRF coating technologies have been developed and marketed, but no standard method to evaluate CRF manufacturer claims or performance existed for regulatory purposes in the United States (Sartain et al., 2004a, 2004b). Therefore, a task force was formed in 1994 to develop an ATCIM to predict CRF release duration. The task force developed a two-step correlation between ATCIM N release and N release from CRFs incubated in soil-filled polyvinyl chloride (PVC) columns in the laboratory (Carson and Ozores-Hampton, 2012; Medina et al., 2009; Sartain et al., 2004a, 2004b). The ATCIM-predicted PVC column incubated CRF N release with greater than 90% accuracy (Medina et al., 2009; Sartain et al., 2004a, 2004b). During the PVC column laboratory incubation, CRFs were maintained at a constant temperature and moisture content between leaching events; thus, CRFs were subjected to minimal variability compared with CRFs placed in the open field. In contrast, field studies are subject to variations resulting from diurnal temperature oscillation, weather pattern, and water table fluctuations (Medina, 2011). Therefore, because of field environment variability, correlation for regulatory purposes needs to be tested between ATCIM and laboratory-based PVC column-incubated CRFs (Carson and Ozores-Hampton, 2012).

The field pouch method has been used to determine CRF N release in the field in several studies (Carson and Ozores-Hampton, 2012). The mesh pouches allow for contact between the soil and CRF prills, which may affect CRF N release because pouches with 1.2-mm² openings had greater N release compared with pouches with 0.07-mm² openings (Wilson et al., 2009). Although this method may be effectively used to determine N release rate from CRFs, the pouch method requires an entire growing season and numerous samples with high analysis costs (Carson and Ozores-Hampton, 2012). However, an ATCIM that predicts CRF field release may assist growers with the selection of a CRF with the correct release duration to be used in vegetable production with lower time and costs.

The two-step CRF prediction method requires correlation of N release from an ATCIM and a long-term CRF incubation to determine CRF-specific N release coefficients. Therefore, to predict N release from a new CRF never tested in tomato production in Florida, a pouch field method would be required to correlate with the ATCIM. Consequently, if a pouch study were conducted, an ATCIM would not be needed to predict field N release. Thus, if CRFs were grouped by release duration to develop a CRF N release model, then perhaps CRF N release may be predicted without a field pouch study. Therefore, the objective of this study was to evaluate the correlation of the ATCIM and

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the field pouch method as a predictor of N release from individual CRFs and CRF grouped by release duration in tomato production in south Florida.

Material and Methods

Accelerated temperature-controlled incubation method. Fourteen CRFs from Florikan ESA L.L.C. (Sarasota, FL), Agrium Advanced Technologies Inc. (Loveland, CO), Chisso-Asahi Fertilizer Co. Ltd. (Tokyo, Japan), and Everris International B.V. (Dublin, OH) were tested during July 2013 using the ATCIM (Table 1) (Medina et al., 2009). A 30-g CRF sample was exposed to four increasingly aggressive (in length and temperature) extractions using 0.2% citric acid as a solvent during the course of 72 h. Extractions were 2 h at 25 °C, 2 h at 50 °C, 18 h at 55 °C, and 50 h at 60 °C (or 2, 4, 22, and 72 h, cumulatively). The extraction device had 16 jacketed chromatography columns; therefore, 14 CRFs and two isobutylidene diurea (31% N) samples as controls were extracted during each incubation cycle, which was replicated three times with CRFs randomized in each replicate. Extract N content was measured by pyrolysis and chemiluminescence using an Antek 9000 N analyzer (PAC Co., Houston, TX). The ATCIM N release data were subjected to analysis of variance and orthogonal contrasts using the general linear model procedure of SAS (Version 9.2; SAS Institute, Cary, NC).

Data were presented as cumulative percentage N released (PNR).

Field pouch method field study. Twelve and 14 CRFs extracted in the ATCIM were used in the pouch method field study during 2011 and 2013, respectively, in Immokalee, FL, on Basinger fine sand (hyperthermic Spodic Psammaquents) (Carson et al., 2013, 2014c). The CRFs were divided into two independent studies containing an equal number of CRFs (Table 1). The CRF fall mixes (M112, M168, and M224) were CRF and SF mixes that when applied at 1493 kg·ha⁻¹ supply 112, 168, and 224 kg·ha⁻¹ CRF N; however, the SF and fillers in the pouch may have affected the N release in 2011. Therefore, FLmix was added in 2013 containing CRF equivalents to the fall mixes that were composed of FL100, FL140, and FL180. All other treatments were individual CRFs.

Fiberglass window screen (18 × 14 mesh) was cut into 15 × 30-cm rectangles, folded in half, and sealed on two sides. A CRF sample containing 3.5 g N was placed in the mesh pouch and the last side was sealed giving inside dimensions of 12.7 × 14 cm. The CRF pouches were buried flat at a 10-cm depth in the center bed of a three-bed, 1.5-m long plot. The pouches in the experimental unit, e.g., a set (six or seven) of pouches representing each CRF, were placed randomly in the plot. The plots were placed in a randomized complete block design with four replications and eight collection dates (Table 2).

After pouch collection, the pouch contents were dried in a beaker at room temperature, placed in plastic bags, and stored until N analysis (Carson et al., 2012). To prepare the sample for analysis, the pouch contents were ground in 300 mL of deionized water using a blender (Model 36BL23; Waring Commercial, New Hartford, CT) to destroy the prill coating. The CRF samples were diluted to 500 mL with deionized water, filtered using Whatman no. 42 filter paper, and frozen at -20 °C until analysis. In 2011, the samples were analyzed for total soluble N by pyrolysis and chemiluminescence using an Antek 9000 N analyzer (Pac. Co.). In 2013, nitrate-N (NO₃⁻-N) and ammonium-N (NH₄⁺-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. Urea-N was 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). The results for NO₃⁻-N, NH₄⁺-N, and urea-N were summed to determine total residual CRF N. The results were expressed in cumulative PNR (Carson et al., 2014c). The pouch method PNR data were subjected to analysis of variance and orthogonal contrasts using the general linear model procedure of SAS (Version 9.2; SAS Institute, Cary, NC).

Correlation of the ATCIM with the pouch method using a two-step process. The non-linear

Table 1. Controlled-release fertilizers (CRFs) used in the accelerated temperature-controlled incubation and the field pouch methods incubated in white polyethylene mulch covered raised tomato beds during Fall 2011 and 2013 in Immokalee, FL.

CRF ^z	Abbreviation	Release duration ^y	Grade ^x	Manufacturer ^w	Pouch study	Group ^v
PCU	PCU90	90	44-0-0	Agrium Advanced Technology	1	1
PCU	PCU120	120	43-0-0	Agrium Advanced Technology	1	2
PCNPK	PCNPK120	120	19-2.6-10.8	Agrium Advanced Technology	1	2
PCU	PCU180	180	43-0-0	Agrium Advanced Technology	1	3
PCNPK ^u	PCNPK180	180	18-2.6-10	Agrium Advanced Technology	1	3
PSCU	PSCU	180	37-0-0	Everris	1	3
RCNPK	RCNPK	120	19-2.6-10	Everris	1	2
PCN	FL100	100	28-0-0	Chisso-Asahi Fertilizer Co.	2	1
PCN	FL140	140	28-0-0	Chisso-Asahi Fertilizer Co.	2	2
PCKN	FL180	180	12-0-33.2	Florikan ESA	2	3
PCM ^u	FLmix	100-180	19.2-0-11.3	Florikan ESA	2	4
Fall Mix 112	M112	100-180	7.5-3.6-10.3	Florikan ESA	2	4
Fall Mix 168	M168	100-180	12.3-3.6-10.3	Florikan ESA	2	4
Fall Mix 224	M224	100-180	15-3.6-10.3	Florikan ESA	2	4

^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; PC = 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 from CRF.

^yRelease durations in days.

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

^wAgrium Advanced Technology, Loveland, CO; Everris International B.V., Dublin, OH; Florikan ESA, LLC., Sarasota, FL; Chisso-Asahi Fertilizer Co. Ltd., Tokyo, Japan.

^vGroups used in the two-step method to predict N release based on CRF release duration.

^uPCU180NPK and PCM were included in 2013.

Table 2. Collection dates and days after placement (DAP) for controlled-release fertilizers in field pouch studies incubated in white polyethylene mulch covered raised tomato beds during Fall 2011 and 2013 in Immokalee, FL.

Yr/study	Collection date (DAP)							
	1	2	3	4	5	6	7	8
2011/1	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	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	1 Oct. (7)	8 Oct. (14)	21 Oct. (27)	6 Nov. (43)	21 Nov. (58)	23 Dec. (90)	21 Jan. (119)	23 Jan. (121)

regression equation, $PNR = a - (a-b) \times e^{-ct}$ in which a = the maximum level of PNR, b = the intercept or PNR when time (t) = 0, and c = the rate of increase, used the Gaussian-Newton iterative method and was fit to each replicate of the pouch incubated CRF N release data by CRF (Sartain et al., 2004a, 2004b). For each year, replicates one and two and three and four of the nonlinear regression coefficients from the pouch incubated CRF N release were averaged and paired with replicate one and two of the ATCIM extracted N release values to fit a multiple regression model. The extraction values were the explanatory variable and the nonlinear regression coefficients were the dependent variable as $a = a_0 + a_1E_1 + a_2E_2 + a_3E_3 + a_4E_4$, $b = b_0 + b_1E_1 + b_2E_2 + b_3E_3 + b_4E_4$, and $c = c_0 + c_1E_1 + c_2E_2 + c_3E_3 + c_4E_4$. The ATCIM extraction values were represented by E_1 , E_2 , E_3 , and E_4 . The fitted multiple linear regression coefficients and the third ATCIM replicate were used to create predicted nonlinear regression coefficients and predicted N release curves (NRCs). Prediction models based on CRF release duration, rather than CRF-specific models, were created by grouping the nonlinear regression coefficients and ATCIM extraction values from the individual prediction models to develop a new set of multiple linear regression coefficients (Table 1). The new multiple linear regression coefficients and third replicate of the ATCIM were used to create a group-predicted NRC for each CRF based on release duration.

An R^2 -type statistic was developed based on the sum of squares (SS) for the predicted and grouped CRF regression models as $(SS1 - SS2)/SS1$, where $SS1$ equals the sum of squared differences between the fitted release curve and the grand mean and $SS2$ equals the sum of the squared differences between points on the fitted release curve and points on the individual predicted or group-predicted NRC. Thus, the statistic measures agreement between the individual or group-predicted NRCs and the fitted release curve compared with a straight horizontal line through the grand mean. Therefore, a value of one indicates that the two NRCs were the exact same, a zero value indicates that the individual or group predicted NRCs fit will be equivalent to a line through the mean, and a negative value indicates that a line through the mean will agree with the fitted NRC better than the individual or group-predicted NRCs.

Results and Discussion

Accelerated temperature-controlled incubation method. The PNR from ATCIM extractions one through four ranged from 0.1% to 2.4%, 0.2% to 5.9%, 1.5% to 29.0%, and 28.4% to 72.5%, respectively (Table 3). The components of FLmix (FL100, FL140, and FL180) and the PCUs (PCU90, PCU120, and PCU180) had a PNR in order of release duration, i.e., FL100 > FL140 > FL180 during extractions one through four and PCU90 > PCU120 > PCU180 during extractions one and two, although the regression was significant at

Table 3. Percentage nitrogen (N) extracted from controlled-release fertilizers (CRFs) during the accelerated temperature-controlled incubation method.

CRF ^z	Extraction number			
	1	2	3	4
	Cumulative N release (%)			
PCU90	1.3	4.4	29.0	48.6
PCU120	0.3	0.6	6.6	36.9
PCNPK120	1.9	3.7	10.5	60.8
PCU180	0.1	0.3	11.8	40.6
PCNPK180	0.5	0.7	1.7	33.0
PSCU	2.4	5.9	21.5	30.7
RCNPK	1.9	4.2	9.7	72.5
FL100	0.2	0.9	17.9	60.5
FL140	0.1	0.6	10.2	43.2
FL180	0.1	0.2	1.5	28.4
FLmix	0.2	0.8	13.5	59.2
M112	1.2	2.8	16.6	55.2
M168	1.1	2.6	14.6	48.0
M224	0.7	2.0	19.1	55.1
<i>P</i> value	0.0001	0.0001	0.0001	0.0001
Significance ^y	***	***	***	***
	Single df contrast (<i>P</i> value)			
PCU90, PCU120, PCU180 ^x	0.005	0.0004	0.006	0.29
PCNPK120 vs. PCNPK180	0.11	0.027	0.018	0.003
PCU120 vs. PCNPK120	0.06	0.019	0.07	0.006
PCU180 vs. PCNPK180	0.16	0.16	0.02	0.023
RCNPK vs. PCNPK120	0.96	0.21	0.07	0.053
PCU90 vs. FL100	0.03	0.006	0.038	0.032
PSCU vs. PCU180	0.001	0.001	0.036	0.08
PCU180 vs. FL180	0.77	0.88	0.031	0.045
FL180 vs. PSCU	0.001	0.001	0.003	0.62
M112, M168, M224 ^x	0.026	0.016	0.21	0.99
FLmix vs. M112, M168, M224	0.0001	0.0001	0.0004	0.0001
FL100, FL140, FL180 ^x	0.027	0.06	0.004	0.013

^zPCU90 = polymer-coated (PC) urea, 90-d release (DR); PCU120 = PC urea, 120 DR; PCNPK120 = PC N, phosphorus, and potassium (NPK), 120 DR; PCU180 = PC urea, 180 DR; PCNPK180 = PC NPK, 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.

^yNS, *, **, *** Nonsignificant or significance at $P \leq 0.05$, ≤ 0.01 , or ≤ 0.001 , respectively.

^xRegression.

Table 4. Regression coefficients and coefficient of determination for predicted controlled-release fertilizer (CRF) nitrogen (N) release curve based on the two-step process from accelerated temperature-controlled incubation and field pouches incubated in white polyethylene mulch covered raised tomato beds during Fall 2011 and 2013 in Immokalee, FL.

CRF ^z	2011				2013			
	a ^y	b	c	R ^{2x}	a	b	c	R ²
PCU90	92.9	-0.7	0.037	0.99	91.2	1.0	0.033	0.99
PCU120	92.2	-0.1	0.029	0.99	88.4	29.5	0.027	0.94
PCNPK120	90.5	7.7	0.032	0.99	93.5	28.7	0.051	0.98
PCU180	93.9	-1.2	0.036	0.97	86.1	20.4	0.031	0.99
PCNPK180	—	—	—	—	98.2	28.5	0.007	0.61
PSCU	97.8	20.9	0.009	0.95	80.0	20.9	0.009	0.99
RCNPK	93.4	13.8	0.026	0.99	96.1	50.5	0.013	0.89
FL100	89.6	34.2	0.073	0.99	95.6	51.9	0.028	0.99
FL140	90.8	4.0	0.110	0.99	88.1	63.8	0.024	0.95
FL180	77.3	-46.6	0.058	0.99	73.4	12.7	0.022	0.93
FLmix	—	—	—	—	89.8	57.8	0.019	0.99
M112	85.2	5.2	0.024	0.99	98.7	38.7	0.012	0.99
M168	86.5	21.4	0.036	0.98	91.0	58.1	0.012	0.87
M224	85.4	25.7	0.048	0.99	82.5	34.6	0.044	0.94

^zPCU90 = polymer-coated (PC) urea, 90-d release (DR); PCU120 = PC urea, 120 DR; PCNPK120 = PC N, phosphorus, and potassium (NPK), 120 DR; PCU180 = PC urea, 180 DR; PCNPK180 = PC NPK, 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.

^yPercent nitrogen release = $a - (a - b) \times e^{-(c \times t)}$, where a = maximum amount of N released during the season, b = the intercept or value when time equals zero, c = the rate of N release and t = time.

^xThe R^2 value $(SS1 - SS2)/SS1$, where $SS1$ = the sum of the squared differences between points on the fitted release curve and the overall mean and $SS2$ = the sum of the squared differences between the points on the fitted time release curve and the points on the predicted N release curve points.

Fig. 1. Field nitrogen (N) release points for controlled-release fertilizers in the field pouch method incubated 10 cm below the surface of a white polyethylene mulched raised bed during Fall 2011 and 2013 in Immokalee, FL, and fitted and predicted N release curves from the two-step correlation of the accelerated temperature-controlled incubation and field pouch incubation in white polyethylene mulch-covered raised tomato beds during Fall 2011 and 2013, respectively, in Immokalee, FL. PCU90 = polymer-coated (PC) urea, 90-d release (DR); PCU120 = PC urea, 120 DR; PCNPK120 = PC N, phosphorus and potassium (NPK), 120 DR; PCU180 = PC urea, 180 DR; PCNPK180 = PC NPK, 180 DR from Agrium Advanced Technologies (Loveland, CO); PSCU = polymer sulfur-coated urea, 180 DR and RCNPK = resin-coated NPK, 120 DR from Everris NA (Dublin, OH); FL100 = PC urea, ammonium nitrate, 100 DR and FL140 = PC urea and ammonium nitrate, 140 DR from Chisso-Asahi Fertilizer (Tokyo, Japan); 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 from Florikan ESA (Sarasota, FL).

extractions one through three. Similarly, PCNPK120 had a greater PNR compared with PCNPK180 at extractions two, three, and four. The coated SFs impacted CRF PNR with PCU120 having lower PNR compared with PCNPK120 at extractions two and four and PCU180 having higher PNR compared with PCNPK180 at extractions three and four. With only a 10-d difference in release duration, PCU90 had a greater PNR at extractions one through three compared with FL100, but FL100 was greater at extraction four. However, N release between PCNPK120 and RCNPK was not different at any extraction. At extractions one through three, the PNR from PSCU was greater than the PNR of FL180 and PCU180, which were different at extractions three and four. The extracted N release of the fall mixes was similar in extractions three and four, but there were significant differences among the CRFs at extractions one and two; thus, the SF and fillers probably affected the extraction. Additionally, FLmix had a lower PNR at extractions one, two, and three but higher in extraction four compared with the fall mixes.

Medina (2011) and Medina et al. (2009) extracted CRFs in the ATCIM at 2, 2, 20, and 50 h (or 2, 4, 24, and 74 h, cumulatively) for extractions one through four, respectively, but CRFs in this study were extracted using a 2-, 2-, 18-, and 50-h (or 2, 4, 22, and 72 h, cumulatively) extraction cycle. According to a ruggedness test conducted by Medina (2011), a 10% reduced time for extractions two and three decreased the second and third N concentrations in two of four CRFs but did not affect the total cumulative PNR. The 180-d release CRFs in the current study had lower and higher cumulative PNR compared with 270-d release polyolefin CRFs (Medina, 2011), thus indicating that the ATCIM is sensitive to different CRF coating technologies.

Prediction model: Correlation of ATCIM and pouch N release. The 2011 and 2013 predicted NRC fit the fitted NRC with R^2 of 0.95 to 0.99 and 0.61 to 0.99, respectively (Table 4). The “a” values of the predicted nonlinear regression coefficients were different from the total season PNR by of 0.3% to 19.6% and 0.1% to 18.2% in 2011 and 2013, respectively, with the lowest and highest differences in PCNPK120 and PSCU in 2011 and FL140 and M112 in 2013, respectively. The “b” values were variable and may affect the rate of N release, but the fitted and predicted PNR were similar to the first PNR points in the majority of the CRFs (Fig. 1). The “c” values were lower or similar in 2013 compared with 2011 for all CRFs except PCNPK120 as a result of the late field trial start date resulting in lower air and soil temperatures.

The high R^2 values indicate that the ATCIM PNR results may predict CRF N release effectively after correlation with pouch field method results. In some CRFs such as PCU90, PCU180, and FL100, the NRCs were similar between years suggesting that mean season soil temperature differences of 2.2 °C between seasons did not impact all CRFs.

However, variability in PNR results may cause differences in fitted and predicted NRCs in CRFs such as PCU180. Furthermore, the high initial release and “b” values caused the initial PNR to differ between the two seasons, but NRCs of some CRFs such as PCU120, RCNPK, M168, and M224 converged 50 to 60 d after placement. Medina (2011) and Sartain et al. (2004a, 2004b) predicted NRCs from CRFs incubated in a PVC column with $R^2 \geq 0.90$ using the two-step process. These results indicated that the two-step process may be used to accurately predict field NRCs from CRFs with release durations of 180 d or lower. Similarly, studies have used different two-step processes and concluded CRF PNR may be predicted by elevating CRF extraction temperatures (Dai et al., 2008; Wang et al., 2011).

Prediction model: Correlation of ATCIM and pouch N release grouped by CRF release duration. Group-predicted CRF NRCs fit the fitted NRCs with R^2 of -0.64 to 0.99 and -0.38 to 0.95 for Fall 2011 and 2013, respectively (Table 5). Thus, a line through the grand mean would fit PCU180, PSCU, and M168 in 2011 and M168 in 2013 better than the group-predicted NRC. However, several group-predicted NRCs fit the fitted NRCs adequately (Fig. 2). In 2011 and 2013, the “a” values ranged from 69.7 to 105.2 and 69.7 to 106.2, the “b” values ranged from -39.1 to 75.3 and 8.6 to 69.8, and the “c” values ranged from 0.02 to 0.107 and 0.005 to 0.045, respectively. The difference between years for the group-predicted nonlinear regression coefficients was the result of soil temperature differences, which were similarly detected among the individual predicted

CRFs. The difference between the “a”, “b”, and “c” group and individual predicted nonlinear regression coefficients averaged 2.9, 13.8, and 0.01 in 2011 and 4.7, 7.7, and 0.009 in 2013, respectively.

Compared with the individual-predicted NRCs, the group-predicted NRCs had lower accuracy, which might be expected as a result of the combination of different CRF technologies, although eight CRFs in each year maintained a $R^2 \geq 0.80$. The group-predicted NRCs had higher agreement with the fitted NRCs among the 90- to 140-d release CRFs compared with the 180-d release CRFs. The lower agreement among the 180-d CRFs was related to the greater variability in response to high soil temperatures among the 180-d release CRF coating technologies that included PSCU and PCF relative to other release durations that included PCF and RCF, which are more closely related. The difference between years in the predicted NRCs was likely the result of differences in soil temperature. Except for the CRFs with a negative R^2 such as PCU180, PSCU, and M168, the group-predicted PNR coefficient probably predicted PNR in the field adequately for a tomato production system in south Florida.

Calibration of the ATCIM with the field pouch study has established the prediction ability for this quick test; thus, a grower would be able to send a CRF sample to a laboratory to obtain the predicted NRC for fall production under polyethylene mulch. The grower will be able to compare the predicted CRF NRC with a seasonal tomato N uptake curve (i.e., 10% and 30% of the total season tomato N uptake in the first 30 and 46 d after transplant). Thus, the ideal CRF NRC will release greater than 10% and

Table 5. Regression coefficients and coefficient of determination for predicted nitrogen (N) release based on controlled-release fertilizer (CRF) coefficient groupings in the two-step process from accelerated temperature-controlled incubation and field pouches incubated in white polyethylene mulch-covered raised tomato beds during Fall 2011 and 2013 in Immokalee, FL.

CRF ^z	2011				2013			
	a ^y	b	c	R ^{2x}	a	b	c	R ²
PCU90	91.9	13.9	0.038	0.96	89.4	8.6	0.045	0.90
PCU120	91.6	4.5	0.058	0.64	89.5	39.6	0.029	0.80
PCNPK120	92.4	13.7	0.039	0.87	96.7	42.1	0.026	0.96
PCU180	105.2	75.3	0.019	-0.64	78.8	9.3	0.040	0.94
PCNPK180	—	—	—	—	106.5	33.7	0.010	0.95
PSCU	90.0	31.8	0.031	-0.17	69.7	17.1	0.022	0.61
RCNPK	91.2	15.2	0.048	0.96	102.3	57.3	0.020	0.66
FL100	89.9	27.9	0.080	0.99	96.8	56.1	0.023	0.94
FL140	90.3	2.4	0.107	0.99	92.0	69.8	0.012	0.84
FL180	85.5	-39.1	0.038	0.89	70.9	12.3	0.048	0.64
FLmix	—	—	—	—	91.4	52.3	0.022	0.80
M112	85.4	5.4	0.020	0.96	102.1	47.8	0.005	0.67
M168	85.4	5.5	0.020	-0.36	101.6	47.1	0.006	-0.38
M224	85.2	45.7	0.038	0.93	78.5	47.8	0.045	0.76

^zPCU90 = polymer-coated (PC) urea, 90-d release (DR); PCU120 = PC urea, 120 DR; PCNPK120 = PC N, phosphorus, and potassium (NPK), 120 DR; PCU180 = PC urea, 180 DR; PCNPK180 = PC NPK, 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 FL180; 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.

^yPercent nitrogen release = $a - (a - b) \times e^{c(-t)}$, where a = maximum amount of N released during the season, b = the intercept or value when time equals zero, c = the rate of N release and t = time.

^xThe R^2 value (SS1-SS2)/SS1, where SS1 = the sum of the squared differences between points on the fitted release curve and the overall mean and SS2 = the sum of the squared differences between the points on the fitted time release curve and the points on the predicted N release curve points.

Fig. 2. Fitted and predicted nitrogen (N) release curve of controlled-release fertilizers grouped based on release duration in the two-step correlation of the accelerated temperature-controlled incubation and field pouch incubation in white polyethylene mulch-covered raised tomato beds during Fall 2011 and 2013, respectively, in Immokalee, FL. PCU90 = polymer-coated (PC) urea, 90-d release (DR); PCU120 = PC urea, 120 DR; PCNPK120 = PC N, phosphorus, and potassium (NPK), 120 DR; PCU180 = PC urea, 180 DR; PCNPK180 = PC NPK, 180 DR from Agrium Advanced Technologies (Loveland, CO); PSCU = polymer sulfur-coated urea, 180 DR and RCNPK = resin-coated NPK, 120 DR from Everris NA (Dublin, OH); FL100 = PC urea, ammonium nitrate, 100 DR and FL140 = PC urea and ammonium nitrate, 140 DR from Chisso-Asahi Fertilizer (Tokyo, Japan); 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 from Florikan ESA (Sarasota, FL).

30% of the N by the time plants have been planted for 30 and 46 d (44 and 52 d after bedding) and will release greater than 80% of the N during the season (Carson et al., 2014a, 2014b; Carson and Ozores-Hampton, 2013).

In conclusion, the ATCIM and field pouch method may be correlated to predict field PNR from the individual CRFs in polyethylene-mulched tomato production for the majority of the CRFs in the market with an $R^2 \geq 0.90$. The differences in field pouch method start dates may have caused differences in predicted PNR among CRFs, which indicated the potential need for future calibration of the ATCIM and field pouch method to include soil temperature. Grouping CRFs by release duration to model CRF PNR performed adequately with 90- to 140-d release CRFs, which includes many CRFs recommended for tomato production. However, grouping CRFs of 180-d release would not be recommended because coating technologies differed in response to high bed temperatures during the fall tomato season in south Florida. With further calibration, grouping CRF release durations of relatively narrow ranges to simulate the release profile of an unknown CRF within a plastic mulch-covered bed may allow for use of an ATCIM without performing a pouch study.

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