Predicting Nitrogen Release from Parabolic-type Resin-coated Urea in Greenhouse Tomato and Cucumber Production

Qiang Xiao
Institute of Plant Nutrition and Resources, Beijing Academy of Agriculture and Forestry Sciences, Beijing 100097, China; Beijing Engineering Technology Research Center for Slow/Controlled-release Fertilizer, Beijing 100097, China

XiaoHui Fan
Tropical Research and Education Center, Soil and Water Science Department, University of Florida, Homestead, FL 33031

XiaoHui Ni, LiXia Li, GuoYuan Zou, and Bing Cao
Institute of Plant Nutrition and Resources, Beijing Academy of Agriculture and Forestry Sciences, Beijing 100097, China; Beijing Engineering Technology Research Center for Slow/Controlled-release Fertilizer, Beijing 100097, China

Additional index words. indoor incubation, pouch method, naturally varying soil temperatures, nutrient dissolved characteristics, vegetables planting

Abstract. Increasing commercial use of controlled release fertilizer (CRF) has prompted the need to predict N release simply and vially in the greenhouse environment. Two CRFs were tested, i.e., P40d and P100d by incubating them for 40 or 100 days either in static water at 10, 15, 20, 25, and 35 °C or in the soil of vially fluctuating greenhouse soil temperatures was established using the order kinetic equation and the method of least squares. N0 was 90.9% to 99.9% for P40d and 72.1% to 87.1% for P100d at 10–35 °C, respectively. A relationship function between the N release rate and naturally fluctuating greenhouse soil temperatures was established using the activation energy of the N release reaction. Then a model was constructed with field temperature as the variable to predict N release throughout the entire greenhouse crop production season. The value of ψ representing a property of the coating material of a CRF is ~1.0 for the release period of the CRF of 35–55 days and ~1.2 of 80–120 days. We validated the model using two seasons of greenhouse tomato, Solanum lycopersicum L., and cucumber, Cucumis sativus L., production data, and found that the error was less than 12% points. This indicated that the constructed model was sufficiently simple, practical, and accurate for use by growers, and fertilizer industry and regulatory personnel.

Received for publication 23 Jan. 2017. Accepted for publication 15 May 2017.

We would like to extend our sincere gratitude to Emeritus, Waldemar Klass, University of Florida, for his instructive advice and useful suggestions on our theses. We are deeply grateful of his help in the writing of this thesis. We are thankful to the national development plan focused on special projects “Developments of technology and products to preventing and controlling nitrogen and phosphorus leaching in main wheat and maize producing areas (No. 2017FY0800060),” the National Natural Science Foundation (No. 31301847, 31301846), the Beijing Research Program of the Engineering Technology Research Center for providing the slow/controlled-release fertilizers, and to the ecological environmental effects and evaluation of once fertilizer in wheat/maize rotation system (201303103) for financial support.

Corresponding authors. E-mail: xqiang1978@163.com or 609284507@qq.com.

N release curve of CRF was divided into the sigmoid pattern, parabolic pattern, and double parabolic pattern (Yu et al., 2006). A CRF whose CNR (from a CRF) curve has a parabolic shape is called a PCRF, but if the curve is sigmoidal or “S” shaped, the CRF is called a SCRF. These two CRFs have different release mechanisms and coating processes used during manufacturing. Formally, PCRFs were used almost exclusively in greenhouses and variable conditions of open fields (Carson and Ozores-Hampton, 2012). During field studies are subject to field temperatures in open fields (Carson et al., 2014b). Indeed, field studies are subject to field temperatures and reduced losses of N to the environment (Carson and Ozores-Hampton, 2012). Over the past 50 years, several CRF coating technologies have been developed and marketed, and several methods to predict CNR release from these CRF technologies have been developed for regulatory purposes including 1) laboratory or growth chamber, 2) greenhouse, and 3) field (Carson and Ozores-Hampton, 2012); however, one method of CRN prediction has yet been selected for regulatory purposes in other countries (Carson et al., 2014b; Fujinuma et al., 2009; Sartain et al., 2004a, 2004b). Laboratory methods include a standard method (Dai et al., 2008; Du et al., 2006; European Committee for Standardization, 2002), and the accelerated temperature-controlled incubation methods (ATCIMs) (Dai et al., 2008). The earlier mentioned standard method is involved in the incubation of PCRFs, which requires the use of selected time periods, temperatures, and/or sampling methods. Compared with the standard method, ATCIMs are used with shorter incubation periods, which reduce time and labor costs. However, these two methods may be used to predict release rates in the laboratory but—by themselves—they are not able to accurately predict release rates in the field (Carson and Ozhores-Hampton, 2012).

Pot-in-pot and pouch methods are two viable field methods for evaluating PCRFs in vegetable crop production research. The pot method—whereby water-porous pouches with PCRF prills are placed within or under vegetable beds and later recovered at predetermined times throughout the growing season—measures CNR by calculating the N remaining in the PCRF prills. In contrast, the pot-in-pot method—whereby the covered upper pot with a screened bottom and filled with soil from the field and mixed with PCRF prills is nested in the water-tight lower pot from which leachate is collected periodically after application.
The objective of this study was to develop and validate a model to accurately predict the N release characteristics of various PCRFs under the conditions of commercial vegetable crop production in nontemperature-regulated greenhouse plots. The approach to achieving this objective was to evaluate correlations between N release rates and soil temperatures as determined by use of a temperature-controlled incubation method and a field pouch method, to develop a predictive model based on a first-order N release equation that was valid under a relevant range of constant temperatures, and then to modify this equation to extend its usefulness to N release from PCRFs under fluctuating temperatures. We postulated that the latter step could be achieved by using the activation energy of the N release reaction to elucidate the relationship between the N release rate and the natural field temperature. The overall purpose of this effort was provide a useful predictive tool to assist growers and manufacturers to easily select PCRFs with the correct N release rates that match the needs of vegetable crops throughout the production process to assure efficient use of fertilizers, minimal off-site impacts, and lower economic costs.

### Materials and Methods

#### Indoor culture and field experiments

Soil and fertilizers selected for determination of N release properties. A field experiment was conducted in a greenhouse of the Beijing Academy of Agriculture and Forestry Sciences, China (39°56'57" N, 116°17'32" E). The soil in the field was a typical cinnamon soil, i.e., a semihydromorphic soil, rich in calcium carbonate, low sandy soil, and with neutral to slightly alkaline reaction. The region has a north temperate semihumid continental monsoon climate with a mean annual temperature of 14.5 °C and precipitation totaling 490 mm (Beijing Municipal Bureau of Statistics, 2015). The soil texture was loam, with a pH of 7.6, a bulk density of 1.2 g·cm⁻³, a field capacity of 370.3 g·kg⁻¹, a nitrate-N content of 22.3 mg·kg⁻¹, an ammonium-N content of 4.5 mg·kg⁻¹, and a soil organic matter content of 11.1 g·kg⁻¹. The experimental crops were the tomato, Solanum lycopersicum L. (Solanales: Solanaceae), variety ‘Hard Powder 8’, and the cucumber, Cucumis sativus L. (Cucurbitales: Cucurbitaceae), variety ‘Beijing Green 10’ (Table 1). The crops were irrigated according to typical grower practice. Details of management and cultural practices can be found in Yang et al. (2014). Two resin-coated PCRFs with different NRC periods [P40d (42.7% N); P100d (41.6% N); Beijing Futelai Compound Fertilizers Co., Ltd., Beijing, China] were used.

### Table 1. Collection dates and number of days since burial (in brackets) of porous pouches containing PCRFs buried 15 cm deep in the root-zone soil beneath the surface of black polyethylene mulch-covered beds of either a tomato or a cucumber crop during 2015 in Beijing. Samples of pouches were retrieved for analysis of N content on six or seven occasions throughout the crop growing season.

| Fertilizer | Crop                        | Planting date | Pouch burial date | Pouch retrieval date |
|------------|-----------------------------|---------------|-------------------|----------------------|
| P40d       | Spring tomato               | 22 Mar.       | 17 Apr. (24 d)    | 5 May (42 d)         |
| P100d      | Autumn                      | 24 Mar.       | 28 Apr. (35 d)    | 12 May (49 d)        |
|            | tomato and cucumber         |               | 5 May (42 d)      | 27 May (64 d)        |
| P40d       | Autumn                      | 31 Mar. (7 d) | 4 May (24 d)      | 12 May (49 d)        |
| P100d      | tomato and cucumber         | 8 Aug.        | 11 Aug. (3 d)     | 17 Nov. (101 d)      |
|            |                             | 10 Aug.       | 15 Aug. (7 d)     | 3 Dec. (117 d)       |
|            |                             | 8 Aug.        | 4 Sept. (27 d)    | 17 Nov. (101 d)      |
|            |                             | 10 Aug.       | 22 Aug. (14 d)    | 3 Dec. (117 d)       |

- P40d and P100d are PCRFs. The numbers 40 and 100 indicate the number of days required for 80% of N in the formulation to be released.
- Date when tomato and cucumber seedlings were transplanted into the soil in the greenhouse.
- Number of occasions when pouches were retrieved.
- Number of days that elapsed between when the pouches were buried and when they were retrieved.

of water to the upper pot—measures the instantaneous amount of N release leached directly from the PCRF. In any case, it is important to consider that environmental conditions in greenhouse plots and open fields are very variable, and that release rates of PCRFs depend strongly on soil temperatures. PCRF prills must meet the needs of the crop as it is influenced by fluctuating soil temperatures throughout all growing seasons and over multiple years (Fraisse et al., 2010).

Therefore, it is necessary to integrate the use of laboratory, growth chamber, and field methods into a single protocol for characterizing the performance of PCRFs under a wide range of conditions encountered in commercial vegetable production. A correlation between an ATCIM and the pouch method was developed using a two-step process in tomato, Solanum lycopersicum L. (Solanales: Solanaceae), production in Florida (Carson et al., 2013). Japanese researchers established a model to predict CNR using field temperatures in an experiment in a rice field (Zhang et al., 2008).

Characterizing the performance of PCRFs involves a range of factors under field conditions, such as release time, temperature, moisture, placement, microbial action, and cultural practices. However, soil temperature may be considered the most influential factor influencing N release from PCRFs in greenhouse plots with irrigated vegetables (Carson et al., 2013; Fujita, 1989; Fujita et al., 1983).

The objective of this study was to develop and validate a model to accurately predict the N release characteristics of various PCRFs under the conditions of commercial vegetable crop production in nontemperature-regulated greenhouse plots. The approach to achieving this objective was to evaluate correlations between N release rates and soil temperatures as determined by use of a temperature-controlled incubation method and a field pouch method, to develop a predictive model based on a first-order N release equation that was valid under a relevant range of constant temperatures, and then to modify this equation to extend its usefulness to N release from PCRFs under fluctuating temperatures.
The pouches were installed in each replication just on 24 Mar. and 10 Aug. 2015. Sixty pouches each of P40d and P100d were buried for an overall total of 120. Sets of pouches were retrieved on six or seven separate occasions (Table 1) throughout the season to track the amount of nitrogen remaining in the CRF with the passage of time. The pouches were taken to the laboratory, where the fertilizer–soil mixture in each pouch was ground in a blender (Model 36BL23; Waring Commercial, New Hartford, CT) with 300 mL DI water to destroy the PCRF coating and dissolve the residual fertilizer in the pulverized remnants of the PCRF prills. The sample solution were diluted to 500 mL using DI water, filtered with Whatman No. 42 filter paper, and frozen until required for N analysis. Total N in the solution was analyzed by pyrolysis and chemiluminescence using an Antek 9000 N analyzer (PAC Co., Houston, TX) (Carson et al., 2014a). The cumulative percentage of N—that had been released by the time the sample was collected—was expressed as \( N_t \). Weather data were obtained through the Beijing Automated Weather Network (BAWN). A Watchdog data logger (Model B100; Spectrum Technologies Inc., Plainfield, IL) collected soil temperatures every 2 h throughout the growing seasons in the greenhouse at 15 cm below the soil surface of the tomato and cucumber plots.

Building the predictive model

Construction of prediction model and calculation of N (CNR), \( N_m \) (maximum release percentage), in the fertilizer. A prediction model of the N release from each PCRF was fitted to a first-order model (Agehara and Warncke, 2005) using the nonlinear curve-fitting PROC NLIN procedure (SAS Institute, 2011) that resulted in Eq. [1].

\[
N_t = N_0 \times \exp(-k \times t) \quad [1]
\]

where \( N_t \) was the cumulative percentage of the CNR from a PCRF applied at time \( t \) (d\(^{-1}\)), \( N_0 \) was the total amount—expressed as 100% of N in the PCRF, and \( k \) (d\(^{-1}\)) was the first-order rate constant (Deans et al., 1986). The values of \( N_0 \) and \( k \) were deemed significantly different (\( \alpha = 0.05 \)) if the 95% confidence intervals did not overlap. All equations were fitted using all data points, and each point was the mean of three replications (Fan and Li, 2010).

The release curve shown in Fig. 1 (line a) suggested that the N remaining in a PCRF decreased with the passage of time, because the slope was negative, whereas the CNR curve of N released from a PCRF should be the opposite with a positive slope as seen in Fig. 1 (line b). Therefore, Eq. [1] must be adjusted as shown in Eq. [2].

\[
(100\% - N_t) = N_0 \times \exp(-k \times t) \quad [2]
\]

Because \( N_0 \) was considered to be 100%, Eq. [2] might also be converted to Eq. [3].

\[
N_t(\%) = N_0 \times [1 - \exp(-k \times t)] \quad [3]
\]

Eq. [2] may be used to tentatively describe and fit the CNR model of a PCRF under a constant temperature; however, several issues still need to be resolved.

Firstly, \( N_0 \) (%) was intended to indicate the maximum N release percentage from the PCRF, which generally has been considered to have a constant value of 100%, but it was not the case because the resin coat prevents the release of all N both in the laboratory and in the field. Accordingly, we needed to determine the maximum percentage of the N in the PCRF that can be released.

However, it was necessary to first establish a new equation to determine the value of \( N_0 \). This was done as follows. The natural logarithms of both sides of Eq. [2] were taken, which resulted in Eq. [4].

\[
\ln(100 - N_t) = \ln N_0 - k \times t \quad [4]
\]

Next, Eq. [4] was transformed into a linear regression equation, \( y = a + b \times t \), in which \( y = \ln (100 - N_t), a = \ln (N_0), \) and \( b = -k \). The linear regression equation was solved by using the least square method (Zou, 2010), then Eqs. [5]–[7] were built and values of \( k, N_0, \) and \( N_t \) could be obtained according to Eqs. [5]–[7]. In Eq. [6], \( N_t \) was replaced with \( N_{\text{m}} \). Eqs. [5]–[7] were suitable for use in predicting CNR under indoor constant temperature conditions but not under the naturally fluctuating temperatures encountered either in the field or in greenhouses lacking precise temperature controls.
k = \frac{1}{n} \left\{ \sum_{i=1}^{n} t_i \times \ln(100 - N_i) - \sum_{i=1}^{n} t_i \times \frac{\ln(100 - N_i)}{n} \right\}
\quad \cdot \frac{1}{\left[ \sum_{i=1}^{n} t_i^2 - \left( \sum_{i=1}^{n} t_i \right)^2 / n \right]} \quad \text{[5]}

N_m = \ln \left\{ \frac{\ln(100 - N)}{k \sum_{i=1}^{n} t_i} \right\}
\quad - \left( -k \times \frac{\ln(100 - N)}{k \times t} \right) \quad \text{[6]}

N_t = N_m \times \left[ 1 - \exp(-k \times t) \right] \quad \text{[7]}

Establishment of a prediction model suitable for use in a vegetable production greenhouse with fluctuating temperatures. There were several algorithms for the introduction of field soil temperatures into a predictive model, but the days of temperature switch (DTS) algorithm (Zhang et al., 2008) was finally selected through a process of screening and comparison and was done using Eq. [8]. And then, the release time, \( t_r \) — number of days at constant indoor 25 °C obtained from Eq. [8] — was entered into Eq. [7], in which the values of the other parameters were obtained from a 25 °C static water incubation experiment. In this way, we obtained the instantaneous amount of CNR in greenhouse plots in which the soil temperature fluctuated.

\[ t_r = \exp \left[ \frac{E_a(T_s/T_f)}{RT_s} \right] \quad \text{[8]} \]

where \( t_r \) (d) was the days of cumulative CNR. The activation energy of the reaction, \( E_a \) (J mol\(^{-1}\)) was the gas constant, and \( T_s \) was the absolute temperature (K) under any natural condition, \( T_f \) was the standard absolute temperature (298 K). The calculation of \( E_a \) was very important and was based on the Arrhenius formula (Eq. [9], Song, 1988). \( E_a \) and the pre-exponential factor \( A \) can be calculated by the linear least square method.

\[ E_a = (\ln A - \ln k) \times R \times T \quad \text{[9]} \]

where \( k \) (d\(^{-1}\)) was the release rate constant at a certain temperature, \( A \) was the frequency factor, \( E_a \) (J mol\(^{-1}\)) was the gas constant, and \( T (K) \) was the absolute temperature. Parameter \( k \) can be measured at several known temperatures, \( E_a \) and \( A \) can be calculated by either of the two-point method, the linear plot method or the linear least squares method. Compared with the other two methods, the linear least squares method
can provide the most accurate estimation of the activation energy although the calculation was more complex. However, we found that the prediction error was still large if the DTS was applied directly to Eq. [7] (Fig. 2).

On this base, experiments of spring tomato and cucumber crops grown in greenhouse plots were involved to build the parameter, $\psi$, to modify Eq. [7] and Eq. [10] was the result at last.

$$N_t = N_{in} \times \left[1 - \exp\left(-k \times \sum_{i=1}^{s} t_i\right)\right] \times \psi$$ \[10\]

The factor, $\psi$, represented a property of the coating material of a PCRF—whose value ranges between 1.0 and 1.2, and $\psi$ was an independent variable in the modified prediction model. According to our many fitting results and the release laws of CRF in general, the value of the $\psi$ factor was $\approx 1.0$ when the designated CNR period to release $N_{in}$ was 35–55 d. However, the value of $\psi$ was $\approx 1.2$ when the designated CNR period to release $N_{in}$ was 80–120 d.

Having explained how we derived the prediction model and the methods of calculating its parameters, we would give examples to illustrate the construction process of the prediction model, and verify and revise the prediction model.

Results

Calculation of the CNR from PCRF and its related parameters. CNR curves at five temperatures (Fig. 3) were obtained by using an indoor hydroponic set up. The CNR curves at the five temperatures had the characteristics of a parabolic release curve. $N_{in}$ (maximum N release amount) and $k$ (N release rate) were calculated by Eqs. [5]–[7] (Table 2). Results showed that the relative coefficient, $r$, values were greater than 0.993 and there were strongly significant correlations between CNR rates and temperatures. The higher the temperature, the steeper the curve. The $N_{in}$ values of the P40d and P100d PCRFs were 90.9% to 99.9% and 72.1% to 87.1% at temperatures in the range 10–35 °C, respectively. These results showed that the values obtained from the regression equations fairly closely matched the determined values.

The linear least squares method and Eq. [9] were applied to calculate the $E_a$ values of P40d and P100d, which were 57,421 J·mol$^{-1}$ and 65,903 J·mol$^{-1}$, respectively. Each of these $E_a$ values was a constant in the range of 10–35 °C.

Characteristics of CNR, modification of parameters, and model verification in greenhouse soil. To illustrate the predictive accuracy of the model, additional greenhouse plot experiments were carried out to determine the CNR characteristics of the two PCRFs, i.e., P40d and P100d, using the pouch-field method in autumn tomato and cucumber plots in the greenhouse.

The average soil temperatures at the same depth as the buried pouches with the two PCRFs decreased gradually with the passage of time from 8 Aug. to 3 Dec., and the average soil temperature was lower than 25 °C from 30 to 120 d (Fig. 4). The rate of CNR trended progressively lower much like the soil temperature. However, the release time required for the same amount of CNR was different between the indoor and greenhouse experiments. Furthermore, the characteristic of their CNR curves were substantially different (Figs. 5 and 6), and these differences were mainly caused by the variable greenhouse soil temperatures. The days required for the P40d and P100d formulations to release 80% of their releasable N contents in the greenhouse soil with autumn tomato were 55 and 150 d, respectively. Similar results were obtained in the experiment with the plot of autumn cucumber.

This study showed that the variable field temperatures led to substantial differences in the CNR between incubation in an indoor constant temperature water bath and the greenhouse soil with fluctuating temperatures used for vegetable production. The longer the NRC period—of the PCRF under the conditions of a constant temperature—the greater the difference between the CNR determined under fluctuating incubation temperatures.
The experiments showed that P40d and P100d released 70% to 87% and 30% to 44% of the releasable N by 30–46 d, respectively, after the tomatoes had been transplanted. Similar results were obtained in the experiment involving autumn cucumber. This showed that the law of CNR from a given PCRF is valid at each soil temperature regardless of the crop cultivar or species and the uptake of nitrogen. The CNR in greenhouse plots that were predicted by the model may assist growers in selecting a specific CRF with a suitable release rate and duration to meet the needs of tomato and cucumber crops (Carson et al., 2014c).

On the basis of the above results and analysis, we can better estimate the parameter values of the model to predict the CNR. Daily records of soil temperature (Fig. 4) in the greenhouse were input into Eq. [8], followed by N release days \( t_n \) and the cumulative release days \( \sum t_n \) at a 25 °C constant indoor temperature. The \( \sum t_n \) and other values of parameters of \( k, N_m \) at a 25 °C constant indoor temperature (Table 2) and the appropriate value of \( \psi \) selected—\( \psi \) values corresponding to P40d and P100d were 1.0 and 1.2, respectively, according to Fig. 3, which were entered into Eq. [10] during an autumn tomato and cucumber crops in the greenhouse. By comparing the predicted value 1 and determined value (Figs. 5 and 6), the errors between them were found to be less than 12% points. However, when the model of Zhang et al. (2008) was applied to predict, the errors between predicted value 2 and determined value were found to be more than 12% points (Figs. 5 and 6). Problems in this model were found that might influence the accuracy of prediction: 1) the method of constructing this model was flawed, 2) the method might not be suitable for the prediction of CNR for all PCRFs in China because of differences in characteristics of the various kinds of CRFs, such as coating materials, and 3) it was not clear whether this model could predict the CNR in greenhouse vegetable production in China because of differences in the properties of various soils used for vegetable production and differences in cultivation practices among crop species and among various growers. Therefore, our application of the model of Zhang et al. (2008) had been modified. The critical problem in the calculation process involving DTS (Zhang et al., 2008) was that the value of the product, \( k \times t_n \), required by the same amount of CNR for different temperatures was thought to be constant so that \( t_1 \times k_1 = t_2 \times k_2 = \cdots = t_n \times k_n \). However, this might be not true, and was found that the \( k \times t_n \) product could have a wide range of values. Thus, the assumption that \( t_1 \times k_1 = t_2 \times k_2 = \cdots = t_n \times k_n \) might produce quite erroneous predictions (Fig. 2). To solve this, the factor, \( \psi \), had been built to solve the problem. This indicates that our model can accurately predict the CNR of a PCRF under the fluctuating greenhouse soil temperature conditions. This demonstrates that more accurate CNR curves of PCRFs can be provided to producers and growers, and the predictive value of these curves can provide them with valuable guidance.

In addition, our prediction method was currently only available for thermoplastic material-coated fertilizers and might be not for nonthermoplastic membrane materials which were not sensitive to temperature. Indeed, the CNR rates of PCRFs with nonthermoplastic membrane materials may not be related to temperature. In contrast, thermoplastic film materials were affected strongly and swiftly by temperature changes so that the CNR rate may be affected greatly. Although some researchers have used ATCIMs to predict the amount of CNR in laboratory studies, more research would be needed. It was found that some of the coating membranes were broken or agglomerated when the temperature rose sufficiently high, which caused abnormal CNR and affected the predicted NRC periods of the affected PCRFs. In fact, many studies showed that ATCIMs were unsatisfactory for predicting CRFs with very long NRC periods (Dai et al., 2008; Medina et al., 2009; Sartain et al., 2004a, 2004b). Based on all of the above considerations, parameters such as \( K \) and \( N_t \) in the 10–35 °C range were examined in this study. The variability of these parameters in the 10–35 °C range was less than that at higher temperatures, and this was also the case with the reactive kinetic parameters. Moreover, the CNR rate remained relatively stable. Furthermore, the annual range of soil temperatures in the greenhouse plots was 13–35 °C without the occurrences of higher temperatures (Fig. 4), which was consistent with the temperatures used in our experiments. Therefore, the values of released N predicted by the model were closer to the values determined in the field than those reported from indoor experiments (Carson and Ozores-Hampton, 2012; Carson et al., 2014b; Medina et al., 2009; Sartain et al., 2004a, 2004b).

Our main purpose in building the predictive model was to improve the accuracy of
predictions by means of a fairly simple and practical approach. In this study, the limiting value of error in the accuracy of prediction of N release was less than 12% points; although this value was greater than has been achieved in the laboratory with some purely rational models, it was smaller than had been achieved for greenhouse fields. Additional improvements in our model should be possible. Thus, the factors of different soil types also may need to be considered. Our model was suitable for application in cinnamon soil currently. Although we did not study the prediction in other soil types, we thought the model might be suitable for use in loam or clay as long as sufficient moisture. For sandy soil, the applicability of our model need to be further researched, because of its simple structure and relative difficulties of water moving.

Conclusions

N release data from PCRFs—obtained through a combination of incubation experiments conducted at a constant temperature indoors and in the soil with naturally fluctuating temperatures in a nontemperature regulated greenhouse—were critically important in developing a model to predict rates and durations of CNR of various PCRFs. The N release properties of each PCRF could be obtained based on a first-order kinetic equation transformation and the least square method the data obtained in the above indoor incubation experiments at five different temperatures. This allowed the formulation of an equation to calculate the percentages of N in PCRFs that have the potential to be mineralized at a constant temperature. This equation was modified to allow estimates of the release of N from PCRFs under fluctuating temperatures by using the activation energy of the N release reaction to elucidate the relationship between the N release rates of each PCRF and the naturally occurring field temperatures. However, the resulting equation allowed the reliable prediction of CNR only for periods of 35–55 d. To make the equation fit the observed CNR data for PCRF with NRC periods 80–120 d, a factor, $\psi$—which represents a property of the coating material of the PCRF, and whose value was 1.2 for PCRFs with long NRC periods—was introduced into the prediction equation. This resulted in a simple, viable model that allows prediction of CNR rates of PCRFs with an error of less than 12% points. Future research should focus on reducing this inherent error in predictions.

**Literature Cited**

Abraham, J. and V.N. Rajasekharan Pillai. 1996. Membrane-encapsulated controlled-release urea fertilizers based on acrylamide copolymers. J. Appl. Polym. Sci. 60:2347–2351.

Agehara, S. and D.D. Warncke. 2005. Soil moisture and temperature effects on nitrogen release from organic nitrogen sources. Soil Sci. Soc. Amer. J. 69:1844–1852.

Beijing Municipal Bureau of Statistics. 2015. Beijing statistical yearbook. China statistics press, Beijing, China. 20–50 (In Chinese).

Broschat, T.K. 1996. Release rates of soluble and controlled-release potassium fertilizers. HortTechnology 6:128–131.

Broschat, T.K. and K.K. Moore. 2007. Release rates of ammonium-nitrogen, nitrate-nitrogen, phosphorus, potassium, magnesium, iron, and manganese from seven controlled-release fertilizers. Commun. Soil Sci. Plant Anal. 38:843–850.

Carson, L.C. and M. Ozores-Hampton. 2012. Methods for determining nitrogen release from controlled-release fertilizers used for vegetable production. HortTechnology 22:20–24.

Carson, L.C., M. Ozores-Hampton, and K.T. Morgan. 2013. Nitrogen released from controlled-release fertilizer in seepage-irrigated tomato production in south Florida. Proc. Annu. Meet. Fla. State Hort. Soc. 126:131–135.

Carson, L.C., M. Ozores-Hampton, K.T. Morgan, and J.B. Sartain. 2014b. Prediction of controlled-release fertilizer nitrogen release using the punch field and accelerated temperature-controlled incubation methods in sand soils. HortScience 49:1575–1581.

Carson, L.C., M. Ozores-Hampton, and J.B. Sartain. 2012b. Controlled-release fertilizer drying methods effect on nitrogen recovery analysis. HortScience 47:S320.

Dai, J.J., X.L. Fan, J.G. Yu, F. Liu, and Q. Zhang. 2008. Study on a rapid method to predict longevity of controlled release fertilizer coated by water soluble resin. Agr. Sci. China 7:1127–1132. (In Chinese).

Deans, J., J. Molina and C. Clapp. 1986. Models for predicting potentially mineralizable nitrogen and decomposition rate constants. Soil Sci. Soc. Amer. J. 50:323–326.

Du, C.W., J.M. Zou, and A. Shaviv. 2006. Release characteristics of nutrients from polymer-coated compound controlled release fertilizers. Environ. J. Polymers Environ. 14:223–230.

European Committee for Standardization. 2002. Slow-release fertilizers: Determination of the nutrients-method for coated fertilizers. EN 13266:2001. European Committee for Standardization, Brussels, Belgium.

Fan, X.H. and Y.C. Li. 2010. Nitrogen release from slow-release fertilizers as affected by soil type and temperature. Soil Sci. Soc. Amer. J. 74:1635–1641.

Fraisie, C.W., Z. Hu, and E.H. Simonne. 2010. Effect of El Nino-southern oscillation on the number of leaching rain events in Florida and implications on nutrient management for tomato. HortTechnology 20:120–132.

Fujinuma, R., N.J. Balster, and J.M. Norman. 2009. An improved model of nitrogen release for surface applied controlled-release fertilizer. Soil Sci. Soc. Amer. J. 73(6):2043–2050.

Fujita, T. 1989. Invention and development of polyolefin-coated urea. Ph.D.dissertation. Tohoku Univ., Sendai, Japan.

Fujita, T., C. Takahashi, S. Yoshida, and H. Himizu. 1983. Coated granular fertilizer capable of controlling the effects of temperature on dissolution out rate. U.S. Patent 4369055. 18 Jan. 1983.

Medina, L.C., J.B. Sartain, and T.A. Obreza. 2009. Estimation of release properties of slow-release fertilizer materials. HortTechnology 19:13–15.

Medina, C. 2011. Method development to characterize nutrient release patterns of enhanced efficiency fertilizers. Univ. Florida, Gainesville, FL, PhD Diss.

Sato, S. and K.T. Morgan. 2008. Nitrogen recovery and transformation from a surface or sub-surface application of controlled-release fertilizer on a sandy soil. J. Plant Nutr. 31:2214–2221.

Song, Y.D. 1988. Arrhenius formula and activation energy. J. Shaxi Agr. Univ. 8(2):230–235.

Yang, J.G., X.H. Ni, B. Cao, Q. Xiao, G.Y. Zou, and B.C. Liu. 2014. Effect of special controlled-release fertilizer on nitrogen and potassium uptakes of tomato and their residue in soil with drip-irrigation in the greenhouse. J. Plant Nutr. Fert. 20(5):1294–1302. (In Chinese).

Yu, J.G., X.L. Fan, N. Li, and F. Liu. 2006. Application of the Richards equation to describe nitrogen release characteristics from controlled release fertilizer (CRF). Zhongguo Nong Ye Ke Xue 39(9):1853–1858. (In Chinese).

Zhang, Y.L., Y.L. Zhang, X.L. Dang, W.S. Yin, and L.P. Zhu. 2008. Prediction on the dissolution rate of nitrogen from coated urea by days of temperature switch. Chin. J. Soil Sci. 39(5):582–585. (In Chinese).

Zou, L.Q. 2010. Principle of least square method and temperature. Soil Sci. Soc. Amer. J. 74:1635–1641.