Development of a Nitrogen-release Algorithm for Slow-release Fertilizers

K. W. King, J. C. Balogh

Abstract. *Current water quality models do not consider the time release rate of sulfur-coated ureas (SCUs). However, the use of these slow-release formulations is prevalent in urban agricultural management. Using documented slow-release fertilizer data, a first-order decay equation was fit with reasonable accuracy for both surface (Efficiency R^2 = 0.63) and incorporated (Efficiency R^2 = 0.70) applications. In both cases the decay coefficient was best represented using a two-parameter model. Temperature and seven-day dissolution amount were determined as best descriptive parameters for the surface model while soil moisture and temperature were used for the incorporated model. Temperature was the more sensitive parameter for the surface applied model while soil moisture was the more sensitive input for the incorporated model. Each model was validated with a limited amount of data. The surface applied model was validated with a prediction efficiency of 0.82 while the subsurface model was validated with a prediction efficiency of 0.63. Even though the models are based on a limited amount of data, incorporation of these results in water quality models will permit the initial simulation of SCUs and allow better simulations of real world situations.*

Keywords. *Sulfur-coated ureas, SCU, Temperature, Moisture, Modeling.*

Methods for modeling fertilizer, currently available in hydrologic water quality models, generally involve a single application approach. In order to model time-released fertilizers, an estimated release schedule is devised (usually on a weekly basis) and input as discrete applications (King and Balogh, 1999). This type of approach could potentially lead to erroneous simulations of water quality due to the fact that the available nitrogen may or may not be represented accurately.

Many land managers have incorporated slow release fertilizers into their practices to retard the potential offsite transport from large runoff events. Slow release fertilizers are available as natural organics, synthetic organics, and coated materials. The common form used in the turfgrass industry is coated materials. The two most common materials used for coating are sulfur and resin. The coated nitrogen source is usually urea, however other soluble N sources are available. The decay of the sulfur coating in sulfur-coated fertilizers is a function of time, temperature (Oertli, 1973; Hashimoto and Mullins, 1979), soil moisture (Dawson and Akratanakul, 1973; Prasad, 1976), and to a lesser degree soil pH (Giordano and Mortvedt, 1970) and microbial activity (Hummel, 1982).

Jarrell and Boersma (1979, 1980) developed a microscopic-scale computer model from single pellet analyses to predict the release rate of sulfur-coated urea (SCU) as a function of time. They also considered temperature and soil water potential. The model was dependent upon specific microorganisms responsible for breakdown and the rate at which those organisms grow. Their single pellet analysis indicated a constant rate release followed by a declining rate.

Jarrell and Boersma (1979, 1980) tested their model with three different SCUs, using a range of temperatures (5 to 35°C) and two soil water potentials (–0.3 and –15.0 bars). The SCUs used in the model validation were SCU-4, SCU-20, and SCU-30. The reported findings (SCU-4) suggest that the model reasonably predicted release rates relative to temperature, soil water content, and coating characteristics. Limitations of this model are the required physical properties for the SCU coating (pore area and length) and estimating microbial growth rates.

Hummel and Waddington (1986) conducted a field study using nine different SCUs with coarse and fine coatings to evaluate dissolution amounts in turfgrass. The SCUs were applied at a rate of 122 kg ha^{-1} to 324 cm^2 'Pennfine' perennial ryegrass (*Lolium perenne* L.) plots. Undissolved residual pellet weights were monitored at two-week intervals for 12 weeks. Temperatures (soil and air), precipitation, and irrigation were recorded daily but no soil moisture measurements were taken. Results indicated a strong correlation between laboratory seven-day dissolution amounts (an industry standard that is calculated as the percentage of nitrogen released in water maintained at 38°C after seven days) and field rates when SCUs were analyzed separately. Combining the coarse and fine SCUs resulted in a less favorable correlation. Hummel and Waddington (1986) concluded that using seven-day dissolution amounts to predict field rates was acceptable as long as differences in coating texture were considered.

Utilizing SCUs has both advantages and disadvantages. The major disadvantage associated with SCUs is the release time may not be commensurate with crop need.

Article was submitted for publication in November 1999; reviewed and approved for publication by the Soil & Water Division of ASAE in March 2000.

The authors are **Kevin W. King**, ***ASAE Member Engineer***, Agricultural Engineer, USDA-ARS, Temple, Texas; and **J. C. Balogh**, Soil Scientist, Spectrum Research Inc., Duluth, Minnesota. **Corresponding author:** Kevin W. King, USDA-ARS, 808 E. Blackland Rd., Temple, TX 76502, phone: 254.770.6616, fax: 254.770.6561, e-mail: <king@brc.tamus.edu>.

sw 3497 ms 7/9/01 9:32 AM Page 662

However, the appealing advantage is the fact that not all the fertilizer is available for washoff or offsite transport and by incorporating or lightly watering in after application the loss potential is further reduced.

The objective of this study was to develop a parsimonious model based on readily available data that could be incorporated into hydrologic water quality models to simulate release rates of slow-release fertilizers. The development data should be documented and the model inputs should be simulated or able to be simulated with relative ease.

METHODS AND MATERIALS

The approach in development of a slow-release fertilizer routine followed the classic first-order decay equation. The first-order decay equation can be expressed as:

$$M_t = M_o e^{-kt} \quad (1)$$

where M_t is the mass remaining at time, t, M_o is the initial mass, and k is a decay coefficient. The decay coefficient, k, would theoretically be related to temperature, moisture, texture, urea coating weight, dissolution amount, etc. and can be expressed as a function of one or more of these variables.

Based on the findings of Oertli (1973), Hashimoto and Mullins (1979), Dawson and Akratanakul (1973), Prasad (1976), Giordano and Mortvedt (1970), and Hummel (1982) and the parameters (temperature and moisture) available in most hydrologic water quality models, an empirical multiplicative relationship between dissolution amount, temperature, and soil moisture was proposed. The proposed decay coefficient, k, can be expressed as:

$$k = C_0 \left(\frac{T}{38}\right)^{C_1} \theta^{C_2} D_7^{C_3} \quad (2)$$

where T is temperature (°C), θ is soil moisture (%), and D_7 is the seven-day dissolution amount (%). The constant 38 scales the temperature to that used in determining the seven-day dissolution amount. C_0, C_1, C_2, and C_3 can be determined by making a log transformation and solving by linear regression (Draper and Smith, 1981).

Sensitivity analysis for each parameter in the decay coefficient was completed based on the methods of Haan et al. (1995). As described by Haan et al. (1995), this coefficient can be expressed as:

$$S_r = \frac{\partial O}{\partial I} \frac{I}{O} \quad (3)$$

where S_r is relative sensitivity (dimensionless), O is specific output, and I is specific input. A sensitivity analysis provides information on the model response to a unit change of one variable. Relative sensitivities are dimensionless, therefore the values can be ranked to determine the most sensitive input variables and further reduce the number of variables necessary to adequately model the release.

Table 1. Summary of data used and associated parameters for slow-release fertilizer model development

Slow-release Fertilizer	Seven-day Dissolution Amount (%)	Time Steps (days)	Temp. (°C)	Soil Moisture (%)	Applied Location	Soil	Source
SCU-13 SCU-19	20.5* 2.2*	14, 35, 56, 84, 112	10, 20, 30	22	Surface/ incorporated	Mountview silt loam (fine-silty *siliceous thermic typic paleudult*)	Allen, Hunt, and Terman (1971)
SCU-19	3.5†	14, 28, 56, 84, 112	35	35	Incorporated	Mountview silt loam (fine-silty *siliceous thermic typic paleudult*)	Giordano and Mortvedt (1970)
SCU-36	11.0	28, 49, 70, 91, 112, 133	20	12	Incorporated	NA	Halevy (1987)
SCU-21 SCU-22 SCU-20	20.7 22.2 20.1	7, 21, 63, 126	8, 25, 35	20	Incorporated	Hartsells fine sandy loam (fine-loamy *siliceous thermic typic hapludult*)	Hashimoto and Mullins (1979)
SCU-10 SCU-11 SCU-15 SCU-16 SCU-25 SCU-30 SCU-32 SCU-42	10, 11, 15, 16, 25, 30, 42	14, 28, 42, 56, 70, 84	26, 29	30	Surface	NA	Hummel and Waddington (1986)
SCU-4	4.0	2, 10, 25, 45, 70, 100, 126	5, 15, 25, 35	8, 30‡	Surface	Woodburn silt loam (fine-silty mixed *mesic aquultic argixeroll*)	Jarrell and Boersma (1979)

* Seven-day dissolution amounts were approximated from data for one-day and five-day dissolution amounts using graphical extrapolation.
† Seven-day dissolution amount was estimated from five-day dissolution amount using graphical extrapolation.
‡ Eight and 30% volumetric water contents were estimated based on –0.3 and –15 bar matric potentials.

A limited set of data was compiled from documented sources for use in this study (table 1). The data vary with respect to temperature, soil moisture, seven-day dissolution and time steps (the parameters used for model development). Thus, the data can be combined. After all data sets were combined, 10% of the cases were randomly selected and removed, for validation purposes, prior to model development (Geisser, 1975).

RESULTS AND DISCUSSION

MODEL DEVELOPMENT AND SENSITIVITY

Using the proposed three-parameter (T, θ, D_7) model, coefficients C_0, C_1, C_2, and C_3 were calculated (table 2) for both surface applied and incorporated SCUs. A development (model) efficiency (American Society of Civil Engineers, 1993) of 0.63 was obtained for the surface

Table 2. Derived values of empirical coefficients for surface-applied and incorporated SCU decay coefficient (eq. 2)

Decay Dependency	C_0	C_1	C_2	C_3	Standard Error	Adjusted R^2	Efficiency R^2
Surface-applied SCU (n = 104)							
k = f (T, θ, D_7)	0.24	0.95	0.23	0.83	0.918	0.496	0.63
k = f (T, D_7)	0.18	0.93	NA	0.86	0.915	0.499	0.63
k = f (T)	0.04	1.33	NA	NA	1.187	0.157	0.27
Incorporated SCU (n = 101)							
k = f (T, θ, D_7)	0.34	1.03	1.54	–0.03	0.876	0.365	0.70
k = f (T, θ)	0.39	1.03	1.58	NA	0.872	0.371	0.70
k = f (θ)	0.36	NA	1.98	NA	1.056	0.079	0.43

sw 3497 ms 7/9/01 9:32 AM Page 663

applied model while an efficiency of 0.70 was obtained for the incorporated model. A relative sensitivity analysis was then completed for each model (table 3). The sensitivity analysis revealed that the decay coefficient, k, was most sensitive to temperature and seven-day dissolution in the surface-applied model and to soil moisture and temperature in the incorporated model.

In the same manner, coefficients for a two-parameter model were calculated based on the two most sensitive parameters in each decay relationship (table 2). In the case of surface-applied SCUs, no model efficiency ($R^2 = 0.63$) was lost by using only temperature and seven-day dissolution amount, and the standard error decreased while the adjusted R^2 increased (indications that the two-parameter model is better than the three-parameter model). Of temperature and soil moisture, temperature was more sensitive (table 3). Similarly, development efficiency for incorporated SCUs ($R^2 = 0.70$) was not reduced using a soil moisture and temperature based model. Both standard error and adjusted R^2 migrated in the desired direction. Soil moisture was the more sensitive of these two parameters (table 3).

A final coefficient calculation for a one-parameter model was completed for each application model based on the more sensitive variable from the two-parameter model (table 2). In both cases, development efficiency decreased considerably, while adjusted R^2 decreased and standard error increased. Thus, a two-parameter model was needed to adequately simulate the release rate for both surface- and subsurface-applied SCUs.

The parsimonious model in each application case (surface-applied and incorporated) was composed of different variables with the exception of temperature. In the incorporated case, the soil moisture was more important than the seven-day dissolution amount. This was attributed to the fact that the fertilizer pellets were completely surrounded by the soil, which has a defined water content. In the surface-applied case, the pellet is not receiving the full effect of soil moisture and the release is better described from some property of the fertilizer pellet (in this case seven-day dissolution amount). In both cases it should be reemphasized that the derived equations were developed on a limited amount of controlled data. It should also be noted that in the case of temperature—and to a lesser degree soil moisture—these variables change constantly throughout the day. The derived equations do not account for that daily fluctuation but use a daily average.

Table 3. Relative sensitivity for each parameter in the decay coefficient

	Temperature, T (°C)	Soil Moisture, θ (% fraction)	Seven-day Dissolution Amount (% fraction)
Base Value	25.0	0.12	0.15
	Surface-applied Model		
k = f (T, θ, D_7)	–0.276	–0.066	–0.241
k = f (T, D_7)	–0.320	NA	–0.296
k = f (T)	–0.378	NA	NA
	Incorporated Model		
k = f (T, θ, D_7)	–0.130	–0.195	0.004
k = f (T, θ)	–0.129	–0.199	NA
k = f (θ)	NA	–0.155	NA

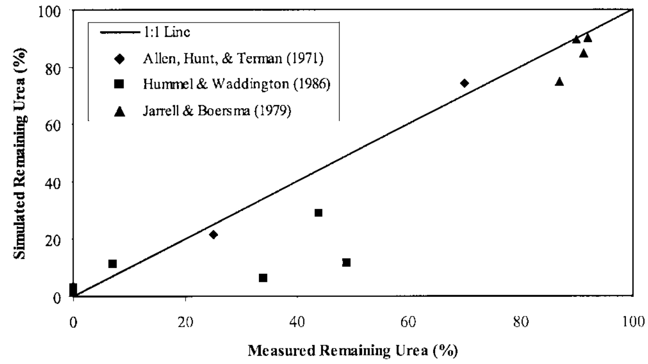

Figure 1–Measured versus simulated validation of surface applied SCU using a decay coefficient dependent on T and D_7 ($R^2 = 0.82$).

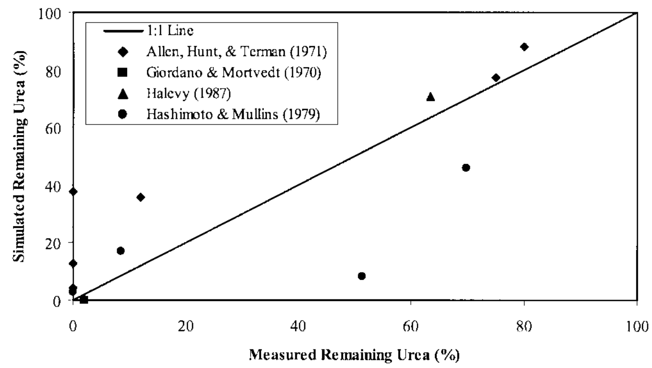

Figure 2–Measured versus simulated validation of incorporated SCU using decay coefficient dependent on T and θ ($R^2 = 0.63$).

VALIDATION

A validation was completed using the developed two-parameter model for each application condition and the reserved data. In the case of surface-applied SCUs, a prediction efficiency of 0.82 was obtained when the temperature and seven-day dissolution-amount-based model was applied to the reserved validation data set (fig. 1). Similarly, a prediction efficiency of 0.63 was obtained from the soil moisture and temperature-based model for incorporated SCUs (fig. 2). Even though the validation data are limited, it is evident that the decay relationship for the surface-applied and incorporated models is reasonable. However, additional data would enhance the validation efforts as well as the model development.

SUMMARY AND CONCLUSIONS

The use of slow release fertilizers is commonplace in many land management systems. However, the ability to model the release of these slow-release formulations is limited to non-existent. A first-order decay relationship was developed with the decay coefficient based on temperature and seven-day dissolution amount for surface-applied SCUs and soil moisture and temperature for incorporated SCUs. A successful validation of each model was accomplished with a limited set of data. The incorporation of these algorithms into hydrologic water quality models will permit the simulation of release rates of slow-release fertilizers and allow for a better representation of real world situations. Use of slow-release fertilizers is considered a best management practice from an agronomic and water quality perspective. The ability to demonstrate the efficacy of this practice will be significantly enhanced by incorporating the developed release algorithm into water quality and crop growth models. As more slow release data are developed for SCU and other nitrogen formulations, this algorithm can be improved and expanded.

REFERENCES

Allen, S. E., C. M. Hunt, and G. L. Terman. 1971. Nitrogen release from sulfur-coated ureas as affected by coating weight, placement and temperature. *Agron. J*. 63(4): 529-533.

American Society of Civil Engineers. 1993. Criteria for evaluation of watershed models. ASCE Task Committee of the Watershed Management Committee. *J. Irrig. & Drng. Eng.* 119(3): 429-443.

Dawson, M. D., and W. Akratanakul. 1973. SCU—The effect of soil temperature and moisture. *Sulfur Inst. J.* 9: 14.

Draper, N. R., and H. Smith. 1981. *Applied Regression Analysis*, 2nd Ed. New York, N.Y.: John Wiley & Sons.

Geisser, S. 1975. The predictive sample reuse method with applications. *J. Am. Statist. Assoc*. 70: 320-328.

Giordano, P. M., and J. J. Mortvedt. 1970. Release of nitrogen from sulfur-coated urea in flooded soil. *Agron. J*. 62: 612-614.

Haan, C. T., B. Allred, D. E. Storm, G. J. Sabbagh, and S. Prabhu. 1995. Statistical procedure for evaluating hydrologic/water quality models. *Transactions of the ASAE* 38(3): 725-733.

Halevy, J. 1987. Efficiency of isobutylidene diurea, sulphur-coated urea and urea plus nitrapyrin, compared with divided dressings of urea, for dry matter production and nitrogen uptake of ryegrass. *Expl. Agric*. 23: 167-179.

Hashimoto, I., and R. C. Mullins. 1979. Dissolution of sulfur-coated urea in soil: I. Wax sealed sulfur-coated urea. *Soil Sci. Soc. Am. J*. 43: 1165-1168.

Hummel Jr., N. W., and D. V. Waddington. 1986. Field dissolution of sulfur-coated urea in turfgrass. *HortScience* 21(5): 1155-1156.

Hummel Jr., N. W. 1982. Evaluation of sulfur-coated urea for fertilization of turfgrasses. Ph.D. thesis. University Park, Pa.: Pennsylvania State University (Diss. Abstr. 82-18908).

Jarrell, W. M., and L. Boersma. 1979. Model for the release of urea by granules of sulfur-coated urea applied to soil. *Soil Sci. Soc. Am. J*. 43: 1044-1050.

Jarrell, W. M., and L. Boersma. 1980. Release of urea by granules of sulfur-coated urea. *Soil Sci. Soc. Am. J*. 44: 418-422.

King, K. W., and J. C. Balogh. 1999. Modeling evaluation of alternative management practices and reclaimed water for turfgrass systems. *J. Environ. Qual.* 28(1): 187-193.

Oertli, J. J. 1973. Effect of temperature, microbial activity, salinity, and pH on the release of nitrogen of sulfur-coated urea. *Z. Pflanzenernaehr. Boedenkd*. 134: 227-236.

Prasad, M. 1976. Release of nitrogen from sulfur-coated urea as affected by soil moisture, coating, weight, and method of placement. *Soil Sci. Soc. Am. J*. 40: 134-136.