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Optimal Spacing of Surface-Banded Nitrogen on Fescue

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ABSTRACT

A recommended N application method for approximately 0.2 million ha of tall fescue (*Festuca arundinacea* Schreb.) grown in Kansas is topdress banding in early spring. Optimal spacing of N fertilizer bands increases N use efficiency, thereby reducing expenditures for fertilizer and the potential for environmental contamination. The objective of this study was to develop and test a model to determine optimal spacing of surface-banded N from tall fescue dry matter measured on plots fertilized with single bands. A major assumption in the development of the model was: the yield at any point between two fertilizer bands is the sum of yield responses from adjacent bands. In 1985 tall fescue yields measured at various distances from single bands of N fertilizer (applied at rates of 30, 60, 90, and 180 kg ha^{-1}) were used to develop the model. The yields on another set of plots fertilized in a complete factorial arrangement at rates of 60 or 180 kg N ha^{-1}, with band spacings of 25 and 50 cm, were used to test the model in 1984 and 1985. Measured and model-predicted yields indicated that optimal band spacing was near 25 cm. The model predicted a decrease in optimal band spacing with increasing N rates. The fitted regression of measured yield on predicted yield had a slope and an intercept not significantly different from one and zero, respectively, indicating a good fit between measured and modeled yields. This research provides a practical tool to predict fertilizer band spacings that maximize fescue yields at N rates between 30 and 180 kg N ha^{-1}.

Application of N to cool-season grasses to increase forage production in the central-midwest USA is a common practice. In a study of N placement for cool-season grasses (Lamond and Moyer, 1983), subsurface bands (knifed) produced greater forage yields and tissue N concentrations than broadcast N. Surface-banded N (46-cm spacing) also produced higher forage yields and N concentrations than broadcast N (Lamond et al, 1984; Moyer et al., 1985). While both surface and subsurface banded N have produced higher forage yields, band application often produces a wavy undulating pattern in fields and meadows when used. In these fields, forage yields are highest in the immediate vicinity of the band and decrease with distance from the band. Farmers often ask what band spacing and N rate should be applied to minimize the wavy pattern and maximize forage yield.

Haby et al. (1987) found a significant interaction between N rate and band spacing that affected forage production of 'Coastal' bermudagrass [*Cynodon dactylon* (L.) Pers. var. *dactylon*] in 2 of 3 yr at first cutting. At later harvests, however, no significant yield response to band spacing was measured. The lack of a yield response at later harvests was attributed to prolific growth of stolons into the band region, allowing for translocation of band-applied N to forage growing between bands. With cool-season grasses, as with bermudagrass, early season growth is often uneven in surface-banded fields. The magnitude of the uneven growth pattern depends on band spacing as well as N rate. Since the growth habit of fescue does not include stolons, however, plants growing farther from fertilizer bands are more likely to be N deficient at final harvest than one would expect with bermudagrass.

The growth rate of forage over and between bands is affected by the amount of N applied along the length of the band (g N m^{-1}), which depends on the N rate, and the band spacing. This relationship may be shown mathematically as follows:

$$\text{g N m}^{-1} = \text{kg N ha}^{-1} \times 1000 \text{ g kg}^{-1} \times \text{ha } 10\,000 \text{ m}^{-2} \times m_{\text{space}} \quad [1]$$

where m_{space} is the spacing between bands (m). Generally, growth is more uneven at wide fertilizer band spacings than at narrow band spacings. Changes in band spacing and N rate should interact to influence yield response of cool-season grasses to banded N, thus resulting in an optimum band spacing that depends on the N rate.

The objectives of this study were to: (i) determine if a model of forage dry matter yield, as a function of distance from a single fertilizer band and the rate of N applied, could be used to predict forage yields at various distances between fertilizer bands; (ii) test the model for its ability to describe forage yields at various distances between fertilizer bands; and (iii) use the model to determine optimal band spacings for fescue yield. Such a procedure could eliminate or reduce the number of field trials to determine optimum band spacing. A major assumption in development of the model was that the yield at any region between two bands is the sum of the N effect that each band has on that region. For our purposes, we have defined the N effect of a band as the effect that N fertilizer in the band has on dry matter yield at various distances perpendicular to the band's center.

MATERIALS AND METHODS

The study was conducted at the Horticultural Research Center of Kansas State University in Manhattan, KS, on a Smolan silty clay loam (fine, montmorillonitic, mesic Pachic Argius-

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Abbreviations: PVC, polyvinyl chloride; RMSE, root mean square error.

toll). On 19 Apr. 1984, NH_4NO_3 solutions and, on 17 Mar. 1985, urea–NH_4NO_3 solutions were surface banded on established tall fescue. Applications were made using a spray boom, constructed of schedule 80 PVC pipe with nozzle bodies spaced 25 cm apart. The spray boom was attached to the three-point hitch of a Massey Ferguson 135 tractor (Massey Ferguson, Des Moines, IA). At each nozzle body, orifice plates were inserted enabling application of fertilizer solution under slight pressure. Fertilizer solutions were metered through a John Blue positive displacement pump (John Blue, Huntsville, AL), driven by the ground-speed power take-off of the tractor.

In 1984 two sets of 2.1 by 6.1 plots were arranged in a randomized complete block design with three replicates. One set of plots, used to develop the model, was fertilized with 0.048 L solution m^{-1} of band, in a single surface band centered along the length of the plot. Different N rates were achieved using four NH_4NO_3 solutions differing in N concentration. Solutions were applied at rates of 1.5, 3.0, 4.5, or 9.0 g N m^{-1} of band, which correspond to N rates of 30, 60, 90, and 180 kg N ha^{-1}, respectively, spaced 50 cm apart. Bands were marked with wire-stem flags while the fertilizer was being applied. Wooden garden stakes were used to mark five 12.5 by 100 cm harvest strips parallel to each band. The first harvest strip was centered over the band and the others were centered every 12.5 cm outward from the center of the band. This arrangement produced five harvest strips, one over the band, and four parallel to the band centered at 12.5, 25, 37.5, and 50 cm from the band.

A second set of plots was established in both 1984 and 1985 to test the model. In 1984 these plots were fertilized with NH_4NO_3 solution in multiple bands. In 1985 urea–NH_4NO_3 solution was used. Fertilizer was applied at all combinations of 60 or 180 kg N ha^{-1} with 25- or 50-cm band spacings. The N solutions were applied at a flow rate of 0.048 L m^{-1} of band for the 50-cm band spacing. For the 25-cm band spacing, a flow rate of 0.024 L m^{-1} of each band was used. As with the single-banded plots, wooden garden stakes were used to mark 12.5 by 100 cm harvest strips. For the 25-cm-band plots, two harvest strips, one centered directly on top of the band and the second centered at 12.5 cm from the center of the band, were used to measure yield. For the 50-cm band spacing, three harvest strips centered at 0, 12.5, and 25 cm away from the band were used to measure forage yield. Three unfertilized check plots were included in the study and harvested in 12.5-cm strips as described.

In mid-June of 1984 and 1985, forage was collected from each harvest strip by clipping plants with hedge trimmers at a height of 4 cm. All forage was collected in paper bags, dried at 60 °C, and weighed.

Model Development

Since our first objective was to develop a model to predict yield as a function of distance from the band and N rate, the yield increase not attributed to N application (the unfertilized forage yield 50 cm away from the single band) was subtracted from the overall forage yield of each harvest strip before model fitting. We felt justified in this subtraction since no N response was measured at this distance from the band. Also, the average check plot yield of 3008 kg ha^{-1} was not significantly different from the average yield 50 cm away (3076 kg ha^{-1}) at the 0.05 level of probability. Check plot yields, which were essentially zero after performing this subtraction, were also included in the regression analysis. The corrected dry matter yields from single bands were then regressed on N rate and distance from the band.

Multiple linear regression was used to fit the following equation:

$$\hat{y} = B_0 + B_1N^{1.5} + B_2ds^{0.75} + B_3Nds + B_4Nds^{0.75} + B_5N^{1.5}ds^{0.5} \quad [2]$$

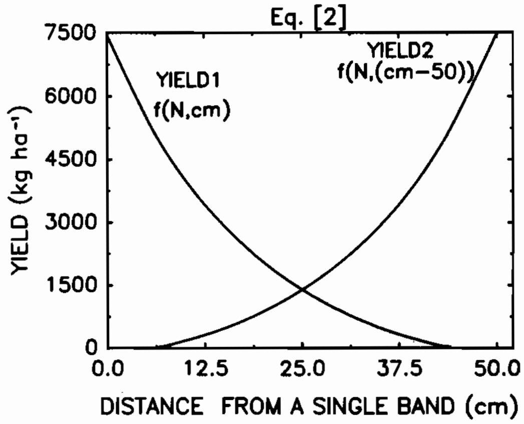

Fig. 1. Forage yields predicted by the functions of YIELD1 and YIELD2 from simulated fertilizer bands 50 cm apart at a N rate of 180 kg ha^{-1}.

where $\hat{y}$ is the predicted yield of dry matter (in kg ha^{-1}) for a harvest strip measuring 12.5 by 100 cm (from which the check plot yield has been subtracted), B_0 through B_5 are fitted parameter estimates, N is N rate (in kg ha^{-1}), and ds is distance from the center of the harvest strip to the center of the fertilizer band.

An optimum subset selection procedure (RSQUARE, SAS Institute, 1985) was used to fit all possible combinations of N and ds raised to the 0.5, 0.75, 1.5, and 2.0 powers in order to find a good general relationship between forage yield as affected by N rate and distance from the band. This subset selection exercise included all possible combinations of the interaction of transformed variables as well. The model reported was the best-fit model as measured by R^2 and RMSE for five independent variables. In most cases, other transformations didn't fit nearly as well as the model reported or were of such complexity as to not warrant practicality. Several other nonlinear regression models were also tried. The nonlinear models were not able to describe the data better than the model presented so they are not reported. For simplicity, models containing more than five fitted parameters were not reported. Models having less than five fitted parameters were not capable of bending enough to reflect the change in measured yields with distance from the band.

Equation [2] was then used in a Pascal computer program to predict yields in plots banded at 25- and 50-cm spacings. In the program, Eq. [2] was assigned to the variable name YIELD1. YIELD1 can be written mathematically as:

$$\text{YIELD1} = f(\text{N, ds}) \quad [3]$$

The fitted equation assigned to the variable name YIELD1 is transformed into a second function, which takes into account the yield increase contributed by a second band of fertilizer in a multiband system. This function, YIELD2, has the same dependency on N rate as YIELD1, but its dependency on distance from the band is modified to reflect an adjacent band of fertilizer; that is, the distance (in centimeters) becomes the distance minus 50 cm, mathematically written as:

$$\text{YIELD2} = f[\text{N}, (\text{ds} - 50)] \quad [4]$$

This approach is illustrated in Fig. 1, where YIELD1 and YIELD2 are drawn as smooth curves for the 180 kg N ha^{-1} rate at a 50-cm band spacing. It is the output values of the two functions, YIELD1 and YIELD2, that are added together to determine forage yield at various regions between bands of fertilizer. In the plots treated with several bands, the highest yield measured from the harvest strip centered directly over the band at the 180 kg N ha^{-1} rate was 6260 kg ha^{-1}. Therefore a yield maximum of 6260 kg ha^{-1} was set for YIELD1 and

Table 1. Mean dry matter yields as affected by N rate and band spacing compared with model-predicted yields.

Band spacing	N rate	1984 measured	1984 predicted	1985 measured	1985 predicted
		kg ha^{-1}			
—	0	3008 (342)†	—	1945 (65)	—
25	60	6749 (354)	6516	4771 (314)	5453
25	180	7616 (431)	8086	6773 (232)	7023
50	60	5999 (239)	5546	3564 (523)	4483
50	180	6889 (15)	7264	5979 (453)	6201
		P > F‡			
Source of variation					
Spacing		0.063		0.037	
N rate		0.035		0.001	
N rate × spacing		0.751		0.770	

† Values in parentheses are the standard errors of the mean of three replicates.
‡ Analysis of variance of plots fertilized at 60 and 180 kg N ha^{-1} at band spacings of 25 and 50 cm.

YIELD2. On occasion Eq. [2] predicted values that were less than the check plot yields. This produced negative values for YIELD1 and YIELD2. In these special cases, YIELD1 and YIELD2 were set equal to zero.

The program was then used to predict yields of harvest strips at distances of 0, 12.5, and 25 cm away from the band for the 25- and 50-cm band spacings at N rates of 60 and 180 kg ha^{-1} for data collected in 1984 and 1985. The predicted values were compared with actual yield data collected from plots fertilized at the same N rates and band spacings in 1984 and 1985. Since the model only predicts forage yield above that found in unfertilized check plots, measured vs. model-predicted yield comparisons were made by subtracting check plots yields from measured yields or by adding check plot yields to model-predicted yields.

The program was then used to generate fescue yields at various band spacings between 12.5 and 50 cm and at various N rates between 30 and 180 kg ha^{-1}. A second regression equation was fitted to the generated data:

$$\hat{y} = B_0 + B_1\text{Sp} + B_2\text{Sp}^2 + B_3\text{Sp}^{1.5} + B_4\text{N}^{0.5} + B_5\text{NSp} + B_6\text{NSp}^{1.5} + B_7\text{N}^{0.75}\text{Sp}^{1.5} \quad [5]$$

where $\hat{y}$ is dry matter (in kg ha^{-1}) above check plot yields, B_0 through B_7 are parameter estimates, N is the N rate (in kg ha^{-1}), and Sp is the band spacing (in cm).

This equation can be used to predict fescue yield as a function of N rate and band spacing (as opposed to distance from the band) and can be manipulated to determine optimum band spacing, i.e., the band spacing at which yield is maximized for a given N rate.

The optimum band spacing was determined by first taking the partial derivative of Eq. [5] with respect to Sp:

$$\partial\hat{y}/\partial\text{Sp} = B_1 + 2B_2\text{Sp} + 1.5B_3\text{Sp}^{0.5} + B_5\text{N} + 1.5B_6\text{NSp}^{0.5} + 1.5B_7\text{N}^{0.75}\text{Sp}^{0.5} \quad [6]$$

After rearranging and setting the first derivative (Eq. [6]) equal to zero, we have:

$$0 = (2B_2)\text{Sp} + (1.5B_3 + 1.5B_6\text{N} + 1.5B_7\text{N}^{0.75})\text{Sp}^{0.5} + (B_1 + B_5\text{N}) \quad [7]$$

Equation [7] is a modified form of the quadratic equation where:

$$a = 2B_2$$
$$b = 1.5(B_3 + B_6\text{N} + B_7\text{N}^{0.75})$$
$$c = B_1 + B_5\text{N}$$

The band spacing at which yield is maximized at various N rates can now be found by solving for Sp, using the following modified quadratic equation:

$$\text{Sp} = \{[-b \pm (b^2 - 4ac)^{1/2}]/2a\}^2 \quad [8]$$

Using the above relationships, optimum band spacing and yield at those spacings were determined for several N rates between 30 and 180 kg ha^{-1}.

RESULTS AND DISCUSSION

Total dry matter yield increased with increasing N rate but decreased with an increase in band spacing both years of the study (Table 1). The late winter and spring growing period for cool-season grasses in Kansas is typically from mid-March when the grass breaks winter dormancy to mid-May when it is in full bloom. Yields in 1985 were less than in 1984 due to warmer spring temperatures during the major portion of the growing season. Early spring temperatures were an average of 3 to 6 °C warmer in 1985 than in 1984 (Table 2). Data in Table 1 indicate that optimal band spacing is narrower than 50 cm.

Dry matter yields in single-band plots were highest in the harvest strip centered directly over the band and decreased with distance from the band for all N rates (Fig. 2). The highest yields measured were from the harvest strip centered directly over the band at the highest N rate (180 kg ha^{-1}). Equation [2], which was fitted to the single-band data, explained 89% of the variability in yield as a function of N rate and distance from the band (Table 3, Fig. 2).

Actual yields for plots fertilized with multiple bands at N rates of 60 and 180 kg ha^{-1} and at band spacings of 25 and 50 cm were compared with predicted yields using Eq. [2] in the program (Table 1, Fig. 3). The comparison included individual 12.5-cm strip plot yields and whole plot yields for both 1984 and 1985 data after

Table 2. Average monthly temperature and total monthly precipitation in Manhattan, KS.

Month	1984 Temp.	1984 Precip.	1985 Temp.	1985 Precip.	Long-term average Temp.	Long-term average Precip.
	°C	mm	°C	mm	°C	mm
March	3	43	9	44	6	40
April	11	104	15	147	13	69
May	17	29	20	83	18	110
June	23	29	22	113	24	121

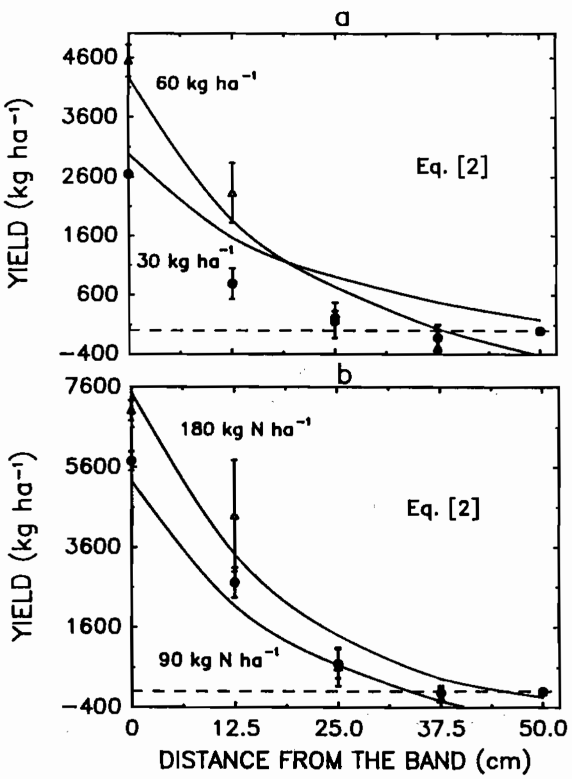

Fig. 2. A comparison between mean measured yields (symbols) and yields predicted by regression Eq. [2] (lines) for N rates of 30, 60, 90, and 180 kg ha^{-1} (assuming 50-cm band spacing). The error bars are the standard errors of the mean.

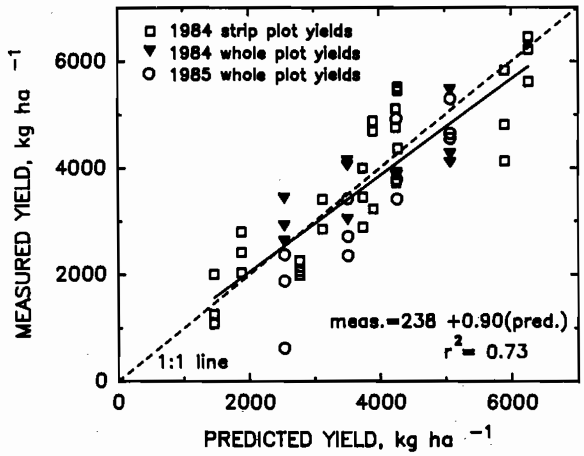

Fig. 3. One-to-one comparison between measured yields in validation plots and model-predicted yields for both years of data. Measured yield is the dry matter yield minus the average check plot yields in 1984 and 1985. Solid line is the fitted regression line. Dashed line is the one-to-one line.

subtracting check plot yield. The model predicted forage yields in plots banded 25 and 50 cm apart that are very close to actual measured yields (Table 1, Fig. 3). The fitted regression between measured and predicted yield (Fig. 3) has a slope and intercept not significantly different from one and zero, respectively (t test at the 0.05 level of probability), indicating a good fit.

In spite of the good prediction, one can observe from these data that competition between plants near and farther away from a band is different in single-band plots than in plots fertilized with several bands. For example, at the highest N delivery rates of 4.5 and 9.0 g N m^{-1} of band, forage yields on strips centered on the band from plots fertilized with a single band were 12 to 13% higher than those observed in plots fertilized with several bands (Table 4). The faster growth of forage near the band appeared to depress the growth of forage farther away. A yield depression below the check plot yield (50 cm away) at 37.5 cm from the band was observed at all N rates (Fig. 2).

Since water use is positively correlated with aboveground dry matter (Hanks et al., 1982; Power, 1985), one might expect that competition between fescue plants nearest the band and plants farther away would be for water. Forage growing directly on top of the band, having greater leaf dry matter and a fuller canopy, would have a greater soil water requirement than less vigorous plants growing on adjacent areas. This may partially explain the observed differences in yields at distances away from the band.

Table 3. Parameter estimates of fitted regression equations.

Parameter	Variable name	Parameter estiamte	Standard error
	Eq. [2]		
B_0	intercept	−84.010	292.151
B_1	$N^{0.5}$	563.017	36.646
B_2	$ds^{0.75}$	−6.878	23.581
B_3	Nds	3.770	0.513
B_4	$Nds^{0.75}$	−16.589	1.884
B_5	$N^{1.5}ds^{0.5}$	0.862	0.119
RMSE = 727, R^2 = 0.8904, n = 75			
	Eq. [5]		
B_0	intercept	−3663.408	332.911
B_1	Sp	683.749	65.927
B_2	Sp^2	8.842	1.131
B_3	$Sp^{1.5}$	−143.146	16.433
B_4	$N^{0.5}$	566.602	19.781
B_5	NSp	−1.256	0.115
B_6	$NSp^{1.5}$	0.414	0.025
B_7	$N^{0.75}Sp^{1.5}$	−1.183	0.061
RMSE = 40.9, R^2 = 0.9986, n = 24			

Table 4. A comparison between mean yields for various harvest strips along the length of the band for plots fertilized with a single band and those fertilized with several bands in 1984.

Band spacing	Distance away from band	N rate	Measured yield: several bands	Measured yield: single band
cm	cm	g N m^{-1}	kg ha^{-1}	kg ha^{-1}
25	0.0	1.5(60)†	4265	3219
	12.5		3212	1360
25	0.0	4.5(180)	4925	5768
	12.5		4295	2739
50	0.0	3.0(60)	5115	4864
	12.5		2412	2645
	25.0		1445	488
50	0.0	9.0(180)	6095	6939
	12.5		3445	4301
	25.0		2105	528

† Data in parentheses are the N rates applied (in units of kg N ha^{-1}) at the given band spacing and delivery rate of N per meter of band.
‡ Measured yields are the yield (on 12.5-cm harvest strip 1 m long) minus mean check yield of 3008 kg ha^{-1}.

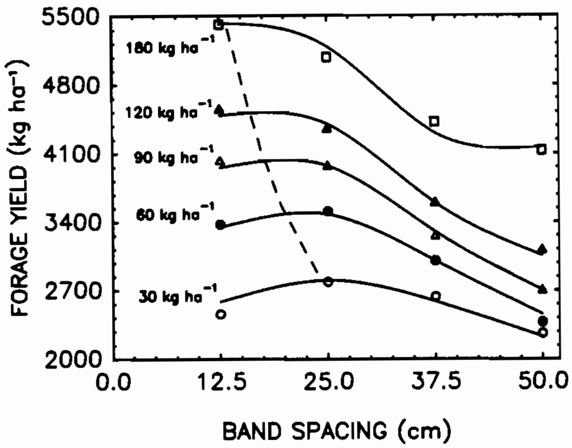

Fig. 4. A comparison between computer program simulated yields using Eq. [2] as input (symbols) and yields predicted by regression Eq. [6] (lines) at various N rates and band spacings. The dashed line indicates band spacings at which yield is maximized for a given N rate.

Equation [5] provided a fairly good description of yields predicted by the program (Table 3, Fig. 4). Because of the close agreement, the band spacing at which yield was maximized for a given N rate (optimum band spacing) was calculated. The optimum band spacings, indicated by the dashed line in Fig. 4, were always less than 50 cm and decreased with increasing N rates. This was consistent with significantly greater yields from plots fertilized at band spacings of 25 cm than from plots fertilized at spacings of 50 cm (Table 1). The optimum band spacings determined in Fig. 4 are also consistent with cool-season grass response to N application. Typically, this response is a curve with a large increase in yield per unit N at low N rates. At higher N rates, a point of diminishing returns is reached, and the yield increase per unit of N is smaller. At a wide band spacing, a higher delivery rate of N m^{-1} would be required for a given N rate than at a narrow band spacing. In the case of a wide band spacing, the forage growing close to the band may already be at the top of the response curve, whereas forage growing farther away may be deficient. A narrower band spacing at a high N rate would spread the total amount of N more evenly among a larger amount of forage, resulting in the greatest increases in yield per unit N.

CONCLUSIONS

Overall, this model accurately predicted actual forage yield in plots fertilized with N solutions in surface bands at 25 and 50 cm during a 2-yr period. The optimization of Eq. [5] indicates that, for tall fescue in eastern Kansas, surface-banded N should be spaced no wider than 25 cm. The optimization also indicates that, for higher N rates, a narrower band spacing than 25 cm will produce greater yields. The model could be improved with a better regression equation developed from additional studies using data generated from several plots banded at different N rates and at various band spacings. Results indicate that data from plots fertilized with a single band would more accurately represent growth in plots with multiple bands if data were generated in a year with minimal water stress or if all plots had been irrigated. The model provides a practical tool for determining optimal band spacings for maximizing fescue yields using surface-banded N. This is important since there are approximately 14 million ha of tall fescue grown in the USA (National Research Council, 1989), and much research has shown surface-banded N to be superior to other methods of N application for cool-season grasses (Moyer et al., 1985; Lamond and Moyer, 1983). This model is applicable to eastern Kansas on Smolan soils. The optimization approach is probably applicable to a wider range of soils, climates, and agronomic problems.

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