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John A. Guretzky
University of Nebraska-Lincoln, jguretzky2@unl.edu

Maru K. Kering
Samuel Roberts Noble Foundation, mkkering@noble.org

Jagadeesh Mosali
Samuel Roberts Noble Foundation, Ardmore, OK, jmosali@noble.org

Eddie Funderburg
Samuel Roberts Noble Foundation, Ardmore, OK, erfunderburg@noble.org

Jon T. Biermacher
The Samuel Roberts Noble Foundation, Ardmore, OK, jtbiermacher@noble.org

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J. Guretzky, M. Kering, J. Mosali, E. Funderburg, and J. Biermacher

The Samuel Roberts Noble Foundation, Inc., Ardmore, Oklahoma, United States

Corresponding author — J. Guretzky, Department of Agronomy and Horticulture, 279 Plant Sciences Hall, University of Nebraska–Lincoln, Lincoln, NE 68583-0915, USA; email jguretzky2@unl.edu

Abstract
Our objectives were to document effects of nitrogen (N), phosphorus (P), and potassium (K) fertilizer rates on forage yields and uptake of N, P, and K by Midland bermudagrass [*Cynodon dactylon* (L.) Pers.] on a Minco fine, sandy loam in southern Oklahoma. After six years of this long-term experiment, forage yield responses to fertilization were mixed and depended on year. Stability analysis indicated forage yields responded positively to N fertilization during favorable weather conditions but negatively during poor weather conditions. Application of 112 kg N ha^{-1} provided the best yield stability and mean annual forage yield among treatments, 11.5 Mg ha^{-1}, across years. In years with near-average weather conditions, uptake of N, P, and K increased linearly with N application rate. Limited water holding capacity of the soil and high soil P and K may have contributed to the limited yield responses to fertilization in this semi-arid environment.

Keywords: nitrogen, phosphorus, potassium, grasses, nutrient uptake, soil fertility

Introduction

Considerable efforts have been expended to develop productive cultivars and determine optimum fertilization strategies of bermudagrass [*Cynodon dactylon* (L.) Pers.] in the southern United States. Soil fertility experiments were first initiated in the 1940s and proliferated throughout the 1950s as use of bermudagrass spread (Wilkinson and Langdale, 1974; Taliaferro et al., 2004). Research has examined effects of rates, sources, and time of application of inorganic N fertilizer (Morris and Celecia, 1962; Woodhouse Jr., 1969; Overman et al., 1993), poultry litter (Evers 2002; Brink et al., 2004; Read et al., 2006), swine effluent (Brink et al., 2005), dairy manure compost (Helton et al., 2008) or a combination of these nutrient sources on yield and nutrient uptake of Coastal bermudagrass. Nitrogen fertilizer rate, source, and time of application effects on yield and N uptake responses of Midland bermudagrass, a more cold hardy variety adapted to areas where Coastal winter kills, have also been examined (Harlan et al., 1954; Taliaferro et al, 1975; Mathias et al., 1978; Osborne et al., 1999).

The experiments have generally shown forage yields respond positively to large rates of N when weather conditions are favorable (Wilkinson and Langdale, 1974; Taliaferro et al., 2004). Coastal bermudagrass produced forage yields of 30 Mg ha^{-1} with applications of 1200 kg N ha^{-1} y^{-1}, forage yields of 18 Mg ha^{-1} were produced with 800 kg N ha^{-1} y^{-1} by common bermudagrass, and Midland bermudagrass produced yields approaching 16 Mg ha^{-1} with 400 kg N ha^{-1} y^{-1} (Wilkinson and Langdale, 1974). Nitrogen rates of 350 kg ha^{-1} optimized dry matter (DM) yields of Coastal, Alecia, and Coastcross-1 bermudagrasses in central Texas (Overman et al., 1993). Midland bermudagrass responded with yields of 19 Mg ha^{-1} with 448 kg N ha^{-1} in West Virginia (Mathias et al., 1978). Midland bermudagrass produced 11 Mg DM ha^{-1} with 269 kg N ha^{-1} in northern Oklahoma (Taliaferro et al., 1975). In southern Oklahoma, Midland produced 13.3 Mg ha^{-1} with 627 kg N ha^{-1} on a silt loam soil and 13.7 Mg ha^{-1} with 112 kg N ha^{-1} on a fine, sandy loam soil (Osborne et al., 1999). Differences of yield and yield-maximizing fertilization rates have largely reflected adaptation of cultivars to locations with different growing season lengths and rainfall regimens (Taliaferro et al., 2004).

Positive yield responses to P and K fertilization rate have also been found. Annual application of 24 kg P ha^{-1} and 46 kg K ha^{-1} maximized forage yields of Coastal bermudagrass across a 14-yr period in North Carolina (Woodhouse Jr., 1968, 1969). Application of 185 kg K ha^{-1} in four equal splits at initiation of spring growth and after each harvest increased forage yield by 66% in a stand of intensively managed, irrigated Coastal bermudagrass in Georgia (Adams et al., 1967). Application of 300 kg K ha^{-1} y^{-1} increased yields of Coastal by 3.1 Mg ha^{-1} across a seven year period in Louisiana (Robinson et al., 1990). Potassium rate had little effect on yield of Midland bermudagrass across a three-year period at two sites in West Virginia (Mathias et al., 1978). Addition of 90 kg P ha^{-1} increased forage yields of N-fertilized Midland bermudagrass from 8 to 11 Mg ha^{-1} in Oklahoma (Taliaferro et al., 1975).

Increasing N rate often increases nutrient uptake and removal. Research has found N contents to increase from 1.3 to 2.6% with 2000 kg N ha^{-1} applied to Coastal and 1.6 to 3.0% with 450 kg N ha^{-1} applied to Midland bermudagrass (Wilkinson and Langdale, 1974; Taliaferro et al., 1975; Mathias et al., 1978). Nitrogen removal at near-maximum yield levels of Coastal bermudagrass was estimated to be over 700 kg ha^{-1} (Wilkinson and Langdale, 1974). Coastal bermudagrass fertilized with a combination of broiler litter and inorganic N equivalent to 269 to 315 kg N ha^{-1} had nutrient removal rates ranging from 259 to 409 kg N ha^{-1}, 31.9 to 41.6 kg P ha^{-1}, and 210 to 250 kg K ha^{-1} (Read et al., 2006). Application of 185 kg K ha^{-1} in four equal splits at initiation of spring growth and after each harvest increased K content by 300% in a stand of intensively managed, irrigated Coastal bermudagrass in Georgia (Adams et al., 1967). Addition of 0 to 600 kg K ha^{-1} to Coastal removed 385 to 449 kg N ha^{-1}, 43 to 48 kg P ha^{-1}, and 137 to 323 kg K ha^{-1} in Louisiana (Robinson et al., 1990).

Removal of P and K in harvested bermudagrass can mine soil of exchangeable P and K and limit forage yields over time if nutrients are not replaced. Yields of intensively managed, irrigated Coastal bermudagrass in Georgia increased over a 4-year period in relation to K application due to a rapid decline in available soil K where no K was applied (Adams et al., 1967). On a sandy soil in North Carolina, exchangeable K in the 0 to 15 cm soil depth decreased across a 14-year period when no K was applied; rates of 86 kg K ha^{-1} y^{-1} were required to balance annual uptake and removal of K (Woodhouse Jr., 1968). Rates of K removal also exceeded rates of supply, causing depletion of available K in Coastal stands in Louisiana (Robinson et al., 1990). Harvesting of Coastal stands removed N-P-K in a 6.4-1.0-6.5 ratio when N was applied at 84 kg ha^{-1} and a 14.4-1.0-7.9 ratio when N was applied at 672 kg ha^{-1} (Day and Parker, 1985).

Although effects of soil fertility on bermudagrass yields and nutrient uptake have been extensively reported, responses of Midland bermudagrass to N, P, and K fertilizer rate in the Great Plains region of the USA have not been well documented. Furthermore, the trials that have examined N fertility responses of Midland in the region have been limited to two to three years in duration. The value of long-term trials to evaluate dynamic soil and crop responses in soil fertility experiments have been emphasized (Woodhouse Jr., 1968, 1969; Girma et al., 2007). In an effort to address these concerns, a long-term experiment was initiated in southern Oklahoma to evaluate effects of N, P, and K fertilizer rates on dry matter yield, uptake and removal of N, P, and K, and soil chemical changes under a Midland bermudagrass stand. Our objectives were to report responses after the first six years of the experiment. These include: i) effects of N rate on yield and nutrient uptake while holding P and K constant on a high fertility site; ii) the adequacy of P and K supplied at low and high N rates to maintain soil P and K through monitoring of forage yields, nutrient concentrations and uptake, and soil chemical changes; iii) yield, nutrient uptake, and soil nutrient availability responses to increasing rates of P and K when nitrogen is held constant; and iv) effects of fertilizer rates on forage yield stability.

Materials and Methods

The research was conducted on a Minco fine sandy loam (course-silty, mixed, superactive, thermic Udic Haplustolls) in Love County, OK. Parent material was sandy alluvium. The site had nearly level relief, was situated on high benches along the Red River, and was well-drained. Adjacent counties to the east and west of Love County include Marshall and Jefferson Counties, respectively. Fine sandy loam soils occupied 76,890 ha or 17% of the land area within these three counties alone (USDA-NRCS, 2007). The research site was established in a bermudagrass pasture that had been used intermittently for grazing and hay production for several years. Soil was sampled on 13 May 2002 and 4 April 2006 from the 0–15 cm-layer and tested for pH at a 1:1 soil:water (Lierop, 1990), organic matter by high temperature combustion (Nelson and Sommers, 1982), P by the Mehlich-3 procedure (Fixen and Grove, 1990), K via ammonium acetate extraction (Haby et al., 1990) and nitrate (NO_3)-N concentrations by reduction to nitrite (NO_2) by cadmium (Cd) (Dahnke and Johnson, 1990).

Twelve fertilization treatments were applied annually during spring from 2002 to 2007 to 3 by 6 m plots. The plots were arranged in a randomized complete block design with three replications. Treatments 1 through 5 increased rates of N (0, 112, 224, 336, and 448 kg ha^{-1}) under non-limiting P and K rates (45 and 112 kg ha^{-1}, respectively). Treatments 6, 3, and 7 increased rates of P (0, 45, and 90 kg ha^{-1}, respectively) under non-limiting N and K rates (224 and 112 kg ha^{-1}, respectively). Treatments 8, 3, 9, and 10 increased rates of K (0, 112, 224, and 448 kg ha^{-1}, respectively) under non-limiting N and P rates (224 and 45 kg ha^{-1}, respectively). Treatments 11 and 12 applied N in split applications during spring and summer periods at the 224 and 448 kg ha^{-1} rates. Nitrogen was applied as urea during all spring applications and as ammonium nitrate in summer applications for treatments 11 and 12. Each spring while bermudagrass remained dormant, the trial was sprayed with glyphosate [N-(phosphonomethyl) glycine] at 1.12 kg a.i. ha^{-1} and 2,4-D-amine (2–4-Dichlorophenoxyacetic acid) at 2.24 kg a.i. ha^{-1} to control broadleaf weeds and annual grasses.

Forage yield was measured through harvest of a 0.95 by 6 m strip from the center of each plot in 2002 and 2003 and a 1.5 by 6 m strip from the center of each plot from 2004 to 2007. Plots were harvested at a 7.5-cm height using a modified GT262 self-propelled mower (John Deere, Moline, IL, USA) from 2002 to 2003 and a HEGE 212 forage plot harvester (Wintersteiger, Salt Lake City, UT, USA) from 2004 through 2007. During spring and summer, harvests occurred at inflorescence emergence: stages 31 to 39 (West, 1990). Fall harvests occurred after late-summer growth of bermudagrass ceased. Harvest dates occurred on 14 May 2002, 12 July 2002, 2 October 2002, 19 June 2003, 1 August 2003, 27 October 2003, 18 June 2004, 30 August 2004, 7 June 2005, 30 June 2005, 18 August 2005, 18 May 2006, 5 July 2006, 16 May 2007, 25 June 2007, 20 July 2007, and 12 September 2007. Because bermudagrass growth and dates of harvest varied among years, individual harvest yields were summed by treatment for determination of annual yields.

Table 1. Calibration statistics for NIRS prediction of forage N, P, and K from NIRS Consortium grass hay equation

Constituent	N	Mean	SD	SEC	R^2	SECV	1-VR
N	957	1.99	0.99	0.12	0.98	0.13	0.98
P	648	0.19	0.07	0.03	0.76	0.04	0.73
K	562	1.60	0.73	0.25	0.88	0.28	0.85

N, number of samples; SD, standard deviation; SEC, standard error of calibration; R2, coefficient of determination; SECV, standard error or cross validation; 1-VR, validation coefficient of determination.

Subsamples were collected at each harvest, weighed wet, and dried at 60°C in a forced air oven for determination of dry matter. After drying, samples were ground with a Wiley Mill (Thomas Scientific, Swedesboro, NJ, USA) to pass through a < 1 mm screen and processed for estimation of N, P, and K uptake. From 2002 through 2005, concentration of N was determined by combustion with the Dumas method (Padmore, 1990), P by photometric method (Padmore, 1990), and K by atomic absorption spectrophotometric method (Isaac, 1990) at Ward Laboratories (Kearney, NE, USA). From 2006 through 2007, nutrient concentrations were estimated with near-infrared reflectance spectroscopy (NIRS) equations (Table 1) from the NIRS Forage and Feed Testing Consortium. Rates of nutrient uptake were determined by multiplication of nutrient concentrations by the annual forage yield. The percentage of N fertilizer recovered was also estimated by the difference method (N uptake in treatment 1, the control [N = 0], subtracted from N uptake in fertilized plots and divided by the rate of N applied).

Analysis of variance was conducted using the mixed models procedure for repeated measure data in SAS (Littell et al., 1996) to determine main effects and interactions of fertilizer rate and year on total forage yield, nutrient concentration, and nutrient uptake. Fertilizer rate was considered a fixed effect; year and year by treatment interactions were considered random effects. Three comparisons were made with polynomial contrasts to determine the effects of increasing N, P, and K rates: treatments 1 to 5 for N effects with constant P and K; treatments 6, 3, and 7 for P effects with constant N and K; and treatments 8, 3, 9, and 10 for K effects with constant N and P. Treatments 3 and 11 and 5 and 12 were compared with linear contrasts to examine effects of split-application of N.

To assess yield stability, we conducted linear regressions of mean forage yields by treatment on the mean yield across treatments (environment mean) for the six years of the trial. We employed similar criteria as Raun et al. (1993) and Guertal et al. (1994) in their evaluations of stability in long-term soil fertility experiments and Eberhart and Russell (1966) in their assessment of yield stability in crop variety evaluations. First, significance of regression of treatment means on year was determined ($P \leq 0.05$). A significant treatment mean and year relationship would indicate a long-term trend with respect to the treatment and would preclude the use of stability analysis to characterize treatment effects (Guertal et al., 1994). Second, significance of regression of treatment means on the environment means was determined. Upon significance, we tested equality of the regression coefficients (b_i) to determine differences among treatments within the planned comparisons (Sokal and Rohlf, 1995). The most stable treatments were defined as those with mean yields greater than the grand mean across treatments and years, regression coefficients (b) ≥ 1.0, and deviations from regression (s_d^2) close to zero (Eberhart and Russell, 1966).

Results and Discussion

Weather and Forage Yields

Averaged across treatments, total annual forage yield ranged from a high of 15.4 Mg ha^{-1} in 2002 to a low of 6.1 Mg ha^{-1} in 2006 (Table 2). Total annual forage yield was negatively correlated to average daily temperature from the previous December through the current November of each year (winter months through autumn months), ranging from 16.5°C in 2002 to 18.4°C in 2006 ($r = -0.86$), and the number of days annually where the high temperature for the day exceeded 32°C, 120 days in 2006 compared to 64 days in 2004 ($r = -0.91$). Average daily temperature from March through August (spring through summer) ranged from 21.5°C in 2002 to 24.1°C in 2006. From June through August, temperature ranged from 25.4°C in 2004 to 29.1°C in 2006. Compared to the long-term record from 1971 to 2000 (Oklahoma Climatological Survey, 2008), average daily temperature was cooler than average in 2002, 2004, 2005, and 2007, warmer than average in 2006, and near average in 2003.

Annual rainfall totals were 83%, 57%, 101%, 56%, 78%, and 91% of the long-term average from 2002 to 2007, respectively. In an average year, 55% of rainfall occurs from March through August, while 16% and 29% occurs during winter and autumn, respectively. March through August precipitation was greater than the long-term average in 2004 and 2007, but less than the long-term average in 2002, 2003, 2005, and 2006. Precipitation between June and August was particularly high in 2004 and 2007, 1.5 to 2.0 folds greater than the 1971 to 2000 average. Total annual forage yield was more closely related to annual precipitation (December through November) than spring and summer or summer only precipitation (Table 2).

Interaction of Year and Fertilizer Rates

Forage Yield

Increasing the rate of N fertilizer while holding P_2O_5 and K_2O constant at 45 and 112 kg ha^{-1}, respectively, had positive, negative, and neutral effects

Table 2. Pearson correlation analysis of weather and mean annual forage yield of Midland bermudagrass on a Minco fine, sandy loam soil in Love County, OK

Year	Yield (Mg DM ha^{-1})	Average daily temperature (°C)				Precipitation (mm)			Wind speed (km h−1)			Solar radiation (MJ m−2)		
		Dec.–Nov.	Mar.–Aug.	June–Aug.	Days≥ 32°C	Dec.–Nov.	Mar.–Aug.	June–Aug.	Dec.–Nov.	Mar.–Aug.	June–Aug.	Dec.–Nov.	Mar.–Aug.	June–Aug.
AVG†		17.3	22.3	27.4	84	977	537	235	12.08					
2002	15.4	16.5	21.5	26.5	73	807	462	191	11.95	12.48	9.82	16.14	20.22	22.87
2003	9.6	17.1	22.4	27.3	83	558	336	144	12.25	12.18	10.25	16.42	21.46	23.20
2004	14.5	17.0	21.7	25.4	64	994	639	451	12.24	12.32	10.04	15.93	19.05	20.80
2005	7.1	17.5	21.7	26.7	110	547	357	271	11.48	11.67	9.50	16.62	20.58	22.70
2006	6.1	18.4	24.1	29.1	120	669	424	79	12.53	12.64	11.27	17.65	22.14	24.28
2007	11.6	16.9	21.8	26.4	70	888	669	357	11.26	10.71	9.23	15.97	19.04	21.04
	r	−0.86	−0.67	−0.75	−0.91	0.76	0.57	0.53	−0.09	0.02	−0.42	−0.81	−0.71	−0.62
	P value	0.02	0.13	0.08	0.01	0.08	0.24	0.27	0.86	0.97	0.40	0.05	0.11	0.19

† Average from 1971–2000 for Love County, OK

Table 3. Fertilizer rate effects on mean annual forage yield of Midland bermudagrass on a Minco fine, sandy loam in Love County, OK

Fertilizer rate	2002	2003	2004	2005	2006	2007	Mean
			Mg DM ha−1				
kg N ha^{-1}							
0	14.0	6.6	11.0	11.9	7.0	13.3	10.6
112	16.4	9.9	15.4	7.9	6.9	12.8	11.5
224	15.8	11.0	15.8	2.7	3.3	8.4	9.5
224†	14.3	10.7	15.2	6.0	8.5	11.9	11.1
336	16.0	9.8	16.0	2.5	5.4	10.5	10.1
448	14.6	8.7	15.9	6.5	5.3	11.4	10.4
448‡	15.5	11.3	14.2	6.2	8.0	11.8	11.2
kg P_2O_5 ha^{-1}							
0	15.5	9.6	14.4	6.4	4.5	10.9	10.2
45	16.4	9.9	15.4	7.9	6.9	12.8	11.5
90	15.4	10.7	12.9	8.3	5.5	11.7	10.8
kg K_2O ha^{-1}							
0	15.9	9.8	15.3	11.8	5.9	11.8	11.7
112	16.4	9.9	15.4	7.9	6.9	12.8	11.5
224	17.7	10.7	16.2	6.7	5.7	11.8	11.5
448	15.0	10.0	16.0	6.3	3.5	9.9	10.1
SE			1.30§				0.68¶
Contrast				*P* value			
N linear	0.787	0.020	0.026	0.019	0.191	0.085	0.374
N quadratic	0.077	0.001	0.086	0.011	0.204	0.030	0.570
N-split 224	0.323	0.744	0.748	0.263	0.004	0.035	0.102
N-split 448	0.746	0.003	0.391	0.928	0.102	0.781	0.424
P linear	0.982	0.197	0.457	0.527	0.559	0.593	0.582
K linear	0.895	0.907	0.690	0.192	0.358	0.626	0.349
K quadratic	0.219	0.133	0.833	0.044	0.898	0.526	0.540

† 112 kg of N as urea applied in early spring and 112 kg of N as ammonium nitrate applied mid-summer.
‡ 224 kg of N as urea applied in early spring and 224 kg of N as ammonium nitrate applied mid-summer.
§ SE for comparison of means by year and treatment.
¶ SE for comparison of treatment means across years.

on forage yield, depending on year (Table 3; Year × Treatment; $P < 0.001$). Positive quadratic and linear relationships between N rate and forage yield occurred in 2003 and 2004, respectively. A negative quadratic relationship to N rate, however, occurred in 2005. Yield and N rate were not related in 2002, 2006, and 2007. Split-application of N between spring and summer periods compared to single applications in spring at the 224 and 448 kg N ha^{-1} rates had minimal effects on bermudagrass yields (Table 3). Increasing the rate of P or K applied while holding N constant at 224 kg ha^{-1}, respectively, also did not affect forage yields (Table 3).

Previous research with Midland on a Minco fine, sandy loam soil in Oklahoma found yield responses to N peaked at 112 kg N ha^{-1}, an increase from controls by only 3 Mg ha^{-1} (Osborne et al., 1999).On a Wilson silt loam, however, forage yield of Midland increased from 3.8 to 13.3 Mg ha^{-1} when N increased from 0 to 672 kg N ha^{-1} (Osborne et al., 1999). Also in Oklahoma,

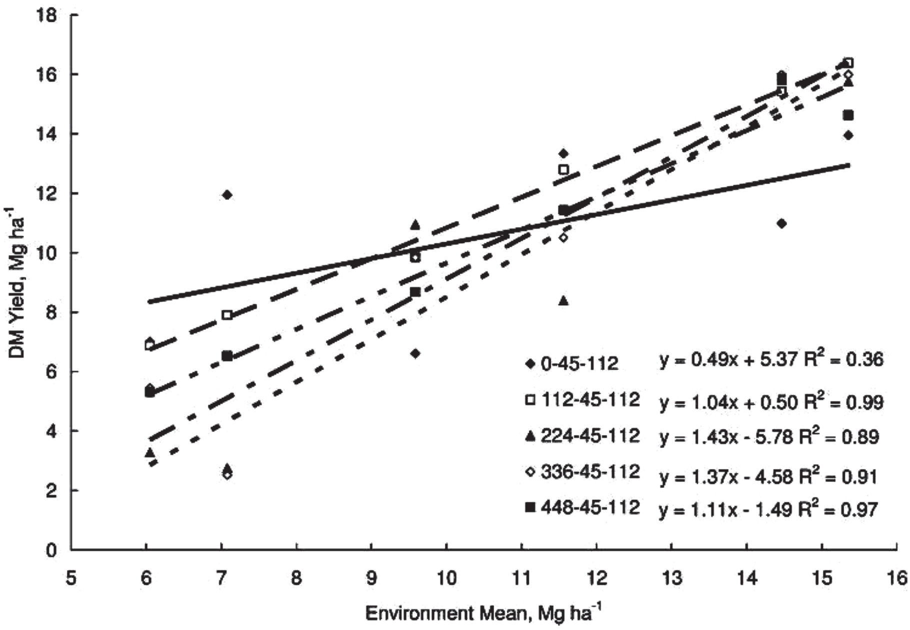

Figure 1. Stability analysis, the regression of fertilizer rate treatment means on environment means (mean across treatments by year), revealed greater response of N-fertilized bermudagrass to changes in growing conditions than non-N-fertilized bermudagrass. Lines represent increasing rate of N fertilizer from 0 to 448 kg ha^{-1}, while P_2O_5 and K_2O remained constant at 45 and 112 kg ha^{-1}, respectively.

Westerman et al. (1983) found that 112 kg N ha^{-1} increased forage yield of bermudagrass on Verdigris, Dale, and Taloka silt loam soils but had no effects on bermudagrass on a Lucien fine, sandy loam. Lack of response to N on the fine, sandy loams was attributed to limited water holding capacity of the soils and presence of droughty conditions during summer months when bermudagrass would normally be growing (Westerman et al., 1983; Osborne et al., 1999). Overall effectiveness of split applications of N also depends in large part on availability of soil moisture and rainfall throughout the summer (Westerman et al., 1983). Perhaps more consistent, positive responses to N rate would have occurred in our study had weather conditions been better relative to long-term location averages.

Yield Stability

Stability analysis indicated Midland yield responses to N fertilization depended on environmental conditions (Figure 1). Regression of yearly N rate treatment means on the environment means (mean across all treatments) was significant (P < 0.005) for all treatments except the non-N-fertilized control (P = 0.20). A test of equality showed that regression coefficients of the N fertilizer rate treatments differed (F_s = 3.03 >> $F_{0.05[4,20]}$ = 2.87).

Regression coefficients were largest for N rates of 224 and 336 kg ha^{-1}, indicating a potential for these rates to produce high yields during years when growing conditions were favorable but less-than-average yields when growing conditions were poor. Total annual mean yields of the non-N-fertilized treatment were unpredictable relative to changing environmental conditions.

Bermudagrass fertilized with 112 kg N ha^{-1} had the most stable yields. Overall mean yields were among the largest of all treatments across years (11.5 Mg ha^{-1}), the regression coefficient exceeded 1.0 (b_2 = 1.04), and deviations from regression were smallest for the 112 kg N ha^{-1} rate (e.g. stability criteria of Eberhart and Russell 1966; Raun et al., 1993, and Guertal et al., 1994). Variability about the intercept (SE = 0.42) and regression coefficient (SE = 0.04) for the 112 kg N ha^{-1} rate was less than variability about the intercept (SE = 3.68, 2.87, 2.34, and 1.12) and regression coefficient (SE = 0.33, 0.25, 0.21, and 0.10) for the 0, 224, 336, and 448 kg N ha^{-1} rates, respectively. Linear regression of treatment means on year were not significant ($P > 0.10$; data not shown), indicating forage yields did not trend upward or downward over time with respect to fertilizer rates, thereby supporting use of stability analysis to assess fertilizer rate effects (e.g. Guertal et al., 1994).

Coefficients of regression of treatment means and environmental means were not significantly different for N applied in spring only versus N applications split between spring and summer at either the 224 kg N ha^{-1} rate (treatments 3 and 11; $b_3 = 1.42$; $b_{11} = 0.856$; $F_s = 3.22 < F_{0.05[1,8]} = 5.32$) or the 448 kg N ha^{-1} rate (treatments 5 and 12; $b_5 = 1.11$; $b_{12} = 0.89$; $Fs = 1.04 < F_{0.05[1,8]} = 5.32$), indicating similar effects of these treatments on forage yield stability. Coefficients from the regression of annual treatment means on environmental means also were not significantly different among the P rate treatments (treatments 6, 3, and 7; $Fs = 2.75 < F_{0.05[2,12]} = 3.88$) or among the K rate treatments (Treatments 8, 3, 9, and 10; $F_s = 1.61 < F_{0.05[3,16]} = 3.24$).

Nutrient Uptake

Uptake of N, P, and K also depended on interactions of year and fertilizer rate ($P < 0.001$; 0.01, and 0.001, respectively). Nitrogen uptake increased with N applied from 0 to 448 kg ha^{-1} in 2002, 2003, 2004, and 2007 but was unaffected during drought years of 2005 and 2006 (Table 4). Nitrogen application also increased P and K uptake in 2004 but did not affect these nutrients from 2005 through 2007. Split-application of N between spring and summer periods compared to single applications in spring at the 224 and 448 kg N ha^{-1} rates had minimal effects on nutrient uptake (Table 4). Increasing rate of P and K applied at constant rates of N also had limited effects on nutrient uptake. Across years at the 112-45-112 kg N-P_2O_5-K_2O ha^{-1} fertilization rate, an average of 166.0 kg

Table 4. Fertilizer rate effects on uptake of N, P, and K in Midland bermudagrass in Love County, OK

	Forage nutrient uptake																
Fertilizer rate	2002	2003	2004	2005	2006	2007	Mean	2004	2005	2006	2007	Mean	2004	2005	2006	2007	Mean
	kg N ha^{-1}							kg P ha^{-1}					kg K ha^{-1}				
kg N ha^{-1}																	
0	154.9	68.7	103.8	158.8	92.4	174.2	125.5	24.2	35.7	15.3	28.2	25.9	137.5	193.0	131.2	281.6	185.8
112	224.9	125.1	196.3	125.4	111.0	213.2	166.0	35.2	25.4	16.3	28.0	26.3	224.4	149.8	138.4	270.1	195.7
224	228.8	176.2	267.0	65.7	70.0	181.1	164.8	40.6	10.2	8.6	19.4	19.7	243.4	58.4	59.9	167.9	132.4
336	267.7	181.2	290.1	64.7	92.7	228.7	187.5	37.3	9.7	12.5	24.7	21.1	240.1	54.9	98.4	200.3	148.4
448	263.1	179.7	344.6	184.7	136.5	279.7	231.4	44.9	25.8	14.6	28.1	28.4	221.2	143.4	91.5	220.7	169.2
224†	200.1	161.5	213.8	118.6	157.4	224.1	179.2	35.3	21.3	21.3	27.7	26.4	211.9	128.0	171.7	248.3	165.7
448‡	247.5	205.8	257.3	146.7	202.6	284.8	224.1	40.1	23.4	21.6	29.3	28.6	217.2	135.2	134.5	234.9	190.0
kg P_2O_5 ha^{-1}																	
0	249.8	158.9	242.2	92.4	92.4	206.6	173.7	29.7	19.4	11.6	24.5	21.3	199.1	101.3	91.5	233.5	156.3
45	228.8	176.2	267.0	65.7	70.0	181.1	164.8	40.6	10.2	8.6	19.4	19.7	243.4	58.4	59.9	167.9	132.4
90	236.4	179.6	149.8	127.0	124.3	235.8	175.5	30.4	26.1	14.9	27.5	24.8	182.6	145.6	116.2	248.4	173.2
kg K_2O ha^{-1}																	
0	245.1	151.3	271.8	179.3	125.0	222.7	199.2	40.8	35.5	13.8	24.2	28.6	210.8	183.6	111.6	215.6	180.4
112	228.8	176.2	267.0	65.7	70.0	181.1	164.8	40.6	10.2	8.6	19.4	19.7	243.4	58.4	59.9	167.9	132.4
224	255.0	172.5	281.3	94.6	122.3	231.2	192.8	39.9	20.7	15.3	28.1	26.0	278.0	114.7	123.2	258.3	193.5
448	227.1	157.1	253.1	98.0	88.5	203.6	171.2	38.1	20.7	9.7	23.5	23.0	252.2	114.6	77.2	218.8	165.7
SE			24.23§				10.19¶		4.55§			2.60¶		28.43§			17.80¶
Contrast	*P* value																
N linear	0.001	0.001	0.001	0.944	0.379	0.014	0.001	0.005	0.116	0.583	0.673	0.982	0.035	0.128	0.107	0.013	0.165
N quadratic	0.045	0.002	0.151	0.011	0.231	0.322	0.423	0.355	0.015	0.226	0.041	0.035	0.024	0.024	0.304	0.028	0.141
N-split 224	0.180	0.401	0.102	0.300	0.073	0.280	0.323	0.404	0.266	0.006	0.033	0.080	0.399	0.219	0.002	0.019	0.031
N-split 448	0.462	0.159	0.009	0.453	0.435	0.898	0.607	0.458	0.802	0.109	0.742	0.945	0.915	0.883	0.188	0.662	0.657
P linear	0.492	0.267	0.007	0.501	0.378	0.455	0.915	0.904	0.497	0.431	0.425	0.355	0.658	0.430	0.447	0.647	0.509
K linear	0.666	0.807	0.670	0.196	0.616	0.959	0.234	0.659	0.279	0.678	0.574	0.377	0.184	0.936	0.696	0.334	0.833
K quadratic	0.691	0.115	0.603	0.114	0.673	0.805	0.540	0.859	0.078	0.938	0.980	0.273	0.271	0.121	0.901	0.858	0.577

† 112 kg of N as urea applied in early spring and 112 kg of N as ammonium nitrate applied mid-summer.
‡ 224 kg of N as urea applied in early spring and 224 kg of N as ammonium nitrate applied mid-summer.
§ SE for comparison of means by year, treatment, and nutrient.
¶ SE for comparison of treatment means across years by nutrient.

N, 26.3 kg P, and 195.7 kg K ha^{-1} were removed annually, corresponding to a removal rate of 14.4 kg N, 2.3 kg P, and 17.0 kg K per Mg DM harvested (mean yield of 11.5 Mg DM ha^{-1} across years).

Uptake rates were less for N and more for K than previously reported values. Uptake of 18.1 to 25.3 kg N ha^{-1} per Mg DM produced was reported for Midland bermudagrass grown at multiple locations in Oklahoma (Westerman et al., 1983). Harvesting of Midland in southern Oklahoma removed 18 to 19 kg N per Mg DM produced on fine, sandy loam and silt loam soils (Osborne et al., 1999). Coastal bermudagrass with a yield of 9.8 Mg ha^{-1} on a sandy loam in Georgia removed N, P, and K at rates of 16.8, 1.9, and 13.5 kg ha^{-1} per Mg DM produced, respectively (Morris and Celecia, 1962). Lower N uptake values may be related to poor N recovery resulting from use of urea as opposed to alternative sources of N (Westerman et al., 1983; Osborne et al., 1999). The percentage of N recovered in Midland was not affected by fertilizer treatment ($P > 0.10$) but did vary among years ($P < 0.05$). Nitrogen recovery averaged 35%, 40%, 59%, −19%, 10%, and 21% from 2002 through 2007, respectively. In drought years of 2005 and 2006, losses of N through volatilization may have resulted in the poor recovery of N. Higher uptake of K may be related to luxury consumption of K at the low rates of N applied. Research on Coastal bermudagrass also found ratios of K uptake relative to application rates of N were greater at lower N fertilizer rates than higher N rates (Day and Parker, 1985; Robinson et al., 1990).

Soil Nutrient Availability

Soil nutrient availability and nutrient removal relative to supply rates are important factors to consider when determining optimum P and K fertilizer rates. Soil P and K availability in the upper 15 cm of soil were maintained at 100% recommended sufficiency levels for bermudagrass (e.g. Johnson et al., 2000) at N rates up to 224 kg ha^{-1} with annual application of 45 kg P_2O_5 ha^{-1} and 112 kg K_2O ha^{-1} (Table 5). Application of 45 kg P_2O_5 ha^{-1} y^{-1}, however, supplied less elemental P (20 kg ha^{-1}) than was removed annually at all N rates (mean of 26 kg ha^{-1} across years) suggesting mining of soil P. Supply of K annually (93 kg ha^{-1}) also was less than elemental K removed (mean of 170 kg ha^{-1} across years) suggesting mining of soil K, as well. At rates of 336 to 448 kg N ha^{-1} applied, soil P and K availability in the upper 15 cm dropped to < 80% sufficiency levels in 2006 (Table 5), possibly contributing to lower forage yields at these rates. Application of 90 kg P_2O_5 ha^{-1} y^{-1} has nearly doubled availability of soil P from controls (Table 5). Soil K accumulated to more than twice necessary for bermudagrass (> 280 kg ha^{-1}) with the 448 kg K_2O ha^{-1} treatment (Johnson et al., 2000). After six years, however, availability of soil P and K remain at 80% sufficiency levels in plots treated with 0 kg P_2O_5 and 0 kg K_2O ha^{-1} explaining limited forage yield responses (Table 3) to these nutrients.

Table 5. Fertilizer rate effects on soil pH, organic matter (OM), nitrate-N (NO_3-N), phosphorus (P), and potassium (K) at a 0 to 15-cm depth of a Minco fine, sandy loam with Midland bermudagrass

	pH		OM		NO_3-N		P		K	
Fertilizer rate	2002	2006	2002	2006	2002	2006	2002	2006	2002	2006
			%		kg ha^{-1}					
kg N ha^{-1}										
0	5.2	6.1	1.5	1.1	3.0	4.9	48.5	138.1	271.0	339.7
112	5.1	6.1	1.3	1.3	3.0	10.1	63.5	65.0	241.9	336.7
224	5.3	5.9	1.3	1.2	3.0	9.7	59.0	81.4	204.6	293.4
336	5.4	5.6	1.2	1.3	1.5	11.6	42.6	58.2	242.6	238.2
448	5.5	5.3	1.7	1.3	3.4	9.0	78.4	59.7	247.9	178.5
224†	5.8	6.0	1.7	1.7	11.9	7.8	41.1	90.3	277.8	253.1
448‡	5.8	5.8	1.6	1.6	13.1	14.6	44.1	76.2	306.1	233.0
kg P_2O_5 ha^{-1}										
0	5.4	6.0	1.4	1.3	3.0	5.2	59.7	46.3	209.1	311.4
45	5.3	5.9	1.3	1.2	3.0	9.7	59.0	81.4	204.6	293.4
90	5.5	6.0	1.4	1.3	4.1	7.1	40.3	92.6	267.3	319.6
kg K_2O ha^{-1}										
0	5.7	5.9	2.2	1.1	4.9	9.7	53.8	64.2	300.2	173.2
112	5.3	5.9	1.3	1.2	3.0	9.7	59.0	81.4	204.6	293.4
224	5.7	6.0	1.4	1.1	11.2	9.3	62.7	114.2	321.1	443.5
448	5.7	5.7	1.5	1.0	10.8	6.0	41.1	90.3	315.1	583.9
SE§		0.14		0.24		1.68		16.24		25.31
Contrast					*P* value					
N linear	0.044	0.001	0.562	0.772	0.886	0.073	0.456	0.004	0.539	0.001
N quadratic	0.502	0.135	0.129	0.806	0.718	0.038	0.626	0.082	0.131	0.289
N-split 224	0.021	0.746	0.240	1.000	0.001	0.428	0.441	0.699	0.053	0.273
N-split 448	0.044	0.519	0.240	0.914	0.001	0.209	0.949	0.441	0.071	0.637
P linear	0.746	0.746	1.000	0.914	0.633	0.428	0.404	0.054	0.118	0.821
K linear	0.387	0.475	0.049	0.707	0.002	0.127	0.669	0.071	0.169	0.001
K quadratic	0.215	0.258	0.040	0.702	0.652	0.315	0.855	0.377	0.091	0.695

† 112 kg of N as urea applied in early spring and 112 kg of N as ammonium nitrate applied mid-summer.
‡ 224 kg of N as urea applied in early spring and 224 kg of N as ammonium nitrate applied mid-summer.
§ SE for comparison of means by year and treatment.

Release of non-readily available P and K from soil colloid reserves may have contributed to the high availability of P and K despite 6 years of nutrient removal (Fixen and Grove, 1990).

Additional considerations are effects of fertilizer rate treatments on soil pH and residual NO_3-N. Year and fertilizer treatment interactions affected soil pH ($P < 0.01$). Soil pH values were lower in 2002 than in 2006. Greater pH values in 2006 may be related to sampling time during wet, cooler weather during early April 2006 compared to sampling under warmer, drier conditions in late May 2002. Soil pH readings have been known to vary from time to time within a year or between years because of the concentrations of salts in the soil solution and concentration of carbon dioxide in the soil air (Lierop, 1990).

Long-term applications of N have previously contributed to poor yield responses of bermudagrass through acidification of the soil profile. Indeed, soil tests in 2006 showed soil pH declined linearly in response to N application rate (Table 5). Coastal bermudagrass grown under irrigation on an acid sandy loam with soil pH of 4.0 to 4.5 in Georgia was dependent on lime application to maintain forage yields at N rates > 448 kg ha^{-1} (Adams et al., 1967). Without lime application, Coastal exhibited chlorosis and died at higher N rates (Adams et al., 1967). Woodhouse Jr. (1969) found N rates > 112 kg ha^{-1} lowered pH of the soil profile relative to unfertilized controls and rates of 448 to 672 kg N ha^{-1} dropped soil pH below 5.0 and limited yields of Coastal across a 14-year period in North Carolina.

Residual soil NO_3-N concentrations were affected by interactions of year and treatment ($P < 0.001$). Although concentrations were mostly similar among fertilizer rate treatments, treatments receiving split-applications of N at the 224 and 448 kg ha^{-1} rates initially had greater soil NO_3-N concentrations in 2002. In 2006, however, there were no trends in NO_3-N concentrations among treatments. At concentrations ranging from 3.0 to 14.6 kg ha^{-1} across treatments and years, availability of residual soil NO_3-N in spring probably did not have large effects on bermudagrass responses in this trial.

Conclusions

Previous research extensively evaluated yield and nutrient uptake responses of different cultivars of bermudagrass to fertilizer rates, sources, and application times. Many of the research trials were limited to 2–3 years, however, not permitting the characterization of dynamic crop and soil responses often discovered in long-term soil fertility experiments. Furthermore, information on fertilization requirements of Midland bermudagrass in the southern Great Plains was limited. In 2002, a long-term trial was initiated in southern Oklahoma to determine effects of N, P, and K fertilizer rates on yield and N, P, and K uptake of Midland. In five of the first six years of the trial, mean annual precipitation was below long-term location averages. Mean annual temperatures exceeded long-term location averages in three of the years. Consequently, drought often suppressed bermudagrass yields. Analysis of variance indicated forage yields and N, P, and K uptake depended on interactions of year and fertilizer rates. Nitrogen fertilizer rates had positive, negative, and neutral effects on forage yields, depending on year. Forage yields were not affected by P or K fertilizer rates or split-application of N fertilizer between spring and summer periods. Stability analysis revealed that fertilized bermudagrass was responsive to changes in environmental conditions, producing above-average yields when growing conditions were favorable but below-average yields when growing conditions were poor. Yields of non-N-fertilized bermudagrass appeared random, complicating determination of optimal fertilizer rates. Forage yield stability was best for Midland fertilized with 112-45-112 kg ha^{-1} N-P_2O_5-K_2O

annually. At these fertilizer rates, forage yields averaged 11.5 Mg DM ha^{-1} after six years and removed 14.4 kg N, 2.2 kg P, and 17.0 kg K per Mg DM harvested annually, rates of removal that exceed supply of P and K. After six years, availability of soil P and K remained at 100% sufficiency levels within the upper 15 cm suggesting mining of soil P and K from lower in the soil profile. Application of 58 kg P_2O_5 ha^{-1} and 235 kg K_2O ha^{-1} would be necessary to balance nutrient supply with nutrient removal rates.

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