Published May, 1999

Bermudagrass Response to High Nitrogen Rates, Source, and Season of Application

Shannon L. Osborne, William R. Raun,* Gordon V. Johnson, Jerry L. Rogers, and Wadell Altom

ABSTRACT

High N rates and source of N have been thoroughly evaluated in bermudagrass [*Cynodon dactylon* (L.) Pers.] forage production, but less is known concerning season of application and estimated fertilizer N recovery in these systems. Two field studies (Ardmore, OK: Wilson silt loam, Vertic Haplustalfs; Burneyville, OK: Minco fine sandy loam, Udic Haplustolls) were conducted at two locations over two years to evaluate the effects of rate, timing, and source of N on bermudagrass forage yield, total N, NO_3 concentration, and estimated fertilizer N recovery. Nitrogen was applied at rates of 112, 224, 448, 672, and 1344 kg N ha^{-1} as NH_4NO_3 or urea in early spring (March) and late summer (August). Fertilizer N recovery can be maximized at rates of 112 and 224 kg N ha^{-1} applied in the early spring and late summer, respectively. Even when N rates of 1344 kg N ha^{-1} were applied annually, bermudagrass forage NO_3–N was seldom above 2000 mg kg^{-1}, which is below published toxic levels (2400–4500 mg kg^{-1}) for cattle (*Bos taurus*) consumption. Early-spring applied N increased yields, N removal, and fertilizer recovery compared with late-summer applied N. Fertilizer N recovery was higher for NH_4NO_3 than for urea, especially when applied in late summer. Late-summer applications of urea should be avoided, due to increased NH_3 volatilization losses. Nitrogen applied at 112 kg N ha^{-1} in early spring can result in fertilizer recoveries in excess of 85%. These high recoveries in forage production systems are possibly a result of continuous preanthesis forage harvesting when gaseous plant N losses are small, but which increase following anthesis.

NITROGEN SOURCE AND RATE have been comprehensively evaluated in bermudagrass production systems. However, relatively less is known about bermudagrass forage yield and N uptake when all N is applied in early spring or late summer. Mathias et al. (1978) found that bermudagrass yields and N concentration increased and percent recovery decreased with increasing N up to 448 kg N ha^{-1}. Morris and Celecia (1962) found increased N removal in bermudagrass when N was applied in the spring, compared with fall application. Prine and Burton (1956) found that increasing the annual N rate from 0 to 1008 kg N ha^{-1} increased yield and percent protein, but decreased N recovery. Mathias et al. (1973) reported that percent N recovery was highest at 224 kg N ha^{-1}. Fisher and Caldwell (1959) found that 'Coastal' bermudagrass produced 0.6 Mg ha^{-1} and 80 g protein kg^{-1} with no fertilization and 2.9 Mg ha^{-1} and 13 g protein kg^{-1} at an N rate of 1120 kg ha^{-1}. Overman and Wilkinson (1992) noted that a reasonable first approximation in yield response to applied N requires at least three years to approach a steady state, thus promoting the need for long-term field experiments. Other work by Overman et al. (1990) has developed models to relate forage yield to applied N for bermudagrass using water availability and harvest interval in both dry and humid climates.

Power (1980) reported that the amount of fertilizer N in plant tops and roots and soil inorganic N were linearly related to the amount of fertilizer N applied. Bermudagrass forage yields and total N were positively correlated with increased N applied, up to 224 kg N ha^{-1}, and the highest N concentration occurred with the highest yields, indicating that N removal was not diluted at high yields (Wiedenfeld, 1988). Burton et al. (1963) found that increased N rates up to 1008 kg ha^{-1} increased total dry matter production up to 15.2 Mg ha^{-1} and 185 g crude protein kg^{-1}.

In a rye–wheat–ryegrass (*Secale cereale* L.-*Triticum aestivum* L.-*Lolium multiflorum* L.) forage production system, N use efficiency was >60% for all rates of N up to 224 kg ha^{-1} (Altom et al., 1996). Hanson et al. (1978) concluded that increasing applied N on perennial grasses resulted in increased fertilizer N recovery at rates up to 448 kg N ha^{-1} for all times of application (split, compared with early spring) and that a split application resulted in the highest percent recovery. Work by Staley et al. (1991) on tall fescue (*Festuca arundinacea* Schreb.) and switchgrass (*Panicum virgatum* L.) noted that increasing applied N increased N concentration; they also reported 47% fertilizer N recovery at a 180 kg ha^{-1} N rate. Eichhorn (1989) found that maximized forage yields occurred at 448 kg N ha^{-1}, while N removal and crude protein concentration continued to increase at N rates up to 672 kg N ha^{-1}. Percent fertilizer recovery decreased as N rates increased from 224 to 672 kg N ha^{-1}.

The major factors that affect NO_3 accumulation in forages were investigated by Crawford et al. (1961). Stage of growth, level of N fertilization, plant part, and light intensity all influenced NO_3–N concentration. Factors that did not affect NO_3–N concentration were cultivar, time, and source and placement of N fertilizer. Although increasing N fertilizer rates increased NO_3

Dep. of Plant and Soil Sciences, Oklahoma State Univ., Stillwater, OK 74078 and The Samuel Roberts Noble Foundation, Ardmore, OK. Contribution from the Okla. Agric. Exp. Stn. Received 15 June 1998. *Corresponding author (wrr@soilwater.agr.okstate.edu).

Published in Agron. J. 91:438–444 (1999).

Abbreviations: SED, standard error of difference; UAN, urea–ammonium nitrate.

concentration in the tissue, N rates as high as 2240 kg ha^{-1} did not result in bermudagrass forage NO_3 accumulation levels that would be toxic to animals (Worker and Peterson, 1962). May et al. (1990) noted that NO_3 accumulation in crop plants is intensified by stress from inadequate moisture. Murphy and Smith (1967) found that increased NO_3–N concentration in sudangrass [*Sorghum bicolor* (L.) Moench] was a direct result of increased N fertilization up to 336 kg ha^{-1}, while advancing plant maturity was indirectly related. Work by Lovelace et al. (1968) indicated that NO_3 accumulation in 'NK-37' bermudagrass was twice that of Coastal bermudagrass, and that soil texture had a greater influence on tissue NO_3 levels than did fertilizer N rate. Wright and Davison (1964) indicated that forages with more than 3400 mg kg^{-1} NO_3–N are considered toxic to cattle and, when fed, should be mixed with safer feeds lower in NO_3–N.

Westerman et al. (1983) showed that bermudagrass yields and N removal were generally lower for urea than for urea–NH_4NO_3 (UAN), while N use efficiency was higher for UAN than urea. Similar results of increased yields when NH_4NO_3 was used on bermudagrass, compared with urea, were reported by Wilkinson and Langdale (1974). Brejda et al. (1995) concluded from a comparison of urea, NH_4NO_3, and $(NH_4)_2SO_4$ that forage yield and percent protein were greater for NH_4NO_3, compared with other sources and that each resulted in a linear increase in yield with N rate up to 235 kg N ha^{-1}. Anderson and Kunkel (1983) found that bermudagrass fertilized with urea compared with NH_4NO_3 and UAN resulted in higher yields, with no differences in N removal. Nitrogen recovery and bermudagrass forage yield were less for liquid fertilizer than for solid NH_4NO_3 (Walker et al., 1979).

Although substantial work has documented response of bermudagrass to high rates of applied N, fertilizer N recovery in these systems is not well understood. Our objectives were to evaluate the effects of N source and N rate when applied in spring and late summer on bermudagrass forage yield, forage total N, forage NO_3–N, and estimated fertilizer N recovery.

MATERIALS AND METHODS

Field experiments were initiated in August 1993 at Ardmore and March 1994 at Burneyville, OK, on sites previously established to 'Midland' bermudagrass. Initial soil test characteristics and soil classification are reported in Table 1. A randomized complete block experimental design with three replications was used at both locations; the same treatments were applied to the same plots each year. Plots were 4.8 m by 7.6 m at Ardmore and 2.4 m by 7.6 m at Burneyville. Nitrogen fertilizers were surface-applied without incorporation as either NH_4NO_3 or urea in August (late-summer cycle) or March (early-spring cycle). Nitrogen rates for the late-summer cycle were 0, 224, 448, 672, and 1344 kg N ha^{-1}; early-spring cycle rates were 0, 112, 672, and 1344 kg N ha^{-1}. Nitrogen treatments applied in late summer and early spring were analyzed independently, since the influence of environment, timing of N application, and harvest time could not be partitioned on the dependent variables evaluated. Late-summer cycles represent all harvests after N fertilization in August but prior to the August fertilization for the following year. Early-spring cycles include all harvests after March fertilization but prior to March fertilization the following year. Since interest was in the total cycle production and total N removal, analysis of variance was performed on the sum of late-summer and/or early-spring harvests, by year, using the GLM procedure in SAS (SAS, 1988). There were two complete cycles for each location and for each cycle (late summer and early spring), except that the

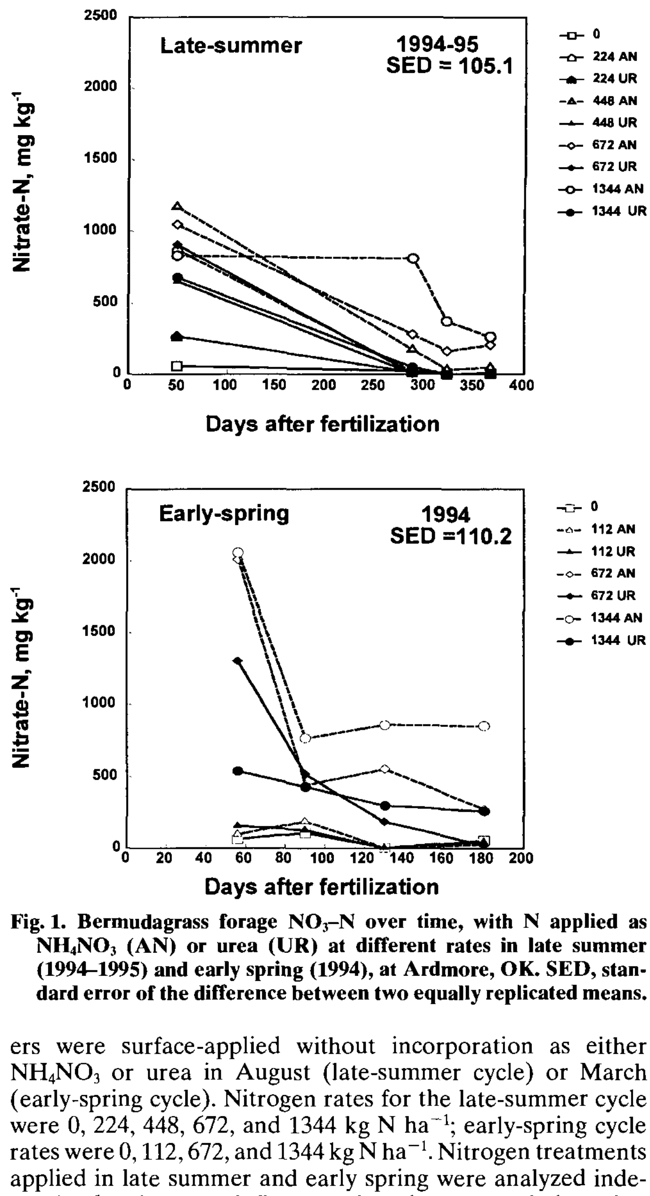

Fig. 1. Bermudagrass forage NO_3–N over time, with N applied as NH_4NO_3 (AN) or urea (UR) at different rates in late summer (1994–1995) and early spring (1994), at Ardmore, OK. SED, standard error of the difference between two equally replicated means.

Table 1. Initial surface (0–15 cm) soil test characteristics and soil classification at Ardmore and Burneyville, OK.†

Location	pH	BI	Total N	Organic C	NH_4–N	NO_3–N	P	K
			g kg^{-1}		mg kg^{-1}			
Ardmore	5.2	6.3	0.69	9.9	10.9	1.8	59	247
Classification: Wilson silt loam (fine, smectitic, thermic Oxyaquic Vertic Haplustalfs)								
Burneyville	5.6	6.8	1.48	20.8	7.6	1.9	26	179
Classification: Minco silt loam (coarse-silty, mixed, superactive, thermic Udic Haplustolls)								

† pH, 1:1 soil:water; BI, buffer index; total N and organic C, dry combustion; NH_4–N and NO_3–N, 2 *M* KCl extract; P and K, Mehlich-3 extraction.

Table 2. Harvest and N fertilization dates, by cycle, with climatic conditions at the time of application (Ardmore and Burneyville, OK).

Ardmore								Burneyville							
		Temperature		Rainfall						Temperature		Rainfall			
Fertilization	Harvest	Daily high	Surface avg.	0–24 h	24–48 h	48–72 h	Growing season	Fertilization	Harvest	Daily high	Surface avg.	0–24 h	24–48 h	48–72 h	Growing season
		°C		mm						°C		mm			
1993–1994 late-summer cycle (August–July)															
27 Aug. 1993	3 Oct.	38.3	30.7	0	0	0	1371	—	—						
	26 May								—						
	29 June								—						
	9 Aug.								—						
1994–1995 late-summer cycle (August–July)															
9 Aug. 1994	26 Sept.	31.0	26.7	0	0	0	1180	9 Aug. 1994	27 Sept.	33.2	26.0	.25	0	0	1280
	22 Mar.								23 May						
	23 May								27 June						
	28 June								10 Aug.						
	11 Aug.														
1995–1996 late-summer cycle (August–July)															
11 Aug. 1995		33.3	26.8	0	0	0	554	10 Aug. 1995	28 Sept.	32.9	26.4	0	0	0	692
	28 May								28 May						
	27 June								27 June						
	8 Aug.								8 Aug.						
1994 early-spring cycle (March–September)															
31 Mar. 1994	26 May	19.9	10.2	0	0	4.8	936	31 Mar. 1994	26 May	22.3	12.4	0	0	2.5	805
	28 June								29 June						
	9 Aug.								9 Aug.						
	26 Sept.								27 Sept.						
1995 early-spring cycle (March–September)															
22 Mar. 1995	23 May	28.9	20.8	0	0	0	547	22 Mar. 1995	23 May	30.1	20.8	0	0	4.3	652
	28 June								27 June						
	11 Aug.								10 Aug.						
									28 Sept.						

late-summer cycle for Ardmore had a total of three complete cycles. Single degree of freedom nonorthogonal contrasts were used to determine linear and quadratic dependent variable response to N fertilizer (by source) and other selected treatment comparisons. The standard error of the difference (SED) between two equally replicated treatment means is reported in Tables 3 to 6 and Fig. 1. Significant treatment differences can be approximated by multiplying SED by 2.0 (value of t from t-table, significance level α, and degrees of freedom in residual error). Fertilization dates and climatic conditions are reported in Table 2. Phosphorus and K were broadcast applied to both experimental areas at 48.9 kg P ha^{-1} as triple superphosphate and 186 kg K ha^{-1} as KCl in early March 1993, late May 1995, and again in late May of 1996. In order to eliminate the effects of low soil pH, lime was applied at a rate of 6.7 Mg ha^{-1} in late May 1995 to each location. A prepackaged mix of 2,4-D and dicamba [BASF Weedmaster: (2,4-dichlorophenoxy)acetic acid + 3,6-dichloro-2-methoxybenzoic acid] at 481 g a.i. kg^{-1} was applied to all plots at a rate of 2.34 L ha^{-1}, in early March of each year.

Plots were periodically harvested through the growing season (Table 2) when the grass was at or near anthesis stages 41 to 49 as morphologically defined by West (1990). Forage yield was determined by harvesting a 0.96- by 7.6-m area from each plot using a self-propelled John Deere 256 rotary mower at a cutting height of 0.07 m. Plot weights were recorded and subsampled for moisture and chemical analysis. Subsamples were dried for 120 h in a forced-air oven at 70°C and ground to pass a 100-mesh screen. Total N was determined on all forage samples using dry combustion (Schepers et al., 1989). Forage NO_3 was determined by extracting 0.2-g forage samples with 20 mL of 0.01 M $CaSO_4$, shaken for 30 min, filtered, and analyzed by Cd reduction using an automated flow injection analysis system (Lachat, 1989). Nitrogen removal was estimated by multiplying total N concentration and dry forage biomass. The difference method was used to estimate fertilizer recovery, by year, using total production (N removal in the check plot [N = 0] subtracted from N removal in fertilized plots and divided by the rate applied).

RESULTS AND DISCUSSION

Results of analysis of variance and single degree of freedom contrasts by cycle for total forage yield, N removal, and fertilizer recovery are reported in Tables 3 to 6. A significant linear and/or quadratic response to applied N was observed for forage yield and N removal in the late-summer and early-spring cycles for both N sources at both locations.

Ardmore (Late Summer)

Total forage yield was maximized at the 672 kg N ha^{-1} rate for NH_4NO_3; however, yields tended to increase at the high N rate (1344 kg N ha^{-1}) when urea was applied (late summer, 1993–1994; Table 3). Forage N removal continued to increase at the high N rates for both N sources (Table 3). For the late-summer cycle of 1994–1995 and 1995–1996, forage yields peaked at the 448 kg N ha^{-1} rate for both NH_4NO_3 and urea, while increases in N removal continued to take place at the 672 kg N ha^{-1} rate (Table 3). Continued N removal at N rates in excess of that required for maximum yield was consistent with work in wheat by Wuest and Cassman (1992), and Rasmussen and Rohde (1991). Similar to previous work by Westerman et al. (1983) and Brejda et al. (1995), NH_4NO_3 produced significantly higher yields

Table 3. Analysis of variance, treatment means, and single degree of freedom contrasts for forage yield, N removal, and percent fertilizer recovery (difference method), late-summer applied N, Ardmore, OK (1993–1996).

		Forage yield (Mg ha^{-1})				N removal (kg ha^{-1})				Fertilizer recovery (%)		
Source†	df	1993–1994	1994–1995	1995–1996	df	1993–1994	1994–1995	1995–1996	df	1993–1994	1994–1995	1995–1996
						Mean Squares						
Rep	2	0.1	0.2	1.7	2	803.2	311.8	1 006.5	2	88.5	752.8**	61.6
Trt	9	32.3**	43.1**	19.2**	9	41 133.6**	49 372.3**	17 103.1**	7	726.4**	1415.7**	279.6**
Contrast												
AN linear	1	128.2**	141.6**	53.5**	1	197 895.5**	179 324.7**	62 711.8**	1	1980.2**	3843.7**	706.8**
AN quadratic	1	42.0**	94.9**	39.4**	1	31 240.5*	95 572.0**	24 977.1**	1	135.2	218.1	25.5
UR linear	1	80.9**	69.7**	56.6**	1	95 171.8**	62 993.0**	42 856.9**	1	605.5**	1265.3**	24.4
UR quadratic	1	1.9	27.1*	9.1**	1	2 708.9	26 380.9**	3 080.9*	1	278.2*	20.9	15.3
AN vs. UR (over N rates)	1	73.8**	79.1**	13.3**	1	57 512.9**	108 873.6**	22 498.2**	1	2072.5**	4447.8**	1140.3**
Error	18	0.9	1.7	0.7	18	697.6	906.4	479.7	13	50.6	80.9	50.6
SED‡		0.8	1.1	0.7		21.6	24.6	17.9		5.8	7.3	5.8
						Treatment Means						
N rate (N source)												
0		4.66	4.09	1.10		80.7	72.7	15.8		—	—	—
0		4.72	4.70	1.01		87.8	86.4	14.2		—	—	—
224 kg ha^{-1} (AN)		9.58	7.34	4.44		226.2	254.1	95.7		63.4	74.9	34.9
448 kg ha^{-1} (AN)		11.69	12.88	6.99		308.9	357.5	173.0		50.1	60.5	36.6
672 kg ha^{-1} (AN)		13.75	13.52	7.77		360.3	395.2	210.3		41.1	46.0	29.9
1344 kg ha^{-1} (AN)		14.51	13.91	7.34		445.7	402.0	216.8		26.9	23.5	16.4
224 kg ha^{-1} (UR)		7.94	6.85	3.13		175.8	178.7	57.5		40.9	41.2	16.6
448 kg ha^{-1} (UR)		8.75	9.87	4.34		203.8	246.5	82.1		26.7	35.7	15.0
672 kg ha^{-1} (UR)		9.21	10.45	6.11		226.8	271.8	139.6		21.2	27.6	18.5
1344 kg ha^{-1} (UR)		12.45	11.58	6.97		331.4	311.3	171.6		18.4	16.7	12.5
AN (over N rates)		12.38	11.91	6.64		335.3	352.2	173.9		45.4	51.2	29.5
UR (over N rates)		9.59	9.69	5.14		234.5	252.1	112.7		26.8	30.3	15.7

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† AN, ammonium nitrate; UR, urea; SED, standard error of the difference between two equally replicated means.

and N removal when applied in late summer as compared with urea (NH_4NO_3 vs. urea over N rate contrast). Increased production from NH_4NO_3 could perhaps be attributed to the immediate availability of NO_3 and NH_4 as compared with urea. Also, NH_3 volatilization from urea was expected to be significant, considering the daily high temperatures (38.3°C in 1993–1994 and 31.0°C in 1994–1995) at the time of application, lack of incorporation, and presence of dew and/or surface residues possibly high in urease. At this site, in all three years, no rainfall was received until 10 d after fertilizers were applied. In the 10 d following fertilization, average surface air temperatures were 30.7, 26.7, and 26.8°C in 1993–1994, 1994–1995, and 1995–1996, respectively. This increased the potential for NH_3 volatilization, as has been shown by Ernst and Massey (1960). Total production levels were lower for the 1995–1996 period than for 1993–1994 and 1994–1995 (Table 3), because of markedly lower rainfall (Table 2). Low production in 1995–1996 resulted from drought conditions during June and July, which decreased the number of harvests per cycle to only three, compared with four in 1993–1994 and five in 1994–1995 (Table 2). However, forage yield and N removed for NH_4NO_3 continued to be significantly greater than urea for all three cycles (NH_4NO_3 vs. urea over N rates; Table 3).

Ardmore (Early Spring)

Total forage yield from early-spring N fertilization was greatest (19.8 Mg ha^{-1}) at the highest N rate (NH_4NO_3) in 1994 (Table 4). Total N removed exceeded 600 kg N ha^{-1} for this same year. Some tissue salt-burn that delayed N response was observed in the high N rate plots soon after fertilization. Unlike data from production cycles with late-summer fertilization, no differences were found in forage yield between N sources (Tables 3 and 4). However, N removal was significantly higher for NH_4NO_3 than for urea in both 1994 and 1995 (average increase of 54 kg N ha^{-1} for NH_4NO_3 compared with urea, over N rates; Table 4). The lack of differences between N sources in total forage yield suggests that NH_3 volatilization losses from urea were not a factor for early-spring applied N. However, N removal was significantly higher for NH_4NO_3 than for urea at the high N rate in both years (Table 4). It is possible that immediate availability and preferential assimilation of NO_3 by bermudagrass from NH_4NO_3 could have increased N removal relative to urea.

Burneyville (Late Summer)

Only two complete cycles of late-summer applied N data were obtained at this site. A significant response to applied N was observed for forage yield and N removed from both N sources (Table 5). Total forage yield was maximized at the 448 kg N ha^{-1} rate for NH_4NO_3 when N was applied in late summer 1994–1995 at this site (Table 5). However, yields continued to increase at higher N rates for urea. Similar to results at Ardmore, forage N removal showed slight increases at N rates in excess of that required for maximum yields (Table 5). It is important to note that forage yields were high for the first harvest following fertilization and all subsequent harvests were roughly half that obtained in late September of 1994. Total N removed at this site was much less than that removed at Ardmore in the same year (1994–1995; Tables 3 and 5) and under similar

Table 4. Analysis of variance, treatment means and single degree of freedom contrasts for forage yield, N removal and percent fertilizer recovery (difference method), early-spring applied N, Ardmore, OK, 1994 and 1995.

Source†	df	Forage yield (Mg ha^{-1}) 1994	Forage yield (Mg ha^{-1}) 1995	df	N removal (kg ha^{-1}) 1994	N removal (kg ha^{-1}) 1995	df	Fertilizer recovery (%) 1994	Fertilizer recovery (%) 1995
				Mean Squares					
Rep	2	1.6	1.1	2	1 728.1	804.1	2	322.8	499.8
Trt	7	140.4**	19.2**	7	166 690.4**	27 750.8**	5	1493.5**	498.2
Contrast									
AN linear	1	488.6**	59.2**	1	616 405.9**	105 987.9**	1	758.7	45.5
AN quadratic	1	66.3**	18.4**	1	56 108.8**	25 202.8**	1	321.6	374.3
UR linear	1	332.6**	51.9**	1	387 804.5**	52 892.2**	1	1268.4*	821.8
UR quadratic	1	98.3**	13.2**	1	100 931.0**	8 939.1**	1	613.8	22.2
AN vs. UR (over N rates)	1	6.1	1.5	1	25 398.8*	11 963.4**	1	1280.0*	361.9
Error	14	2.7	0.6	14	3 211.6	634.2	10	174.2	195.4
SED		1.4	0.6		46.3	20.6		10.8	11.4
				Treatment Means					
N rate (N source)									
0		4.29	2.83		77.7	49.8		—	—
0		4.62	3.45		89.9	62.4		—	—
112 kg ha^{-1} (AN)		9.16	5.16		192.1	108.0		96.8	46.3
672 kg ha^{-1} (AN)		17.80	8.89		511.1	280.7		63.6	33.4
1344 kg ha^{-1} (AN)		19.84	8.83		614.4	287.1		39.5	17.2
112 kg ha^{-1} (UR)		8.92	4.66		163.2	96.3		71.0	35.9
672 kg ha^{-1} (UR)		17.80	8.20		504.9	203.0		62.7	21.9
1344 kg ha^{-1} (UR)		17.29	8.33		481.6	221.9		29.6	12.3
AN (over N rates)		15.60	7.63		439.2	225.3		66.6	32.3
UR (over N rates)		14.67	7.06		383.2	173.7		54.4	23.4

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† AN, ammonium nitrate; UR, urea; SED, standard error of the difference between two equally replicated means.

climatic conditions. Differing results were in part due to one less harvest obtained at Burneyville over the same time period. Unlike late-summer cycle results at Ardmore, 1994–1995, no significant differences were observed between NH_4NO_3 and urea sources. This could be due to rainfall (25 mm) received at Burneyville soon after fertilization (within 8 h). The second late-summer cycle resulted in lower yields (half that obtained in the 1994–1995) with no yield response to applied N, but a significant linear response for N removal (Table 5). No differences were detected among the different N sources.

Table 5. Analysis of variance, treatment means and single degree of freedom contrasts for forage yield, N removal and percent fertilizer recovery (difference method), late-summer applied N, Burneyville, OK, 1994–1995 and 1995–1996.

Source†	df	Forage yield (Mg ha^{-1}) 1994–1995	Forage yield (Mg ha^{-1}) 1995–1996	df	N removal (kg ha^{-1}) 1994–1995	N removal (kg ha^{-1}) 1995–1996	df	Fertilizer recovery (%) 1994–1995	Fertilizer recovery (%) 1995–1996
				Mean Squares					
Rep	2	1.9	3.2	2	958.4	1 028.6	2	39.4	379.5
Trt	9	13.3**	2.3	9	14 515.1**	4 247.9*	7	357.9**	157.9**
Contrast									
AN linear	1	25.9**	0.2	1	35 529.8**	9 771.2*	1	1616.1**	340.9**
AN quadratic	1	7.9*	0.1	1	10 630.1**	723.4	1	328.5*	89.0
UR linear	1	50.8**	7.7	1	54 161.3**	22 291.6**	1	248.3*	361.1**
UR quadratic	1	4.5	0.2	1	5 894.9*	239.5	1	11.8	60.8
AN vs. UR (over N rates)	1	0.1	3.3	1	1 101.8	1 187.1	1	236.5*	206.7*
Error	17	1.2	2.4	17	836.1	1 242.0	13	43.5	34.2
SED		0.9	1.3		23.6	28.8		5.4	4.8
				Treatment Means					
N rate (N source)									
0		7.67	5.56		120.0	89.8		—	—
0		6.38	4.92		92.5	83.3		—	—
224 kg ha^{-1} (AN)		10.03	5.84		212.5	118.2		47.4	22.1
448 kg ha^{-1} (AN)		11.45	5.78		252.2	139.2		32.6	18.8
672 kg ha^{-1} (AN)		11.06	5.87		249.5	140.8		21.3	8.5
1344 kg ha^{-1} (AN)		12.20	5.96		288.1	170.9		13.5	7.7
224 kg ha^{-1} (UR)		9.28	6.64		161.8	130.3		24.8	29.1
448 kg ha^{-1} (UR)		10.77	5.02		229.5	120.0		27.5	21.1
672 kg ha^{-1} (UR)		11.68	7.02		251.3	168.9		21.6	17.6
1344 kg ha^{-1} (UR)		13.27	7.73		299.4	205.9		14.4	12.7
AN (over N rates)		11.19	5.86		250.6	142.3		28.7	14.3
UR (over N rates)		11.25	6.60		235.5	156.3		22.1	20.1

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† AN, ammonium nitrate; UR, urea; SED, standard error of the difference between two equally replicated means.

Burneyville (Early Spring)

In both 1994 and 1995, applied N increased forage yield and N removed for both N sources (Table 6). In general, yields peaked at the low N rate (112 kg N ha^{-1}), while significant increases in N removed were noted at the higher 672 kg N ha^{-1} rate (both 1994 and 1995). Similar to results from early-spring applied N at Ardmore, no differences were found between N sources for total forage yield or N removed in either 1994 or 1995. Unlike Ardmore, the yield increases relative to the check (no N applied) were generally small at this site (2–4 Mg ha^{-1}). Organic C and total N in the surface 0 to 15 cm were roughly two times greater at Burneyville than at Ardmore (Table 1). This may have contributed to the lower response to applied N at this site. Using Oklahoma State University soil test recommendations, P and K were roughly 80% sufficient at Burneyville and 100% at Ardmore (Table 1). The P and K fertilization rates may not, therefore, have been adequate at Burneyville, and this could be reflected in the lower production levels. Because yield levels at Burneyville never approached that found at Ardmore (similar climatic conditions), some other nutrient or growth factor, such as water holding capacity in this sandy soil, may have been controlling response.

Fertilizer Recovery

Fertilizer recoveries were generally higher for NH_4NO_3 than for urea when N rates were ≤224 kg N ha^{-1} (Tables 3 to 6). Fertilizer recoveries decreased with increased N rates for all cycles, application times, sources, and years. Higher percent fertilizer recovery for NH_4NO_3 than for urea was generally observed for late-summer and early-spring cycles at both locations, excluding the late-summer cycle at Burneyville, 1995–1996. Estimated fertilizer recovery exceeded 85% for NH_4NO_3 applied at 112 kg N ha^{-1} in early spring at Ardmore in 1994 and Burneyville in 1994 and 1995 (Tables 4 and 6). This system of bermudagrass forage harvest (four to five times per year) at preanthesis stages of growth led to unusually high recoveries. This was likely because plants were harvested prior to anthesis when gaseous plant N losses are small, but which increase significantly following anthesis (Hooker et al., 1980; Francis et al., 1993). Similarly, Altom et al. (1996) suggested that forage yield systems have improved N use efficiency, compared with grain production systems, since plants are harvested before flowering, thus avoiding potential plant N loss.

At N rates > 112 kg N ha^{-1}, fertilizer recovery decreased dramatically in early-spring cycles (Tables 4 and 6). The 112 kg N ha^{-1} rate was not included in the late-summer cycles, thus restricting comparisons at this rate. Although estimated fertilizer recovery levels were greatest at the lowest N rates (112 and 224 kg N ha^{-1} in the early spring and late summer, respectively), forage yield and N removal were doubled when applying much higher N rates (>672 kg N ha^{-1}) at the N-responsive Ardmore site.

Bermudagrass Forage NO_3–N

At Ardmore, for the late-summer and early-spring cycles (1994–1995 and 1994, respectively), bermudagrass tissue NO_3 increased significantly as a result of applying N (Fig. 1). However, this was observed only immediately following fertilization. Similar results were

Table 6. Analysis of variance, treatment means and single degree of freedom contrasts for forage yield, N removal and percent fertilizer recovery (difference method), early-spring applied N, Burneyville, OK, 1994 and 1995.

		Forage yield (Mg ha^{-1})			N removal (kg ha^{-1})			Fertilizer recovery (%)	
Source†	df	1994	1995	df	1994	1995	df	1994	1995
				Mean Squares					
Rep	2	3.9	4.1*	2	2 145.1	1 836.7	2	94.2	127.9
Trt	7	5.8*	9.3**	7	172 496.0**	19 071.2**	5	2321.0**	1706.9**
Contrast									
AN linear	1	4.8	7.7*	1	47 978.0**	37 622.0**	1	5917.1**	3783.9**
AN quadratic	1	3.4	5.0**	1	1 646.6*	5 442.5**	1	3265.0**	3112.9**
UR linear	1	20.3**	27.9**	1	56 562.6**	63 635.6**	1	802.1**	6.0
UR quadratic	1	1.1	0.1	1	406.4**	529.1	1	952.4**	116.2
AN vs. UR (over N rates)	1	1.5	0.1	1	116.2	601.9	1	668.6**	1515.6**
Error	14	1.5	1.0	14	747.2	583.6	10	33.9	90.0
SED		1.0	0.8		22.3	19.7		4.8	7.7
				Treatment Means					
N rate (N source)									
0		11.44	7.22		182.9	122.0		—	—
0		10.93	5.89		165.3	94.7		—	—
112 kg ha^{-1} (AN)		13.65	10.10		269.7	210.7		85.4	91.2
672 kg ha^{-1} (AN)		13.70	10.09		322.4	279.4		22.1	25.5
1344 kg ha^{-1} (AN)		13.09	9.22		349.7	257.7		13.1	11.1
112 kg ha^{-1} (UR)		12.16	7.32		226.3	131.4		46.6	21.0
672 kg ha^{-1} (UR)		14.90	10.55		332.2	260.2		23.5	22.7
1344 kg ha^{-1} (UR)		14.41	10.69		352.3	296.2		13.3	14.0
AN (over N rates		13.60	9.87		316.5	251.0		40.2	42.6
UR (over N rates)		13.82	9.52		303.6	229.3		27.8	19.2

*,** Significant at the 0.05 and 0.01 probability levels, respectively.
† AN, ammonium nitrate; UR, urea; SED, standard error of the difference between two equally replicated means.

observed at both locations and both years. At all fertilization rates, sources, and dates, forage NO_3–N was below the level considered toxic (2300–4500 mg kg^{-1}) for cattle consumption (Worker and Peterson, 1962, Murphy and Smith, 1967 and Wright and Davison, 1964).

CONCLUSIONS

At one of the two locations, 1344 kg N ha^{-1} as NH_4NO_3 applied in early spring, resulted in a yield of 19.8 Mg ha^{-1} and total N removed exceeded 600 kg N ha^{-1}. In general, late-summer NH_4NO_3 application resulted in increased yields, N removal, and fertilizer recovery compared with urea. Increased forage yields and N removal for NH_4NO_3 than for urea are believed to be due to increased NH_3 volatilization from urea. Although estimated fertilizer recovery levels were greatest at the low N rates (112 and 224 kg N ha^{-1} in the early spring and late summer, respectively), forage yield and N removal were doubled when applying much higher N rates (>672 kg N ha^{-1}). Nitrogen applied at 112 kg N ha^{-1} in early spring consistently resulted in fertilizer recoveries in excess of 85%, while 1344 kg N ha^{-1} resulted in <20% recovery. For the rainfed conditions evaluated in this work, fertilizer N should be applied in early spring. Late-summer applications of urea should be avoided, due to increased NH_3 volatilization losses. This work suggests that fertilizer N recoveries in excess of 85% can be achieved in bermudagrass, since forage is harvested prior to the onset of post-anthesis gaseous plant N loss, found to exist in grain cropping systems.

REFERENCES

Altom, W., J.L. Rogers, W.R. Raun, G.V. Johnson and S.L. Taylor. 1996. Long-term rye–wheat–ryegrass forage yields as affected by rate and date of N application. J. Prod. Agric. 9:510–516.

Anderson, W.B., and T.E. Kunkel. 1983. The effects of various nitrogen fertilizers on yield and N uptake of bermudagrass. p. 174–177. *In* Tex. Agric. Exp. Stn. Bull 4141.

Brejda, J.J., J.R. Brown, and C.L. Hoenshell. 1995. Indiangrass and caucasian bluestem responses to different nitrogen sources and rates in the Ozarks. J. Range Manage. 48:172–180.

Burton, G.W., J.E. Jackson, and R.H. Hart. 1963. Effects of cutting frequency and nitrogen on yield, in-vitro digestibility, and protein, fiber, and carotene content of Coastal bermudagrass. Agron. J. 55:500–502.

Crawford, R.F., W.K. Kennedy, and W.C. Johnson. 1961. Some factors that affect nitrate accumulation in forages. Agron. J. 53:159–162.

Eichhorn, M.M., Jr. 1989. Effects of fertilizer nitrogen rates and sources on Coastal bermudagrass grown on Coastal Plain soil. La. Agric. Exp. Stn. Bull. 797.

Ernst, J.W., and H.F. Massey. 1960. The effects of several factors on volatilization of ammonia formed from urea in the soil. Soil Sci. Soc. Am. Proc. 24:87–90.

Fisher, F.L., and A.G. Caldwell. 1959. The effects of continued use of heavy rates of fertilizers on forage production and quality of Coastal bermudagrass. Agron. J. 51:99–102.

Francis, D.D., J.S. Schepers, and M.F. Vigil. 1993. Post-anthesis nitrogen loss from corn. Agron. J. 85:659–663.

Hanson, C.L., J.F. Power, and C.J. Erickson. 1978. Forage yield and fertilizer recovery by three irrigated perennial grasses as affected by N fertilization. Agron. J. 70:373–375.

Hooker, M.L., D.H. Sander, G.A. Peterson, and L.A. Daigger. 1980. Gaseous N losses from winter wheat. 72:789–792.

Lachat Instruments. 1989. Quickchem method 12-107-04-1-B. Lachat Instr., Milwaukee, WI.

Lovelace, D.A., E.C. Holt, and W.B. Anderson. 1968. Nitrate and nutrient accumulation in two varieties of bermudagrass [*Cynodon dactylon* (L.) Pers.] as influenced by soil applied fertilizer nutrients. Agron. J. 60:551–554.

Mathias, E.L., O.L. Bennett, and P.E. Lundberg. 1973. Effect of rate of nitrogen on yield, nitrogen use, and winter survival of Midland bermudagrass [*Cynodon dactylon* (L.) Pers.] in Appalachia. Agron. J. 65:67–68.

Mathias, E.L., O.L. Bennett, and P.E. Lundberg. 1978. Fertilization effects on yield and N concentration of Midland bermudagrass. Agron. J. 70:973–976.

May, M.L., J.M. Phillips, and G.L. Cloud. 1990. Drought-induced accumulation of nitrate in grain sorghum. J. Prod. Agric. 3:238–241.

Morris, H.D., and J.F. Celecia. 1962. Effect of time of fertilizer application on yield and nutrient uptake of Coastal bermudagrass on Cecil sandy loam. Agron. J. 54:335–338.

Murphy, L.S., and G.E. Smith. 1967. Nitrate accumulation in forage crops. Agron. J. 59:171–174.

Overman, A.R., C.R. Neff, S.R. Wilkinson and F.G. Martin. 1990. Water, harvest interval, and applied nitrogen effects on forage yield of bermudagrass and bahiagrass. Agron. J. 82:1011–1016.

Overman, A.R., and S.R. Wilkinson. 1992. Approach of yield response curves to steady state. Commun. Soil Sci. Plant Anal. 23:761–768.

Prine, G.M., and G.W. Burton. 1956. The effect of nitrogen rate and clipping frequency upon the yield, protein content and certain morphological characteristics of a Coastal bermudagrass [*Cynodon dactylon* (L.) Pers.]. Agron. J. 48:296–301.

Power, J.F. 1980. Response of semiarid grassland sites to nitrogen fertilization: II. fertilizer recovery. Soil Sci. Soc. Am. J. 44:550–555.

Rasmussen, P.E., and C.R. Rohde. 1991. Tillage, soil depth, and precipitation effects on wheat response to nitrogen. Soil Sci. Soc. Am. J. 55:121–124.

SAS Institute. 1988. SAS/STAT procedures. Release 6.03 ed. SAS Inst., Cary, NC.

Schepers, J.S., D.D. Francis, and M.T. Thompson. 1989. Simultaneous determination of total C, total N and ^{15}N on soil and plant material. Commun. Soil Sci. Plant Anal. 20:949–959.

Staley, T.E., W.L. Stout, and G.A. Jung. 1991. Nitrogen use by tall fescue and switchgrass on acidic soils of varying water holding capacity. Agron. J. 83:732–738.

Walker, M.E., T.C. Keisling, and W.H. Marchant. 1979. A comparison of solid and liquid fertilizer for Coastal bermudagrass hay production. Soil Sci. Soc. Am. J. 43:597–601.

West, C.P. 1990. A proposed growth stage system for bermudagrass. p. 38–42. *In* Proc. Am. Forage and Grassl. Conf., Blacksburg, VA. 6–9 June 1990. AFGC, Georgetown, TX.

Westerman, R.L. J.O. O'Hanlon, G.L. Fox, and D.L. Minter. 1983. Nitrogen fertilizer efficiency in bermudagrass production. Soil Sci. Soc. Am. J. 47:810–817.

Wiedenfeld, R.P. 1988. Coastal bermudagrass and Renner lovegrass fertilization responses in a subtropical climate. J. Range Manage. 41:7–12.

Wilkinson, S.R., and G.W. Langdale. 1974. Fertility needs of the warm-season grasses. p. 119–145. *In* D.A. Mays (ed.) Forage fertilization. ASA, CSSA and, SSSA, Madison, WI.

Worker, G.F., Jr., and M.L. Peterson. 1962. Nitrogen fertilizer effects on yield and composition of Coastal bermudagrass forage. Calif. Agric. 16(11):14.

Wright, M.J., and K.L. Davison. 1964. Nitrate accumulation in crops and nitrate poisoning in animals. Adv. Agron. 16:197–217.

Wuest, S.B., and K.G. Cassman. 1992. Fertilizer-nitrogen use efficiency of irrigated wheat: I. uptake efficiency of preplant versus late-season application. Agron. J. 84:682–688.