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Alfalfa Yield Response to Nitrogen Applied After Each Cutting

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ABSTRACT

Although alfalfa (*Medicago sativa* L.) usually obtains a high percentage of its required N via symbiotic N fixation, additional fertilizer N applied once in the spring can increase forage yields. However, little is known about alfalfa yield response to low N rates (<50 kg N ha^{-1}) immediately following each cutting. Low N rates (immediately following each cutting) were evaluated for total alfalfa dry matter production on a Grant silt loam (fine-silty, mixed, thermic, Udic Argiustoll). This nonirrigated experiment was initiated on a 2-yr-old alfalfa stand where sufficient P and K had been applied. Nitrogen rates of 11, 22, and 44 kg N ha^{-1} were applied immediately following each cutting for 5 yr (4–5 cuttings yr^{-1}). After 5 yr of continuous N application, no differences in soil NH_4–N or NO_3–N were found at depths >15 cm (0- to 240-cm sampling depth). In 1994, total alfalfa dry matter yield (sum of five harvests) increased 1.29 Mg ha^{-1} from a total annual N application of 110 kg N ha^{-1} (22 kg N ha^{-1} following each cutting). Total forage N decreased from the second to the fifth harvest in most years. By-harvest dry matter yield increases due to applied N were only found in late-season harvests, consistent with late-season decreased N_2-fixing capacity in alfalfa documented by others.

Nutrient use efficiency has been investigated in alfalfa production systems for many of the essential macro- and microelements. However, except for investigating N needs for stand establishment, these studies have not examined in-season applied N following each harvest on established stands.

Woodhouse and Griffith (1975) found that fertilizer N applied to legumes was not beneficial. They noted that applied N tends to cause N-fixing bacteria to cease fixation and may then replace, rather than supplement, the N that normally would be fixed. Similar results were reported by Markus and Battle (1965). Alternative work by Fishbeck and Phillips (1981) concluded that Rhizobium symbiosis cannot produce sufficient reduced N for optimum alfalfa growth during stand establishment, because N fertilization increased yields and N percentage in the first two regrowth cycles while having no benefit at later stages.

Increased alfalfa yield from applied fertilizer N has been observed under irrigation and simulated-irrigation conditions (Fishbeck and Phillips, 1981; Feigenbaum and Hadas, 1980) and in nonirrigated environments (Schertz and Miller, 1972; Nutall, 1985; Eardly et al., 1985). A comprehensive review by Hannaway and Shuler (1993) reported that fertilizer N applied at planting can increase yields when soils are low in N (<15 mg kg^{-1} NO_3) or organic matter (<15 g kg^{-1}).

Recently, Lamb et al. (1995) showed that in spite of fertilizer N application of up to 840 kg ha^{-1}, biological N fixation (BNF) in alfalfa continued to take place, and that alfalfa obtained 20 to 25% of its N from BNF. In a cool northern climate, Nuttall (1985) found that a single N application (45 kg N ha^{-1}) in early spring significantly increased alfalfa dry matter production when compared with the check (no N application), but that this practice was not economical. Feigenbaum and Ha-

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Abbreviations: BNF, biological nitrogen fixation; NUE, N use efficiency; SED, standard error of the difference between two equally replicated means.

Table 1. Surface (0–15 cm) soil test characteristics of a fine-silty, mixed, thermic, Udic Argiustoll prior to treatment establishment (1992), and after 5 yr of N applied to alfalfa in Lahoma, OK.

	1992	1996					
	Composite	0	11	22	44	22+Lime	SED
		N applied, kg cutting^{-1} ha^{-1}					
pH†	7.2	6.73	6.75	6.52	6.38	6.60	0.14
Total N, g kg^{-1}‡	0.96	0.67	0.69	0.63	0.79	0.78	0.09
Organic C, g kg^{-1}‡	9.51	8.53	8.25	7.70	9.29	8.94	0.72
NH_4–N, mg kg^{-1}§	15	8	10	8	22	6	4.9
NO_3–N, mg kg^{-1}§	16	16	19	8	19	18	5.3
P, mg kg^{-1}¶	49	18	21	15	27	16	4.2
K, mg kg^{-1}¶	236	165	151	141	192	156	20

† 1:1 soil/water.
‡ Dry combustion.
§ 2 *M* KCl extraction.
¶ Mehlich III.
SED is standard error of the difference between two equally replicated treatment means.

das (1980) showed that 100 kg N ha^{-1} as ammonium sulfate applied after the first cutting in the spring increased alfalfa yields. This same work also found that fertilizer N recovery was greatest in the first two cuttings, in an arid environment using supplemental irrigation. Kunelius (1974) found that N applied at seeding increased first but not second cutting yields, and increased weed growth in trials conducted near Charlottetown, Prince Edward Island, Canada.

Daliparthy et al. (1995) found that dairy manure can be applied to alfalfa immediately after the first cutting in June (Massachusetts) at rates ranging between 112 and 336 kg N ha^{-1} without any adverse effects on herbage yield or weed incidence and with no economic risk to productivity. Goss and Stewart (1979) found that feedlot manure had a higher P utilization efficiency than superphosphate; however, they did not consider the N contributions from manure on alfalfa yield and did not report total protein content in the alfalfa forage. Application of N fertilizer to alfalfa as ammonium nitrate or dairy manure at a rate of 112 kg N ha^{-1} yr^{-1} had no effect on dry matter yields, N accumulation in herbage, or soil NO_3–N at depths of 0 to 15, 25 to 50, and 50 to 100 cm in Massachusetts (Daliparthy et al., 1994). However, increased soil water NO_3–N concentrations were observed when a rate of 336 kg N ha^{-1} yr^{-1} was applied compared with the check (no N application), thus having the potential to adversely effect water quality.

One-time N applications up to 224 kg N ha^{-1} did not increase soil profile NO_3–N in alfalfa; therefore, alfalfa was considered to have a value in a rotation for reducing soil profile NO_3–N, which can accumulate in continuous corn (*Zea mays* L.) (Schertz and Miller, 1972). Campbell et al. (1994) noted that deep-rooted forage crops such as alfalfa can remove NO_3–N and water to a depth of 2.4 m. They also reported that considerable NO_3–N leaching can occur, especially if legume plowdown is followed by a fallow period, when N mineralization increases with increased soil moisture storage in fallow systems. Blumenthal and Russelle (1996) showed that non-N_2-fixing alfalfa cultivars would be more useful for bioremediation of NO_3-contaminated sites.

The rationale for this work is that favorable growing conditions immediately following harvest may create a growth potential and N requirement by the plants in excess of the N-supplying capacity of *Rhizobium meliloti*. The objectives of this experiment were (i) to evaluate the effect of applying low rates of N (11–44 kg N ha^{-1}) following each cutting on alfalfa dry matter production and forage N removed, and (ii) to characterize soil profile inorganic N accumulation following long-term N applications in a perennial legume production system.

Table 2. Harvest, soil sampling dates, and rainfall received from 1992 to 1996, Lahoma, OK.

Year	Harvest date	Rainfall	Average yield
		mm†	Mg ha^{-1}
1992	June 18	–	1.27
1992	July 22	203	2.54
1992	August 17	96	1.95
1992	September 28	60	1.62
1993	May 14		3.38
1993	June 17	70	1.31
1993	July 20	260	0.99
1993	August 25	25	1.56
1993*	October 5	58	1.69
1994	May 17	–	5.04
1994	June 13	122	2.02
1994	July 13	5	1.38
1994*	August 12	70	2.87
1994	September 16	121-hail‡	1.63
1995	May 11	–	2.33
1995	June 19	262	3.62
1995	July 26	138	2.34
1995	August 29	221	2.42
1995*	October 6	82	1.04
1996	May 16	–	1.71
1996	June 13	62	1.95
1996	July 16	115	1.75
1996	August 28	234	2.48
1996	November 13	245	1.11

* By-harvest increase in alfalfa dry matter yield as a result of applying N significant at the 0.05 probability level.
† Rainfall since last consecutive summer harvest.
‡ Hail = hail damage observed on all plots.

MATERIALS AND METHODS

A field experiment was initiated on a Grant silt loam to evaluate applications of low N rates applied immediately following each cutting on total alfalfa dry matter production. The experimental area (North Central Research Station near Lahoma, OK) was selected from a weed-free 2-yr-old alfalfa stand where sufficient P and K had been applied. Initial soil test analyses from a composite surface (0–15 cm) sample col-

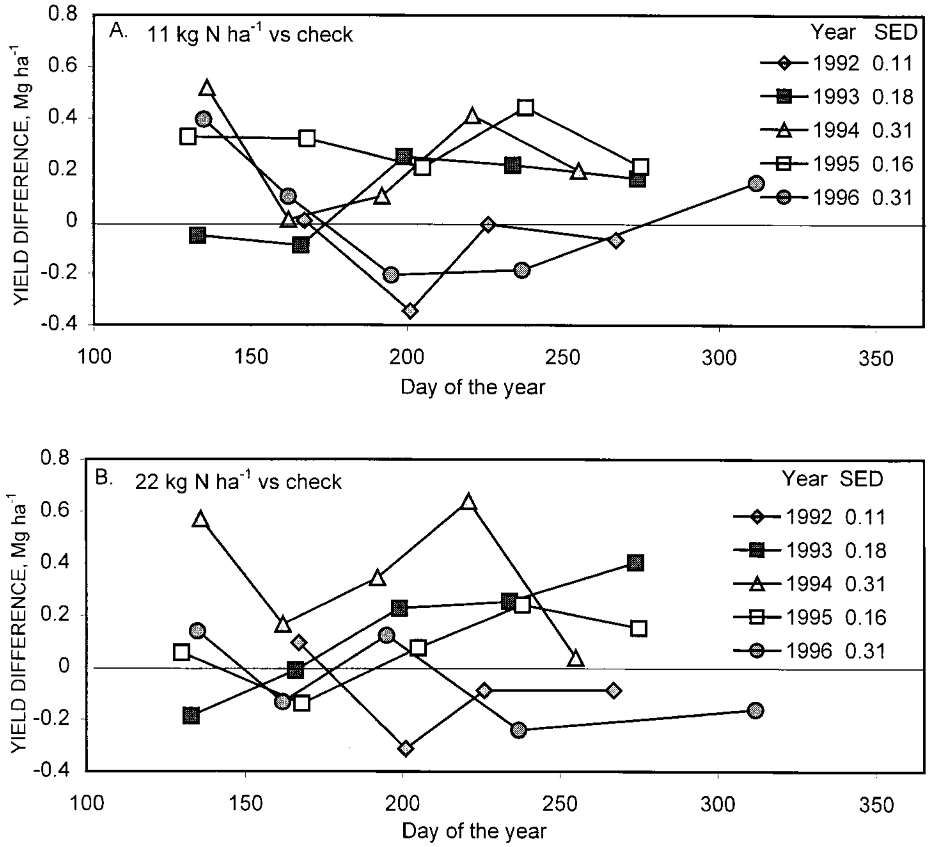

Fig. 1. By-harvest alfalfa dry matter yield differences for treatments receiving (A) 11 or (B) 22 kg N ha^{-1} following each harvest compared with the check (no N application), for 24 harvests from 1992 to 1996 in Lahoma, OK. SED is standard error of the difference between two equally replicated means.

lected from the entire experimental area (16 May 1992) prior to treatment establishment is reported in Table 1. Rates of 11, 22, and 44 kg N ha^{-1} were applied following each cutting from 1992 to 1996 (total of 24 cuttings), excluding the final harvest of 1992 on September 28 when no fertilizer was applied following harvest. Nitrogen was applied as ammonium nitrate (34-0-0, N-P-K). Check (no N application) and 22 kg N ha^{-1} plus 4480 kg dolomitic limestone ha^{-1} treatments (lime only applied once at the start of the experiment) were included within a randomized complete block design with four replications. Plots were 4.9 m wide by 15 m long. For each harvest date, alfalfa was cut 5 cm above the ground using a John Deere GT262 garden tractor with a 96-cm deck that was modified for forage collection. Harvest area from each plot was 5.8 m^2, from which total biomass was weighed and subsampled for moisture and total N analysis. Harvest and fertilization dates for the years the study was conducted are reported in Table 2. Alfalfa yields were determined on a dry weight basis. For each harvest, alfalfa forage samples were ground to pass a 0.125-mm sieve (120 mesh) and analyzed for total N using a Carlo-Erba (Milan, Italy) NA-1500 dry combustion analyzer (Schepers et al., 1989). Total N removal was calculated by multiplying dry matter yield by forage N content.

Because we were interested in annual production, analysis of variance was performed on the sum of dry matter production and total N removed for each year. By-harvest analysis of variance within years (harvest, split-in-time) was used for specific by-harvest data reported in Fig. 1 and 2. Significance of specific treatment comparisons was determined using nonorthogonal contrasts. The standard error of the difference (SED) between two equally replicated treatment means is reported in Tables 1, 3, and 4, and Fig. 1, 2, and 3. 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).

Following the final harvest in 1996, two soil cores 4.5 cm in diameter were taken to a depth of 240 cm from each plot and divided into increments of 0 to 15, 15 to 30, 30 to 45, 45 to 60, 60 to 90, 90 to 120, 120 to 150, 150 to 180, 180 to 210, and 210 to 240 cm. Samples were air dried at ambient temperature and ground to pass a 0.075-mm sieve (200 mesh). Samples were extracted using 2 *M* KCl (Bremner, 1965) and analyzed for NH_4–N and NO_3–N using an automated flow injection analysis system (Lachat Instruments, 1989, 1990). Accumulation of NH_4–N and NO_3–N was determined on the mean of the two cores after concentration was converted to kilograms per hectare based on measured bulk density to a depth of 240 cm. Total soil N and organic C were determined using a Carlo-Erba NA 1500 dry combustion analyzer (Schepers et al., 1989). Apparent N use efficiency (NUE) was determined by subtracting the total sum of forage N removed during 5 yr in the check plot (no N application) from N removal in plots receiving additional N and dividing by the total amount of N applied during 5 yr.

RESULTS

Rainfall from 1992 to 1996 was generally higher than normal for this site located in a region where dryland continuous winter wheat (*Triticum aestivum* L.) is the common crop. Average annual rainfall at this site is 794

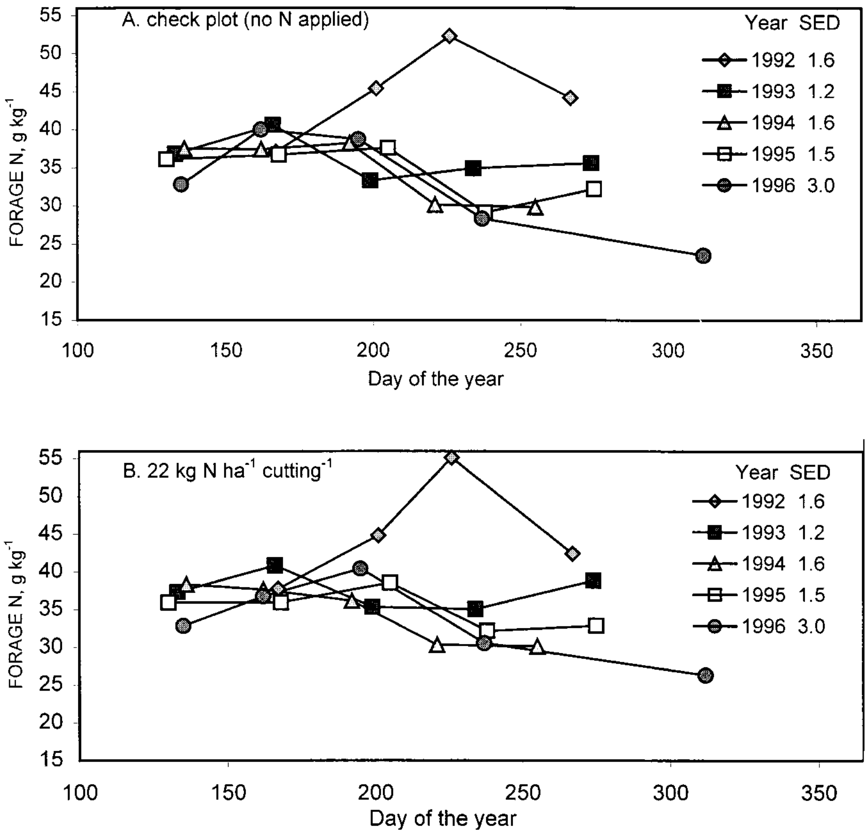

Fig. 2. By-harvest alfalfa forage N in (A) the check plot (no N application) and (B) the 22 kg N ha^{-1} treatment, for 24 harvests from 1992 to 1996 in Lahoma, OK. SED is standard error of the difference between two equally replicated means.

mm, and the majority of the total (527 mm) is received during the growing season months of May to October. During the course of this experiment, rainfall departure-from-normal values for May through October were +2, +66, −63, +191, and +147 mm for 1992, 1993, 1994, 1995, and 1996, respectively.

Analysis of variance for total alfalfa dry matter yield and N removed by yr (4 to 5 harvests yr^{-1}) is reported in Table 3. The main effect of treatment was not significant from 1992 to 1995. This is evident in the small differences in total by-yr yield and N removed means (Table 3). However, a significant quadratic response to applied N was detected in the single-degree-of-freedom nonorthogonal contrast in 1994. Across the five harvests in 1994, a yield increase of 1.29 Mg ha^{-1} was observed when comparing the 22 kg N ha^{-1} treatment to the check where no N was applied (Table 3). In general, the 44 kg N ha^{-1} cutting^{-1} rate tended to result in somewhat lower yields and N removed when compared with the 11 and 22 kg N ha^{-1} cutting^{-1} rates (Table 3).

Table 3. Analysis of variance by year and treatment means on total alfalfa dry matter yield and total N removed, 1992 to 1996, Lahoma, OK.

Treatment	df	1992		1993		1994		1995		1996	
		Yield	N Removed	Yield	N Removed	Yield	N Removed	Yield	N Removed	Yield	N Removed
		Mg ha^{-1}									
Check (no N)		7.45	0.352	8.62	0.316	12.54	0.423	11.04	0.388	9.50	0.319
11 kg N ha^{-1}		7.32	0.328	9.16	0.342	12.88	0.455	12.56	0.443	9.76	0.321
22 kg N ha^{-1}		7.35	0.335	9.35	0.351	13.83	0.488	11.42	0.405	9.22	0.313
44 kg N ha^{-1}		7.42	0.332	8.93	0.329	12.53	0.455	11.39	0.404	8.44	0.296
22 kg N ha^{-1} + Lime‡		7.15	0.330	8.63	0.322	13.06	0.468	12.34	0.443	8.05	0.281
SED§		0.26	0.011	0.42	0.018	0.84	0.036	0.97	0.044	0.51	0.019
Source of variation		Mean squares									
Rep	3	0.447	0.00112	0.165	0.00018	3.718	0.00709	3.017	0.00517	16.641**	0.01988*
Treatment	4	0.190	0.00039	0.385	0.00082	1.766	0.00226	1.739	0.00252	2.081*	0.00111
Error	12	0.144	0.00025	0.360	0.00067	1.442	0.00267	1.913	0.00381	0.511	0.00069
N rate linear	1	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
N rate quadratic	1	NS	NS	NS	†	†	NS	NS	NS	NS	NS
11 and 22 vs. 44	1	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
22 vs. 22 + Lime‡	1	NS	NS	†	NS	NS	NS	NS	NS	*	NS

†, *, ** Significant the the 0.10, 0.05, and 0.01 levels of probability, respectively; NS is not significant.
‡ 4480 kg ha^{-1} dolomitic limestone applied following the first cutting.
§ SED is standard error of the difference between two equally replicated means.
¶ Mean squares not followed by a symbol are not significant.

Table 4. Analysis of variance and treatment means on total alfalfa dry matter yield, total N removed, and estimated N use efficiency (NUE), 1992 to 1996, Lahoma, OK.

Treatment	df	Total N applied	Yield	N Removed	NUE‡
		————	Mg ha^{-1}	————	%
Check, (no N)		0	49.02	1.798	–
11 kg N ha^{-1}		0.253	50.48	1.845	18.6
22 kg N ha^{-1}		0.506	51.16	1.891	18.4
44 kg N ha^{-1}		1.012	48.72	1.817	1.9
22 kg N ha^{-1} + Lime‡		0.506	49.23	1.845	9.3
SED§			2.34	0.103	12.6
Source of variation				Mean square	
Rep	3		41.70*	0.0613†	1620
Treatment	4		5.39	0.0055	2900
Error	12		10.92	0.0214	320
N rate linear	1		NS	NS	NS
N rate quadratic	1		NS	NS	NS
11 and 22 vs. 44	1		NS	NS	NS
22 vs. 22 + Lime‡	1		NS	NS	NS

†, *, ** Significant the the 0.10, 0.05, and 0.01 levels of probability, respectively; NS is not significant.
‡ 4480 kg ha^{-1} dolomitic limestone applied following the first cutting.
§ SED is standard error of the difference between two equally replicated means.
¶ Mean squares not followed by a symbol are not significant.

Total yield and N removed were greater in 1994 than in the other 4 yr. Demand for N was therefore expected to be greater during this year. Timely but not excessive rainfall and the lack of excessively high temperatures from July to August presumably contributed to increased yields and a significant N response. In 1996, a significant depression in alfalfa yield was found from applied N. Although soil pH declined significantly from 1992 to 1996, and pH decreased with increasing rates of applied N, soil pH levels remained above the 6.0 that is considered suitable for alfalfa production (Table 1). Soil test P and K declined during the 5-yr period, were not affected by treatment, and remained above 85 and 100% sufficiency at the end of the experiment, respectively (Johnson et al., 1997).

Alfalfa dry matter yield and N removed during the entire 5-yr period are reported in Table 4 along with analysis of variance. Differences in total N removed by year were generally small. Treatment differences for alfalfa protein were very similar to results reported for total N removed (data not reported). When evaluated across the 5-yr period, as would interest alfalfa producers, no significant treatment differences in either yield or N removed were apparent. Estimated N use efficiencies were all <18.6% (Table 4).

The application of dolomitic limestone (4480 kg ha^{-1}) did not produce a significant response in yield or N removal (Tables 3 and 4). This treatment was evaluated based on work by Fenn et al. (1991) that reported increased ammonium absorption with increased Ca supply even on calcareous soils. Similarly, the initial soil pH was relatively high (7.2) at this site although no significant response was found either by harvest or across years.

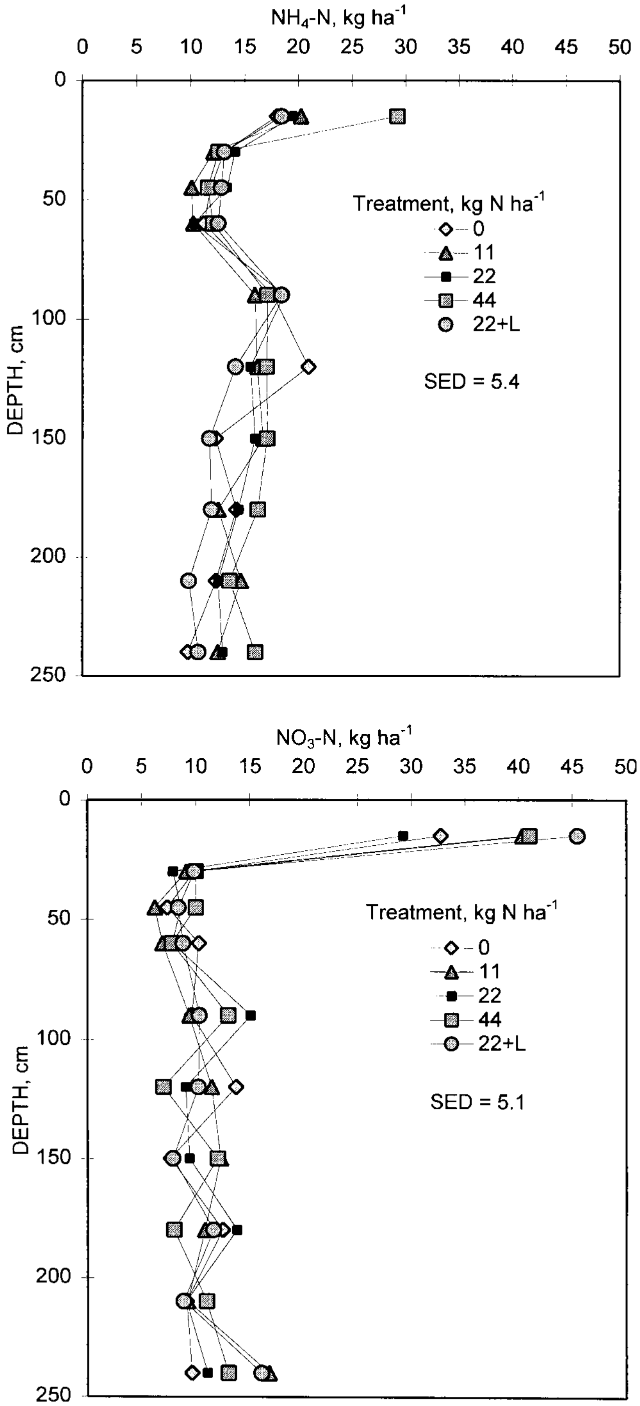

Fig. 3. Soil NH_4–N and NO_3–N per profile increment as a function of N applied, following 5 yr of applied N after each cutting in a continuous alfalfa production experiment in Lahoma, OK. SED is standard error of the difference between two equally replicated means.

By-Harvest Yield Differences

Significant yield increases as a result of applying N immediately following harvest were detected only on three of the 24 harvest dates (Fig. 1 and Table 2). These took place on 5 Oct. 1993 (22 kg N ha^{-1}), 12 Aug. 1994 (11 and 22 kg N ha^{-1}), and 6 Oct. 1995 (11 and 22 kg N ha^{-1}). For these three dates, yield increases (percentage of check yield) ranged from 17 to 26%. These increases all took place in either the last or second-to-last harvest. This was consistent with work by Jenkins and Bottomley (1984) who demonstrated that the number of effective nodules in alfalfa plants declined from the first to the third harvest, suggesting the possible need for added N later in the season. Response to added fertilizer N observed by Jenkins and Bottomley (1984) took place in the third and final harvest. For the growing periods encompassing the three dates where we observed significant increases in yield, rainfall received since the previous cutting ranged between 58 and 82 mm and was generally evenly distributed across the 30- to 40-d growing periods. For some of the growing periods, much higher than normal rainfall (> 200 mm) was received during relatively short periods of time (Table 2). Although single-harvest yield increases in excess of 0.4 Mg ha^{-1} were observed on several dates, treatment variability was high, thus reducing the number of significant responses (Fig. 1).

Using \$0.11 kg^{-1} of alfalfa (\$100 ton^{-1}), \$0.62 kg^{-1} of N as 34-0-0 (\$190 ton^{-1}), and \$2.00 application cost per cutting (23 total applications), applying 11 kg N ha^{-1} following each cutting resulted in a net loss of \$42 ha^{-1}. Similarly, applying 22 kg N ha^{-1} following each cutting would have resulted in a net loss of \$125 ha^{-1} for the 5-yr period.

Total Forage Nitrogen

Total forage N in the check plot (no N applied) and the 22 kg N ha^{-1} treatment is reported by harvest and year in Fig. 2a and 2b, respectively. Excluding the first year of the study, forage N tended to decline from the second to the fifth harvest. This paralleled work by Jenkins and Bottomley (1984), who found decreased tissue N and effective nodules with advancing harvest. They attributed this to a seasonal decline in the N_2-fixing capacity of the alfalfa plants. Also, similar to the work of Jenkins and Bottomley (1984), the three significant yield increases as a result of applying N reported here took place in either the last or second to last harvest.

Soil Profile Inorganic Nitrogen Accumulation

Soil profile accumulations of NH_4–N and NO_3–N following 5 yr of alfalfa production where N was applied following each cutting are illustrated in Fig. 3. Surface (0–15 cm) NO_3–N levels in plots receiving additional N generally were higher compared with the check. Surface NH_4–N levels were significantly higher where 44 kg N ha^{-1} had been applied following each harvest, but no differences were detected when compared with the check for the lower N rates. No significant differences among treatments were found for NH_4–N or NO_3–N at depths >15 cm. Although there were significant treatment differences in surface NH_4–N and NO_3–N, neither exceeded 50 kg ha^{-1}, which indicates that these amounts were apparently residual from the last 1 to 2 yr.

DISCUSSION AND CONCLUSIONS

For this 5-yr study, total fertilizer N applied to alfalfa exceeded 1.0 Mg N ha^{-1}, for the 44 kg N ha^{-1} cutting^{-1} treatment (Table 4). Because total alfalfa forage N removed was similar in plots with or without added fertilizer N, and no increase in soil profile inorganic N accumulation was observed, the soil–plant system was apparently able to compensate for the surplus N. If increased subsoil inorganic N accumulation were an indicator of increased risk for NO_3–N leaching (Westerman et al., 1994), applied fertilizer N in this nonirrigated alfalfa experiment cannot be considered to increase leaching risk. Soil–plant buffering was proposed by Johnson and Raun (1995) to explain why limited amounts of inorganic N were found in soil profiles of long-term wheat experiments, even when N rates exceeded that required for maximum yield. Their work documented the fates of inorganic N that can take place before leaching (storage in soil organic matter, removal by increased plant uptake and gaseous N loss from soil and plants) and that buffer against accumulation of soil profile inorganic N. Lamb et al. (1995) found that BNF in alfalfa declined with increasing N fertilization, but that BNF was not reduced to zero, even with high N fertilization. Because no increase in soil profile inorganic N accumulation was observed in this study (Fig. 3), BNF probably was lower in plots receiving additional fertilizer N, especially since total N removed was similar for fertilized and unfertilized plots. Increased total N in the surface (0–15 cm) horizon was evident at the 44 kg N ha^{-1} rate (Table 1); however, no differences in total N were noted at depths >15 cm (data not reported). Decreased BNF as a result of adding fertilizer N is yet another buffering mechanism in a legume production system, and this helps explain why no observed increase in soil profile inorganic N accumulation was found.

This work suggests that low N rates can be applied to alfalfa following each cutting without increasing the risk of subsurface NO_3–N accumulation. In our work, increased yields due to applied N were found in either the last or second to last harvest. This agrees with work by Jenkins and Bottomley (1984) that suggested a seasonal decline in N_2-fixing capacity and forage tissue N in alfalfa. We speculate that the potential benefits of applying low N rates in alfalfa will take place in later harvests and in arid, irrigated systems with high yield potential and good water management.

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