Journal of Plant Nutrition

ISSN: 0190-4167 (Print) 1532-4087 (Online) Journal homepage: http://www.tandfonline.com/loi/lpla20

# Winter wheat fertilizer nitrogen use efficiency in grain and forage production systems

**W. E. Thomason , W. R. Raun & G. V. Johnson**

**To cite this article:** W. E. Thomason , W. R. Raun & G. V. Johnson (2000) Winter wheat fertilizer nitrogen use efficiency in grain and forage production systems, Journal of Plant Nutrition, 23:10, 1505-1516, DOI: 10.1080/01904160009382118

**To link to this article:** http://dx.doi.org/10.1080/01904160009382118

Published online: 21 Nov 2008.

JOURNAL OF PLANT NUTRITION, 23(10), 1505–1516 (2000)

# Winter Wheat Fertilizer Nitrogen Use Efficiency in Grain and Forage Production Systems



**W. E. Thomason, W. R. Raun,[1] and G. V. Johnson**

*Department of Plant and Soil Sciences, 165 Agricultural Hall, Oklahoma State University, Stillwater, OK 74078*

**ABSTRACT**

Nitrogen use efficiency (NUE) is known to be less than fifty percent in winter wheat grain production systems. This study was conducted to determine potential differences in NUE when winter wheat (*Triticum aestivum* L.) is grown strictly for forage or grain. The effects of different nitrogen rates on plant N concentrations at different growth stages and on grain yield were investigated in two existing long-term winter wheat experiments near Stillwater (Experiment 222) and Lahoma (Experiment 502), OK. At both locations in all years, total N uptake was greater when wheat forage was harvested twice (Feekes 6 and flowering) compared to total N uptake when wheat was grown only for grain. Percent N content immediately following flowering was much lower compared to percent N in the forage harvested prior to flowering, indicating relatively large losses of N after flowering. Averaged over locations and years, at the 90 kg N ha$^{-1}$ rate, wheat produced for forage had much higher NUE (82%) compared with grain production

[1]Corresponding author (e-mail address: wrr@mail.pss.okstate.edu).

systems (30%). While gaseous N loss was not measured in this trial, the higher NUE values found in the forage production systems were attributed to harvesting prior to anthesis and the time when plant N losses are known to be greater.

## INTRODUCTION

Nitrogen use efficiency is important when discussing fertilizer applications and plant growth. Two principal components of NUE are efficiency of uptake and efficiency of N utilization to produce grain or forage (Moll et al., 1982). Nitrogen use efficiency is influenced by nitrification rate of the soil, form of N applied, growth stage of the plant, and weather. Farmers desire to apply N at the ideal time and using the fertilization method that will optimize efficiency. Environmentally, it is important to know how much fertilizer is used by the plant and how much is lost. Scientifically, it is important to understand the processes and storage methods for N and other nutrients.

Nitrogen content varies with the growth stage of the plant (Wuest and Cassman, 1992). Gaseous plant N loss has been found to be significant from flowering to physiological maturity (Harper et al., 1987). Recent work has found that the total N content in the grain and straw is not equal to total N content of plants at flowering (Harper et al., 1987). Fertilizer N use efficiency, as reflected in grain yield of winter wheat, has also been shown to change with time and rate of application (Ellen and Spiertz, 1980). Nitrogen use efficiency varies with different genotypes of winter wheat, a result of gaseous plant N loss from flowering to physiological maturity that was estimated to range between 4 and 28 kg N $ha^{-1}$ (Kanampiu et al., 1997). Work with winter wheat has shown that high N concentrations in plants at flowering are associated with increased plant N loss (Parton et al., 1988). Many authors have noted that grain yield and N content of cereal grain crops increase significantly with applied N (Simonis, 1987; Raun and Johnson, 1995). However, the higher N rates generally result in decreased NUE values. Harper et al. (1987) found that much of the loss of fertilizer N is due to gaseous loss from plants at senescence. At flowering, N is translocated to the grain causing gaseous N losses to increase and efficiency to decrease (Harper et al., 1987). O'Deen (1989) detected volatile ammonia emissions from winter wheat and attributed the source of ammonia to the decomposition of protein during translocation from the leaf to the seed. Similar work by Bruno et al. (1987) indicated that NUE decreases at grain fill in cereals, mostly due to gaseous N loss. Whitehead (1995) found that N concentration in the plant tends to decrease as plants age, mostly due to the increase in cell wall material and decrease in cytoplasm.

In the south central United States, producers often use winter wheat as a forage crop for cattle and also for grain production. The period of winter growth and the relatively high N content of winter wheat make it a good forage crop for ruminant grazing. However, it should be noted that the NUE in livestock production is generally much lower (usually less the 20%) due to inefficiency of conversion and harvest (Van der Ploeg et al., 1997). Whitehead (1995) suggested that forage production systems are more efficient users of N than grain production systems because harvest before maturity prevents loss of volatile ammonia. Many research sources are available discussing NUE in either forage or grain production systems, but there is little information comparing forage-only versus grain-only production systems for the same crop. The objective of this experiment was to determine potential differences in NUE when winter wheat is grown strictly for either forage or grain.



## MATERIALS AND METHODS

Experimental sites were selected as sub-plots in two existing long-term winter wheat experiments near Stillwater (Experiment 222) and Lahoma (Experiment 502), OK, where N rates have been applied annually since 1969 and 1970, respectively. Both experiments employed randomized complete block experimental designs with four replications. Plots were 6.1x18.3 and 4.9x18.3 m at 222 and 502, respectively. At both sites, N has been applied preplant and incorporated utilizing a conventional tillage system. Nitrogen rates were 0, 45, 90, and 134 kg N $ha^{-1}$ $yr^{-1}$ at Stillwater and 0, 45, 67, 90, and 112 kg N $ha^{-1}$ $yr^{-1}$ at Lahoma. Ammonium nitrate (34-0-0) was applied broadcast and incorporated preplant at both sites. Phosphorus (P) and potassium (K) as triple superphosphate (0-46-0) and potassium chloride (0-0-62) were applied with the N each year at rates of 29 and 20 kg P $ha^{-1}$ and 38 and 56 kg K $ha^{-1}$ at Stillwater and Lahoma, respectively. Initial soil test data taken from the check plots is shown in Table 1. In all years, forage sub-plots (1.44-2.08 $m^2$) were hand harvested at Feekes growth stages 6 and again from the same area at Feekes 10 (Large, 1954). Grain was harvested from sub-plots, adjacent to forage sub-plots, with a combine from an area of 3.66 $m^2$. Forage and grain samples were dried and ground to pass a 140 mesh sieve (100 μm) and analyzed for total N content using a Carlo-Erba NA 1500 automated dry combustion analyzer (Schepers et al., 1989). Total N uptake in the forage was determined by multiplying N content and dry matter yield for both harvests taken from the same area. Grain N uptake was determined by multiplying dry matter grain yield and grain total N. Nitrogen use efficiency was determined as N uptake in N treated plots minus N uptake from the check (0-kg N applied) divided by the applied N rate. Fertilizer applications, planting and harvest dates are reported in Table 2.

## RESULTS AND DISCUSSION

Analyses of variance and associated means for total forage yield and N uptake, grain yield, and grain N uptake are reported in Tables 3-10 for Stillwater and

TABLE 1. Surface soil (0-15cm) chemical characteristics and classification at Stillwater (Experiment 222) and Lahoma, (Experiment 502) OK in check plots, 1995.

| Location | pH[a] | $NH_4$-N | $NO_3$-N | P[b] | K[b] | Total N[b] | Organic C[c] |
|---|---|---|---|---|---|---|---|
| | | mg kg$^{-1}$ | | | | g kg$^{-1}$ | |
| Stillwater | 5.7 | 4.6 | 2.3 | 33 | 159 | 0.9 | 10.6 |
| Classification: Kirkland silt loam (fine-mixed, thermic Udertic Paleustoll) | | | | | | | |
| Lahoma | 5.6 | 5.6 | 4.0 | 77 | 467 | 0.9 | 11.0 |
| Classification: Grant loam (fine-silty, mixed, thermic Udic Argiustoll) | | | | | | | |

[a]pH: 1:1 soil:water.
[b]P and K: Mehlich III.
[c]Organic C and Total N:dry combustion.

Lahoma for 1996-99. A significant grain yield and grain N uptake response to N fertilization was found for the grain production system at both sites. Similarly, forage and forage N uptake responded to applied N at both sites (Tables 3-10). It was interesting to note that dry matter production levels were nearly double for forage-only when compared to the grain production system at both sites. Although less pronounced, forage N uptake or removal was nearly double in the forage-only system when compared to grain-only at both locations (Tables 3-10).

TABLE 2. Planting and harvest dates for Stillwater (Experiment 222) and Lahoma (Experiment 502) OK, 1996-1999.

| | year | | | |
|---|---|---|---|---|
| Procedure | 1996 | 1997 | 1998 | 1999 |
| Stillwater 222 | | | | |
| Fertilization | Oct 9 | Sept 5 | Oct 2 | Sept 3 |
| Planting | Oct 10 | Oct 3 | Oct 3 | Oct 13 |
| Forage harvest 1 | Mar 1 | Jan 6 | Feb 18 | Mar 3 |
| Forage harvest 2 | May 7 | May 13 | May 12 | Apr 30 |
| Grain harvest | June 11 | June 19 | June 10 | June 15 |
| Lahoma 502 | | | | |
| Fertilization | Aug 31 | Sept 4 | Sept 10 | Sept 12 |
| Planting | Oct 10 | Oct 3 | Oct 17 | Oct 9 |
| Forage harvest 1 | Mar 5 | Jan 3 | Mar 25 | Feb 25 |
| Forage harvest 2 | May 6 | May 6 | May 11 | May 11 |
| Grain harvest | June 21 | June 13 | June 12 | June 30 |

TABLE 3. Analysis of variance and means for total dry matter forage yield (sum of harvests in March and May) grain yield, N uptake, and nitrogen use efficiency (NUE) Stillwater, OK, 1996.

| | | Forage | | | Grain | | |
|---|---|---|---|---|---|---|---|
| | | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† |
| Source of variation | df | mean squares | | | | | |
| Replication | 3 | 0.690 | 164 | 192 | 0.037 | 38 | 3 |
| N rate | 3 | 1.956* | 1995* | 332 | 0.329* | 628* | 403 |
| Residual error | 9 | 0.612 | 396 | 192 | 0.059 | 108 | 109 |
| SED‡ | | 0.553 | 14.0 | 9.7 | 0.171 | 7.3 | 6.9 |
| N rate, kg ha$^{-1}$ | | Mg ha$^{-1}$ | kg ha$^{-1}$ | % | Mg ha$^{-1}$ | kg ha$^{-1}$ | % |
| 0 | | 2.719 | 49.6 | - | 1.007 | 29.0 | - |
| 44 | | 2.841 | 59.0 | 21 | 1.274 | 35.6 | 15 |
| 90 | | 3.553 | 83.1 | 37 | 1.382 | 48.5 | 22 |
| 134 | | 4.228 | 98.6 | 36 | 1.701 | 56.8 | 21 |

*Significant at the 0.05 probability level.
†df for NUE, N rate=2.
‡SED- Standard error of the difference between two equally replicated means.

TABLE 4. Analysis of variance and means for total dry matter forage yield (sum of harvests in March and May) grain yield, N uptake, and nitrogen use efficiency (NUE) Stillwater, OK, 1997.

| | | Forage | | | Grain | | |
|---|---|---|---|---|---|---|---|
| | | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† |
| Source of variation | df | mean squares | | | | | |
| Replication | 3 | 1.10 | 336 | 1113 | .0364 | 235 | 3 |
| N rate | 3 | 19.1* | 3667** | 4016 | 1.011* | 725* | 403 |
| Residual error | 9 | 0.79 | 793 | 1046 | 0.126 | 79 | 109 |
| SED‡ | | 1.21 | 20.0 | 22.9 | 0.251 | 6.3 | 6.9 |
| N rate, kg ha$^{-1}$ | | Mg ha$^{-1}$ | kg ha$^{-1}$ | % | Mg ha$^{-1}$ | kg ha$^{-1}$ | % |
| 0 | | 3.334 | 49.9 | - | 0.872 | 20 | - |
| 44 | | 5.077 | 76.1 | 58 | 0.859 | 21 | 17 |
| 90 | | 7.460 | 103.8 | 60 | 1.069 | 29 | 19 |
| 134 | | 9.668 | 143.1 | 69 | 1.920 | 50 | 21 |

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
†df for NUE, N rate=2.
‡SED-Standard error of the difference between two equally replicated means.

TABLE 5. Analysis of variance and means for total dry matter forage yield (sum of harvests in March and May) grain yield, N uptake, and nitrogen use efficiency (NUE) Stillwater, OK, 1998.

| | | Forage | | | Grain | | |
|---|---|---|---|---|---|---|---|
| | | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† |
| Source of variation | df | mean squares | | | | | |
| Replication | 3 | 1920.4** | 377** | 744 | 1.876 | 103 | 163* |
| N rate | 3 | 6265.5** | 2766** | 1709 | 1012** | 324** | 319** |
| Residual error | 9 | 187.23 | 41.20 | 261 | 109 | 32.42 | 40.75 |
| SED‡ | | 0.306 | 4.54 | 11.42 | 0.233 | 4.03 | 4.51 |
| N rate, kg ha$^{-1}$ | | Mg ha$^{-1}$ | kg ha$^{-1}$ | % | Mg ha$^{-1}$ | kg ha$^{-1}$ | % |
| 0 | | 1.886 | 23.2 | - | 1.153 | 22 | - |
| 44 | | 2.768 | 41.2 | 40 | 1.434 | 31 | 20 |
| 90 | | 3.276 | 51.0 | 31 | 1.808 | 38 | 18 |
| 134 | | 4.868 | 80.8 | 47 | 2.316 | 43 | 15 |

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
†df for NUE, N rate=2.
‡SED-Standard error of the difference between two equally replicated means.

TABLE 6. Analysis of variance and means for total dry matter forage yield (sum of harvests in March and May) grain yield, N uptake, and nitrogen use efficiency (NUE) Stillwater, OK, 1999.

| | | Forage | | | Grain | | |
|---|---|---|---|---|---|---|---|
| | | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† |
| Source of variation | df | mean squares | | | | | |
| Replication | 3 | 735.16 | 354.8 | 425 | 144.88 | 181.09 | 2607.94 |
| N rate | 3 | 2288.79* | 2720.4** | 1988** | 2196.43* | 2024.04** | 1037.88 |
| Residual error | 9 | 514.61 | 164.4 | 255 | 377.71 | 263.60 | 710.94 |
| SED‡ | | 0.253 | 4.53 | 5.65 | 0.217 | 5.74 | 9.43 |
| N rate, kg ha$^{-1}$ | | Mg ha$^{-1}$ | kg ha$^{-1}$ | % | Mg ha$^{-1}$ | kg ha$^{-1}$ | % |
| 0 | | 2.792 | 44.6 | - | 1.315 | 37 | - |
| 44 | | 3.217 | 57.4 | 29 | 1.529 | 46 | 22 |
| 90 | | 4.537 | 91.2 | 52 | 2.124 | 60 | 27 |
| 134 | | 3.799 | 98.7 | 40 | 2.970 | 88 | 38 |

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
†df for NUE, N rate=2.
‡SED-Standard error of the difference between two equally replicated means.

TABLE 7. Analysis of variance and means for total dry matter forage yield (sum of harvests in March and May) grain yield, N uptake, and nitrogen use efficiency (NUE) Lahoma, OK, 1996.

| | | Forage | | | Grain | | |
|---|---|---|---|---|---|---|---|
| | | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† |
| Source of variation | df | mean squares | | | | | |
| Replication | 3 | 1.300 | 1394 | 2.580 | 324 | 660* | 1341* |
| N rate | 4 | 3.197* | 4844* | 5.708 | 1510** | 1140** | 2850** |
| Residual error | 12 | 0.520 | 568 | 4.033 | 184 | 156 | 387 |
| SED‡ | | 0.509 | 16.8 | 1.16 | 0.247 | 7.2 | 11.4 |
| N rate, kg ha$^{-1}$ | | Mg ha$^{-1}$ | kg ha$^{-1}$ | % | Mg ha$^{-1}$ | kg ha$^{-1}$ | % |
| 0 | | 2.89 | 58.0 | - | 1.48 | 33 | - |
| 45 | | 3.49 | 87.3 | 65 | 2.22 | 58 | 55 |
| 67 | | 4.29 | 113.3 | 80 | 2.17 | 54 | 32 |
| 90 | | 5.24 | 149.9 | 102 | 2.87 | 74 | 46 |
| 112 | | 4.91 | 133.9 | 68 | 3.17 | 80 | 42 |

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
†df for NUE N rate=4.
‡SED-Standard error of the difference between two equally replicated means.

TABLE 8. Analysis of variance and means for total dry matter forage yield (sum of harvests in March and May) grain yield, N uptake, and nitrogen use efficiency (NUE) Lahoma, OK, 1997.

| | | Forage | | | Grain | | |
|---|---|---|---|---|---|---|---|
| | | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† |
| Source of variation | df | mean squares | | | | | |
| Replication | 3 | 17412** | 2541** | 6744* | 663 | 426 | 879 |
| N rate | 4 | 32914** | 17434** | 19830** | 4265** | 2361* | 3049 |
| Residual error | 12 | 2012 | 344 | 1675 | 462 | 201 | 811 |
| SED‡ | | 0.82 | 10.7 | 23.6 | 0.39 | 8.2 | 16.5 |
| N rate, kg ha$^{-1}$ | | Mg ha$^{-1}$ | kg ha$^{-1}$ | % | Mg ha$^{-1}$ | kg ha$^{-1}$ | % |
| 0 | | 3.94 | 69 | - | 1.47 | 35 | - |
| 45 | | 8.37 | 123 | 121 | 2.30 | 55 | 45 |
| 67 | | 9.17 | 146 | 114 | 3.05 | 73 | 56 |
| 90 | | 10.99 | 206 | 153 | 3.58 | 81 | 51 |
| 112 | | 12.20 | 143 | 162 | 4.32 | 104 | 62 |

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level,
†df for NUE, N rate=4.
‡SED-Standard error of the difference between two equally replicated means.

TABLE 9. Analysis of variance and means for total dry matter forage yield (sum of harvests in March and May) grain yield, N uptake, and nitrogen use efficiency (NUE) Lahoma, OK, 1998.

| | | Forage | | | Grain | | |
|---|---|---|---|---|---|---|---|
| | | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† |
| Source of variation | df | mean squares | | | | | |
| Replication | 3 | 858.3 | 1308 | 6155 | 250.8** | 506.2 | 1979 |
| N rate | 4 | 5536.2** | 5171** | 4064 | 3415.4** | 2640** | 4183 |
| Residual error | 12 | 567.1 | 461 | 3134 | 44.0 | 314.8 | 1086 |
| SED‡ | | 0.435 | 12.4 | 32.3 | 0.121 | 10.24 | 19.02 |
| N rate, kg ha$^{-1}$ | | Mg ha$^{-1}$ | kg ha$^{-1}$ | % | Mg ha$^{-1}$ | kg ha$^{-1}$ | % |
| 0 | | 4.06 | 86 | - | 2.112 | 49.4 | - |
| 45 | | 4.86 | 112 | 57 | 3.719 | 88.7 | 78 |
| 67 | | 5.79 | 139 | 79 | 3.665 | 87.2 | 56 |
| 90 | | 6.65 | 160 | 82 | 3.426 | 83.1 | 37 |
| 112 | | 6.89 | 180 | 83 | 4.542 | 117.1 | 60 |

**Significant at the 0.01 probability level.
†df for NUE, N rate=4.
‡SED-Standard error of the difference between two equally replicated means.

TABLE 10. Analysis of variance and means for total dry matter forage yield (sum of harvests in March and May) grain yield, N uptake, and nitrogen use efficiency (NUE) Lahoma, OK, 1999.

| | | Forage | | | Grain | | |
|---|---|---|---|---|---|---|---|
| | | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† | Yield Mg ha$^{-1}$ | N uptake kg ha$^{-1}$ | NUE† |
| Source of variation | df | mean squares | | | | | |
| Replication | 3 | 43060.9* | 26570.7* | 45169 | 312.2* | 90.5 | 662 |
| N rate | 4 | 10126.4 | 9095.7 | 86306 | 3316.8** | 2568.2** | 1717** |
| Residual error | 12 | 7134.0 | 7802.9 | 42767 | 76.8 | 109.8 | 258 |
| SED‡ | | 0.629 | 20.8 | 48.7 | 0.065 | 2.50 | 3.79 |
| N rate, kg ha$^{-1}$ | | Mg ha$^{-1}$ | kg ha$^{-1}$ | % | Mg ha$^{-1}$ | kg ha$^{-1}$ | % |
| 0 | | 5.24 | 80 | - | 1.29 | 36.2 | - |
| 45 | | 8.41 | 155 | 166 | 2.08 | 52.6 | 27 |
| 67 | | 7.25 | 137 | 83 | 2.49 | 63.1 | 14 |
| 90 | | 8.95 | 207 | 141 | 3.19 | 82.7 | 17 |
| 112 | | 9.81 | 204 | 111 | 3.63 | 103.1 | 15 |

*Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.
†df for NUE, N rate=4.
‡SED-Standard error of the difference between two equally replicated means.

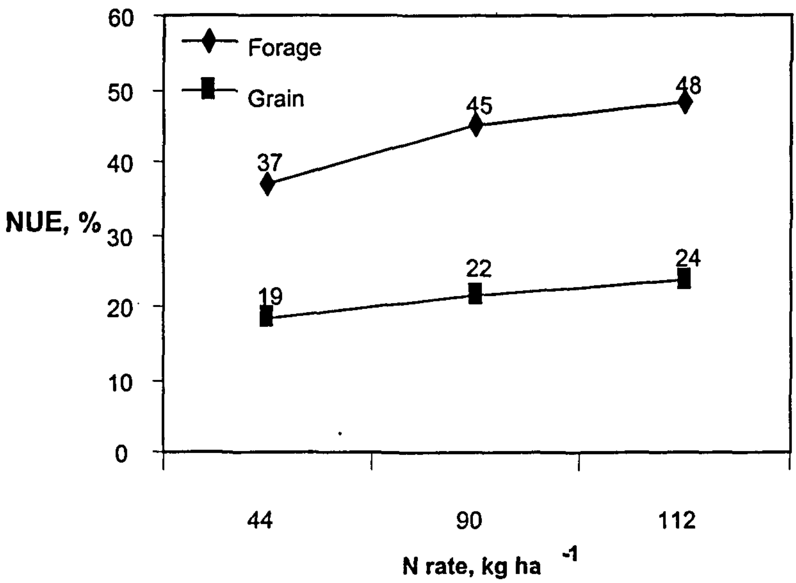


FIGURE 1. Average nitrogen use efficiency (NUE) for forage and grain production systems, Stillwater, OK (Experiment 222), 1996-1999.



As a result of increased dry matter production and N removal, NUE's were much greater for the forage-only systems at both sites when compared to grain-only systems (Tables 3-10). As per the work of Francis et al. (1993), gaseous plant N losses are known to be greatest between flowering and maturity. The two forage harvests (March, Feekes 6 and May, Feekes 10) were both prior to flowering. Regrowth, including secondary tillers, following the March harvest did produce plants with heads by May, however, flowering did not occur prior to the last forage harvest. Only limited growth was observed in the forage-only plots following the May harvest. By harvesting the plant for forage before grain fill, potential losses were avoided, thus increasing NUE.

Averaged over locations and years, NUE values for forage production systems (76%) were substantially higher than those for grain only production systems (34%). At both locations, grain-only production systems had estimated NUE's less than 62 percent in all years excluding the low N rate. With forage-only production systems, NUE's were much greater, exceeding 80% at Lahoma. The forage system was shown to be a more efficient user of N than the grain-only system with a 41% increase at Lahoma and a 49% increase at the Stillwater site. Although NUE's were expected to decrease with increasing N rates for grain

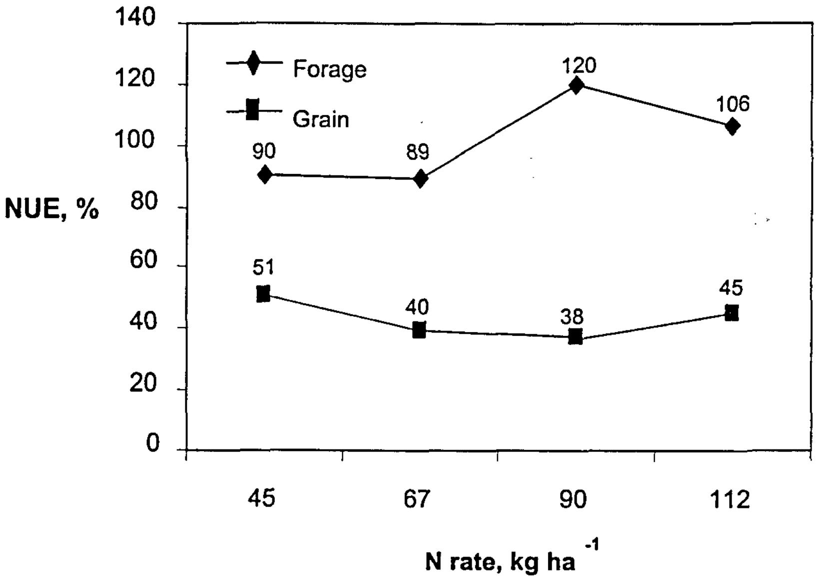


FIGURE 2. Average nitrogen use efficiency (NUE) for forage and grain production systems, Lahoma, OK (Experiment 502), 1996-1999.



production, this effect was not consistent, excluding the high N rates where depressed NUE's were found. Figures 1 and 2 represent 4-year average NUE values at Stillwater and Lahoma, respectively. Four-year average NUE values were included because the purpose of this study was to evaluate the long-term differences between forage and grain production systems. In 1997, forage yields were well above normal, exceeding 10 Mg ha$^{-1}$ at both sites at the highest N rates. Forage production conditions were ideal with a mild wet winter and cool spring. Increased production at the high N rates was a result of depressed yields in both 1995 and 1996 due to poor growing conditions, leaving significant residual N in an environment where nitrate leaching is not expected (Raun and Johnson, 1995). When environmental conditions favored higher yields than the current fertilizer application could support, N was possibly mineralized from the soil organic pool and made available to growing plants. While the 1998 crop year was also conducive to superior forage production, we did not see yields as high as those achieved in 1997, because the reserve of soil-N ($NO_3$ or mineralizable N) was depleted in 1997. At Stillwater in 1999, NUE values for forage and grain were higher than all years other than 1997. Good soil moisture levels and mild fall temperatures allowed the crop to proceed at high levels of growth. Forage yields at Lahoma were again much higher than those at Stillwater, nearly reaching 10 Mg $ha^{-1}$, and forage NUE's were consistently higher at this site. Grain NUE's and yields were among the lowest of the four years, largely due to heavy rains that delayed harvest by several weeks causing heads to shatter, thus reducing harvested grain yield.

## CONCLUSIONS

Averaged over locations and years, NUE values for forage production systems (76%) were substantially higher than those for grain only production systems (34%). At 90 kg N $ha^{-1}$, a commonly applied preplant rate in this region, wheat produced for forage had much higher NUE's (83%) when compared with grain production systems (30%). This is largely due to continuous pre-anthesis harvesting, prior to the onset of gaseous plant N loss. This work indicates that NUE's can be increased using a forage production system, but that these systems will be heavily dependent upon an inefficient animal component. The human requirement for grain will necessitate future improvements in NUE that consider holistic management strategies.



## REFERENCES

Bruno, M., R. Sylvie, and J.Machet. 1987. A comprehensive approach to the fertilizer part of plant nitrogen uptake. pp. 85-94. In: D.S. Jenkinson and K.A. Smith (eds.), Nitrogen Efficiency in Agricultural Soils. Elsevier Science, New York, NY.

Ellen, J. and J.H.J. Spiertz. 1980. Effects of rate and timing of nitrogen dressings on grain yield formation of winter wheat. Fert. Res. 1:177-190.

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

Harper, L.A., R.R. Sharpe, G.W. Langdale, and J.E. Evans. 1987. Nitrogen cycling in a wheat crop: Soil, plant, and aerial nitrogen transport. Agron. J. 79:965-973.

Large, E.C. 1954. Growth stages in cereals. Plant Pathol. 3:128-129.

Kanampiu, F.K., W.R. Raun, and G.V. Johnson. 1997. Effect of nitrogen rate on plant nitrogen loss in winter wheat varieties. J. Plant Nutr. 20:389-404.

Moll, R.H., E.J. Kamprath, and W.A. Jackson. 1982. Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. Agron. J. 74:562-564.

O'Deen, W.A. 1989. Wheat volatilized ammonia and resulting nitrogen isotopic fractionation. Agron J. 81:980-985.

Parton, W.J., J.A. Morgan, J.M Altenhofen, and L.A. Harper. 1988. Ammonia volatilization from spring wheat plants. Agron J. 80:419-425.

Raun, W.R. and G.V. Johnson. 1995. Soil-plant buffering of inorganic nitrogen in continuous winter wheat. Agron. J. 87:827-834.

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.

Simonis, A.D. 1987. Studies on nitrogen use efficiency in cereals. pp. 110-124. In: D.S. Jenkinson and K.A. Smith (eds.), Nitrogen Efficiency in Agricultural Soils. Elsevier Science, New York, NY.

Van der Ploeg, R.R., H. Ringe, G. Machulla, and D. Hermsmeyer. 1997. Postwar nitrogen use efficiency in west german agriculture and groundwater quality. J. Environ. Qual. 26:1203-1212.

Whitehead, D.F. 1995. Grasses uptake of nitrogen and effects on morphology and physiology. p.16. In: Grassland Nitrogen. CAB Intl. Publishers, Wallingford, UK.

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.