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PRODUCTION SYSTEM TECHNIQUES TO INCREASE NITROGEN USE EFFICIENCY IN WINTER WHEAT*

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ABSTRACT

Most current research on winter wheat (*Triticum aestivum* L.) focuses on increasing yields of either grain or plant biomass. Increased production costs and environmental awareness will promote the development of methods to increase the efficiency of applied nutrients. Nitrogen (N) is often the most limiting nutrient for cereal grain production and represents one of the highest input costs in agricultural systems. This study was conducted to evaluate the effects of several short-term practices on nitrogen use efficiency (NUE) in winter wheat at three locations in Oklahoma. The variables evaluated included variety, nitrogen source, nitrogen timing, nitrogen rate, production system (forage only vs. grain only and a combination of the two), resolution of

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nitrogen application based on in-season estimated yield (INSEY), and application of a late-season senescence delaying chemical and late-season KH_2PO_4. Results indicate that many approaches can be taken to increase NUE in wheat production systems. Averaged over 9 site yrs, the highest NUE was for forage-only production systems (66% for "Jagger" and 52% for "2174") far higher than grain-only production systems (26% for "Jagger" and 37% for "2174"). The combination of a 3-way split application using sensor measurements and 1 m^2 application resolution produced the highest average grain-only NUE at 81% for 2174 and 48% for Jagger compared with 29% NUE for pre-plant applied N. The most critical components of NUE from this study appear to be production system, variety, N fertilizer timing, and INSEY based topdress N applications.

INTRODUCTION

Nitrogen use efficiency is defined as grain production per unit of N available in the soil and calculated as grain weight divided by N supplied (Gw/Ns).[1] In this study, we calculated NUE as uptake efficiency (the difference of N uptake in the treated plot and N uptake in the 0-N check, divided by the total applied N rate. Uptake efficiency from the soil is critical to the overall NUE of the system, therefore techniques that enhance uptake or provide N directly to the plant need to be developed and evaluated. Conversion of N to plant material and grain are both critical when considering increased NUE. A plant more efficient at converting N from the tissue to grain N will have increased NUE.

It has been noted that different NUEs among different corn hybrids are largely due to differing utilization of N already accumulated in the plant prior to anthesis, especially with low N levels.[1] Eghball and Maranville[2] found that NUE usually parallels water use efficiency in corn, thus the two traits can be selected simultaneously where such parallels exist. Wheat varieties with high harvest index values are known to have higher NUEs.[3] It has been reported that wheat varieties that accumulate large amounts of N early in the growing season do not necessarily have high NUE. Plants must convert this accumulated N to grain nitrogen and must assimilate N after anthesis to produce high NUEs.[4] Since most variety selection is done under high N fertility conditions, efficiency of N use is often considered second in importance to total yield. This approach will have to change in response to the worldwide need for more nutrient efficient crops.

In the south-central United States, producers often use winter wheat as a forage crop for cattle as well as for grain production. Research indicates that forage production systems are more efficient users of N than grain production systems with forage system NUEs over 70% and grain-only NUEs less than 40%.[5] Working in corn, O'Leary and Rehm[6] reported that NUE values were greater for silage than those for grain. Much of the loss of applied N fertilizer efficiency is due to the loss of N to the atmosphere at senescence.[7] At flowering, N is translocated to the grain and movement at this stage of development causes gaseous N losses to increase and efficiency to decrease.[8]

Some researchers have noted that application of N as NH_4 will produce plants with higher total N uptake and therefore higher NUE. As stated earlier, late-season N uptake and assimilation are critical for increasing NUE. Nitrogen in the NH_4 form is not mobile in the soil and may therefore be available for late-season uptake by the plant. Plants with preferential uptake of NH_4 during grain fill may provide increases in NUE over plants without this preference.[9] Ammonium–N supplied to high yielding corn genotypes increased yield over plants supplied with NO_3 during critical ear development.[10] Plant assimilation of NO_3 requires the equivalent of 20 ATP mol^{-1} NO_3, but NH_4 assimilation requires only five ATP mol^{-1} of NH_4.[11] It is evident that this energy savings could be beneficial to the plant late in the season.

Fertilizer use efficiency as reflected in grain yield of winter wheat has been shown to change with time and rate of application.[12] Studies by Harper et al.[8] noted decreased N concentrations in winter wheat with time during the growing season. Olson and Swallow[13] noted in-season N application resulted in increased efficiency in four of five years when compared to pre-plant incorporated nitrogen in winter wheat. Nitrogen supplied late-season has been shown to increase grain protein and NUE over pre-plant applied nitrogen.[14] In another study by Wuest and Cassman[15] recovery of pre-plant N was found to be less than 55%, while recovery of N applied at anthesis was noted at 55–80%.

Precision agriculture practices can increase NUE by providing precise in-season application of N fertilizer. To capitalize on any potential N fertilizer savings and increased NUE, management decisions need to be made at the appropriate field element size.[16–18] Field element size is defined as that area or resolution which provides the most precise measure of the available nutrient where the level of that nutrient changes with distance.[17] Random variability in soil test and plant biomass has been documented at resolutions less than or equal to one square meter.[16–18] When N management decisions are based on this information, the variability in the crop present at that resolution can be detected using optical sensors (normalized difference vegetative index or NDVI).[17,19] Differences can then be addressed by supplying N at prescribed rates, thus increasing NUE.[19]

Ethephon [(2-chloroethyl) phosphonic acid] applied at either Feekes growth stage 6 or 9 has shown increased N remobilization from vegetative plant parts and increased dry matter levels at harvest.[20] Foliar applications of KH_2PO_4 at rates of 10 kg ha^{-1} have been shown to increase grain yields in regions where late-season drought and temperature stress occurs.[21] The objectives of this trial were to evaluate the effects of variety, nitrogen source, nitrogen timing, nitrogen rate, production system (forage only vs. grain only and a combination of the two), resolution of nitrogen application, and application of a late-season senescence delaying chemical and late-season KH_2PO_4 on NUE in winter wheat.

MATERIALS AND METHODS

Three experiments were conducted at Stillwater, OK on a Norge loam (fine-silty, mixed, active, thermic Udic Paleustolls), Tipton, OK on a Tillman–Hollister sandy loam (fine, mixed, superactive, thermic Typic Paleustolls), and Haskell, OK on a Taloka silt loam (fine-mixed, thermic Mollic Albaqualf) (Table 1). The treatment variables were wheat variety, nitrogen source, nitrogen timing, nitrogen rate, production system (forage only vs. grain only and a combination of the two), resolution of nitrogen application, and application of a late-season senescence delaying chemical and late-season KH_2PO_4. The effects of these treatments on NUE were evaluated, which in this case, was calculated as (N uptake in the treated plot–N uptake in the check plot)/total N rate applied. Two wheat varieties,

Table 1. Initial Soil Chemical Characteristics and Classification (0–15 cm) at Stillwater, Tipton, and Haskell, OK

Location	pH[a]	NH_4–N	NO_3–N	P[b]	K[b]	Total N[c]	Organic C[c]
		mg kg^{-1}				mg g^{-1}	
Stillwater	6.2	2.2	5.6	28	472	0.09	1.06
Classification: Norge loam (fine-silty, mixed, thermic Udic Argiustoll)							
Tipton	7.4	23.6	5.6	85	1,006		
Classification: Tillman–Hollister sandy loam (fine, mixed, superactive, thermic Typic Paleustoll)							
Haskell (pre-liming)	4.8	43.1	32.1	45	240		
Haskell (post-liming)	6.1	28.2	33.0	41	252		
Classification: Taloka silt loam (fine-mixed, thermic Mollic Albaqualf)							

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

Table 2. Treatment Structure Including Variety, Winter Wheat Production System, Pre-plant N Rate, Topdress N Rate, Topdress Resolution, and N Applied at Flowering, 1998–2001

Treatment	Variety	Production System	PP N Rate $kg\,ha^{-1}$	TD N Rate $kg\,ha^{-1}$	TD Resolution $kg\,ha^{-1}$	N at Flowering $kg\,ha^{-1}$	Chemical
1	2174	Grain	0	0	—	0	
2	2174	Grain	112	0	—	0	
3	Jagger	Grain	0	0	—	0	
4	Jagger	Grain	112	0	—	0	
5	2174	Grain	0	INSEY	1 m	22	
6	Jagger	Grain	0	INSEY	1 m	22	
7	2174	Grain	0	78	—	22	
8	2174	Grain	34	INSEY	1 m	22	
9	Jagger	Grain	34	INSEY	1 m	22	
10	2174	Grain	34	45	—	22	
11	2174	Grain	0	INSEY	1 m	0	
12	2174	Grain	0	78	—	0	
13	2174	Grain	0	INSEY	1 m	22	Ethephon
14	Jagger	Grain	0	INSEY	1 m	22	KH_2PO_4
15	2174	Forage	56	INSEY	1 m	0	
16	Jagger	Forage	56	INSEY	1 m	0	
17	2174	Forage & grain	56	INSEY	1 m	22	
18	Jagger	Forage & grain	56	INSEY	1 m	22	

All N rates applied as actual N in $kg\,ha^{-1}$.
Topdress resolution is square meters.
Ethephon applied at Feekes 9 at $0.42\,kg\,ai\,ha^{-1}$.
KH_2PO_4 applied at anthesis at $10\,kg$ material ha^{-1} in water carrier (2 L).
Variety 2180 was planted in crop year 1998–99 in lieu of 2174.
INSEY: NDVI at Feekes 5 divided by days from planting with average temp above 4.4°C.

2174 and Jagger were planted in plots with pre-plant N rates of 0, 34, 56, or 112 kg ha^{-1} as ammonium nitrate (34–0–0) in the 1999–00 crop year. Variety "2180" was planted instead of 2174 in 1998. Two treatments received fixed-rate topdress N applications of 78 kg ha^{-1} and one treatment received 45 kg N ha^{-1}, with eleven others receiving a prescribed topdress N rate based on NDVI readings and INSEY values.[22,23] The INSEY index is computed by taking one NDVI reading between Feekes growth stages 4 and 6,[24] and dividing by the number of days from planting to the date the reading was taken with average temperature daily above 4.4°C. The plots receiving N based on INSEY values were sensed and treated on a 1 m^2 resolution, while plots receiving fixed rates of N were fertilized on a whole plot basis (13.9 m^2). Variable rates were applied at a range of 0–78 kg N ha^{-1}. Ten treatments, some with variable and some with fixed topdress rates received an additional 22 kg N ha^{-1} as urea ammonium nitrate (28–0–0) at flowering. Two treatments, one for each variety, were grown for forage-only with forage removed at Feekes growth stage 5 and again at flowering. Two treatments, again one for each variety, were managed for both forage and grain with only one forage harvest at Feekes growth stage 5. A late-season senescence-delaying chemical, Ethephon (CAS# 16672-87-0), was applied to one treatment at Feekes 9 to attempt to increase nitrogen use efficiency (Table 2). Potassium dihydrogen phosphate (KH_2PO_4) was applied at a rate of 10 kg ha^{-1} of material in 2 L of H_2O at flowering to one treatment.

Forage samples from forage-only, and forage + grain plots were harvested from 1 m^2 areas in the center of the plots at Feekes 5 and the entire plot was mowed to a height of 15 cm. In the forage-only plots, forage was again harvested from 1 m^2 in the center of the plot at flowering. In the forage + grain plots, forage was harvested from a 1 m^2 area in the center of the plot at Feekes 5 and the plot was then mowed but allowed to re-grow and produce grain. Forage harvests were taken by hand at both growth stages. From all grain and forage + grain plots, grain was harvested from an area of 3.05×2 m using a self-propelled combine. Forage and grain samples were dried and ground to pass a 140 mesh sieve (100 um) and analyzed for total N content using a Carlo-Erba NA 1500 automated dry combustion analyzer.[25] Statistical evaluation and analysis of variance was performed using SAS.[26] Nitrogen use efficiency was calculated by subtracting the yield of the unfertilized check from the yield of the fertilized plot and then dividing by the total N rate applied.

RESULTS

Results will be presented as individual years and locations with grain data following in Tables 3–5, forage-only data in Table 6 and data from forage and grain plots in Table 7.

Table 3. Treatment; Mean Grain Yield, Grain N Uptake, Topdress N Rate, Pre-plant N Rate, Flowering N Rate, Total N Rate, NUE; Variety, Production System, and Chemical Application, 1999, Stillwater, Haskell, and Tipton, OK

Trt	Yield kg ha^{-1}	N Uptake kg ha^{-1}	Pre-plant N kg ha^{-1}	Winter Topdress kg ha^{-1}	Flowering N kg ha^{-1}	Total N Rate kg ha^{-1}	NUE %	Variety	Production System	Chemical
					Stillwater					
3	2,282	60	0	0	0	0	—	Jagger	Grain	
4	2,091	85	112	0	0	112	22	Jagger	Grain	
6	1,687	53	0	68	22	90	−8	Jagger	Grain	
9	3,211	121	0	48	22	70	87	Jagger	Grain	
14	2,173	68	0	74	22	96	8	Jagger	Grain	KH_2PO_4
18	1,832	57	56	76	22	154	2	Jagger	f_g	
SED	392	22					21			
					Haskell					
3	2,067	54	0	0	0	0	—	Jagger	Grain	
4	1,971	66	112	0	0	112	11	Jagger	Grain	
6	1,777	53	0	32	22	54	−2	Jagger	Grain	
9	1,758	51	0	33	22	55	−5	Jagger	Grain	
14	1,939	53	0	32	22	54	−2	Jagger	Grain	KH_2PO_4
18	1,059	35	56	34	22	112	−17	Jagger	f_g	
SED	181	6					11			
					Tipton					
1	1,956	42	0	0	0	0	—	2180	Grain	
2	2,951	91	112	0	0	112	44	2180	Grain	
3	719	16	0	0	0	0	—	Jagger	Grain	
4	2,960	96	112	0	0	112	71	Jagger	Grain	

(continued)

Table 3. Continued

Trt	Yield $kg\,ha^{-1}$	N Uptake $kg\,ha^{-1}$	Pre-plant N $kg\,ha^{-1}$	Winter Topdress $kg\,ha^{-1}$	Flowering N $kg\,ha^{-1}$	Total N Rate $kg\,ha^{-1}$	NUE %	Variety	Production System	Chemical
5	2,090	51	0	37	22	59	15	2180	Grain	
6	1,924	51	0	35	22	57	61	Jagger	Grain	
7	2,443	63	0	78	22	100	21	2180	Grain	
8	3,842	106	34	13	22	69	93	2180	Grain	
9	3,038	87	34	14	22	70	101	Jagger	Grain	
10	3,361	97	34	0	22	56	97	2180	Grain	
11	1,991	41	0	31	0	31	−3	2180	Grain	
12	2,324	55	0	78	0	78	17	2180	Grain	
13	2,098	48	0	35	22	57	11	2180	Grain	Ethephon
14	2,222	64	0	39	22	61	79	Jagger	Grain	KH_2PO_4
17	2,568	76	56	22	22	100	34	2180	f_g	
18	1,774	56	56	12	22	90	16	Jagger	f_g	
SED	412	11					4			

SED: Standard error of the difference between two equally replicated means.
Ethephon applied at Feekes 9 at 0.42 kg ai ha^{-1}.
f_g: forage + grain production system.
KH_2PO_4 applied at anthesis at 10 kg material ha^{-1} in water carrier (2 L).

Table 4. Treatment; Mean Grain Yield, Grain N Uptake, Topdress N Rate, Pre-plant N Rate, Flowering N Rate, Total N Rate, NUE; Variety, Production System, and Chemical Application, 2000, Stillwater, Haskell, and Tipton, OK

Trt	Yield kg ha^{-1}	N Uptake kg ha^{-1}	Pre-plant N kg ha^{-1}	Winter Topdress kg ha^{-1}	Flowering N kg ha^{-1}	Total N Rate kg ha^{-1}	NUE %	Variety	Production System	Chemical
					Stillwater					
1	3,395	75	0	0	0	0	—	2174	Grain	
2	3,894	117	112	0	0	112	38	2174	Grain	
3	2,816	52	0	0	0	0	—	Jagger	Grain	
4	2,925	93	112	0	0	112	37	Jagger	Grain	
5	3,498	88	0	37	22	59	22	2174	Grain	
6	3,370	78	0	35	22	57	46	Jagger	Grain	
7	4,135	112	0	78	22	100	37	2174	Grain	
8	3,873	108	34	13	22	69	48	2174	Grain	
9	3,290	93	34	14	22	70	59	Jagger	Grain	
10	3,792	106	34	0	22	56	55	2174	Grain	
11	3,921	89	0	31	0	31	45	2174	Grain	
12	4,248	103	0	78	0	78	36	2174	Grain	
13	3,894	98	0	35	22	57	40	2174	Grain	Ethephon
14	3,552	75	0	39	22	61	38	Jagger	Grain	KH_2PO_4
17	3,031	87	56	22	22	100	12	2174	f_g	
18	2,911	74	56	12	22	90	24	Jagger	f_g	
SED	295	11					23			
					Haskell					
1	1,935	51	0	0	0	0	—	2174	Grain	
2	1,938	71	112	0	0	112	18	2174	Grain	

(*continued*)

Table 4. Continued

Trt	Yield $kg\,ha^{-1}$	N Uptake $kg\,ha^{-1}$	Pre-plant N $kg\,ha^{-1}$	Winter Topdress $kg\,ha^{-1}$	Flowering N $kg\,ha^{-1}$	Total N Rate $kg\,ha^{-1}$	NUE %	Variety	Production System	Chemical
3	1,180	36	0	0	0	0	—	Jagger	Grain	
4	780	30	112	0	0	112	−5	Jagger	Grain	
5	2,042	60	0	35	22	57	16	2174	Grain	
6	1,088	37	0	39	22	61	2	Jagger	Grain	
7	1,955	65	0	0	22	22	63	2174	Grain	
8	2,223	73	34	29	22	85	26	2174	Grain	
9	1,168	43	34	30	22	86	8	Jagger	Grain	
10	1,909	69	34	0	22	56	32	2174	Grain	
11	2,005	56	0	41	0	41	14	2174	Grain	
12	2,033	63	0	78	0	78	15	2174	Grain	
13	2,082	62	0	34	22	56	19	2174	Grain	Ethephon
14	1,089	37	0	40	22	62	1	Jagger	Grain	KH_2PO_4
17	1,439	50	56	28	22	106	−1	2174	f_g	
18	572	21	56	27	22	105	−14	Jagger	f_g	
SED	215	6					11			

					Tipton					
1	1,794	36	0	0	0	0	—	2174	Grain	
2	2,501	81	112	0	0	112	40	2174	Grain	
3	1,602	38	0	0	0	0	—	Jagger	Grain	
4	3,288	102	112	0	0	112	57	Jagger	Grain	
5	2,222	52	0	20	22	43	37	2174	Grain	
6	2,144	50	0	18	22	40	30	Jagger	Grain	
7	3,151	76	0	78	22	100	40	2174	Grain	
8	3,491	96	34	9	22	65	92	2174	Grain	
9	4,269	109	34	4	22	60	118	Jagger	Grain	
10	3,513	101	34	45	22	101	64	2174	Grain	
11	2,196	44	0	20	0	20	40	2174	Grain	
12	2,895	67	0	78	0	78	40	2174	Grain	
13	2,285	52	0	19	22	41	39	2174	Grain	Ethephon
14	2,820	62	0	17	22	39	62	Jagger	Grain	KH_2PO_4
17	1,983	58	56	10	22	88	25	2174	f_g	
18	1,825	57	56	4	22	82	20	Jagger	f_g	
SED	224	7					13			

SED: Standard error of the difference between two equally replicated means.
Ethephon applied at Feekes 9 at 0.42 kg ai ha^{-1}.
f_g: forage + grain production system.
KH_2PO_4 applied at anthesis at 10 kg material ha^{-1} in water carrier (2 L).

Table 5. Treatment; Mean Grain Yield, Grain N Uptake, Topdress N Rate, Pre-plant N Rate, Flowering N Rate, Total N Rate, NUE; Variety, Production System, and Chemical Application, 2001, Stillwater, Haskell, and Tipton, OK

Trt	Yield kg ha^{-1}	N Uptake kg ha^{-1}	Pre-plant N kg ha^{-1}	Winter Topdress N kg ha^{-1}	Flowering N kg ha^{-1}	Total N Rate kg ha^{-1}	NUE %	Variety	Production System	Chemical
					Stillwater					
1	2,061	49	0	0	0	0	—	2174	Grain	
2	1,744	45	112	0	0	112	−4	2174	Grain	
3	2,677	58	0	0	0	0	—	Jagger	Grain	
4	2,721	70	112	0	0	112	10	Jagger	Grain	
5	2,232	58	0	41	22	63	14	2174	Grain	
6	2,710	71	0	42	22	64	20	Jagger	Grain	
7	2,201	53	0	78	22	100	4	2174	Grain	
8	2,153	58	34	40	22	96	10	2174	Grain	
9	2,892	69	34	43	22	99	12	Jagger	Grain	
10	2,222	54	34	45	22	101	5	2174	Grain	
11	2,054	53	0	41	0	41	9	2174	Grain	
12	2,039	48	0	78	0	78	−1	2174	Grain	
13	2,224	57	0	42	22	64	12	2174	Grain	Ethephon
14	2,447	64	0	42	22	61	9	Jagger	Grain	KH_2PO_4
17	1,809	48	56	41	22	119	−1	2174	f_g	
18	2,303	62	56	42	22	120	4	Jagger	f_g	
SED	183	5					8			
					Haskell					
1	1,739	38	0	0	0	0	—	2174	Grain	
2	1,197	28	112	0	0	112	−9	2174	Grain	
3	1,088	20	0	0	0	0	—	Jagger	Grain	

4	976	22	112	0	0	112	2	Jagger	Grain	
5	1,627	37	0	28	22	50	−2	2174	Grain	
6	1,236	28	0	28	22	50	16	Jagger	Grain	
7	1,684	35	0	78	22	100	−3	2174	Grain	
8	1,626	42	34	27	22	83	5	2174	Grain	
9	1,062	24	34	28	22	84	5	Jagger	Grain	
10	1,370	32	34	45	22	101	−6	2174	Grain	
11	1,755	35	0	27	0	27	−9	2174	Grain	
12	1,675	33	0	78	0	78	−6	2174	Grain	
13	1,594	34	0	27	22	49	−8	2174	Grain	Ethephon
14	1,488	33	0	27	22	49	28	Jagger	Grain	KH_2PO_4
17	1,491	38	56	26	22	104	0	2174	f_g	
18	957	24	56	28	22	106	3	Jagger	f_g	
SED	168	5					8			
					Tipton					
1	1,635	26	0	0	0	0	—	2174	Grain	
2	3,650	77	112	0	0	112	45	2174	Grain	
3	2,421	37	0	0	0	0	—	Jagger	Grain	
4	3,448	82	112	0	0	112	40	Jagger	Grain	
5	3,173	61	0	28	22	50	70	2174	Grain	
6	3,319	68	0	31	22	53	58	Jagger	Grain	
7	3,324	72	0	78	22	100	46	2174	Grain	
8	3,756	89	34	43	22	99	63	2174	Grain	
9	3,648	88	34	39	22	95	53	Jagger	Grain	
10	3,775	92	34	45	22	101	65	2174	Grain	
11	3,108	56	0	29	0	29	103	2174	Grain	
12	3,372	68	0	78	0	78	54	2174	Grain	

(*continued*)

Table 5. Continued

Trt	Yield $kg\,ha^{-1}$	N Uptake $kg\,ha^{-1}$	Pre-plant N $kg\,ha^{-1}$	Winter Topdress N $kg\,ha^{-1}$	Flowering N $kg\,ha^{-1}$	Total N Rate $kg\,ha^{-1}$	NUE %	Variety	Production System	Chemical
13	3,093	64	0	29	22	51	74	2174	Grain	Ethephon
14	3,548	76	0	29	22	51	75	Jagger	Grain	KH_2PO_4
17	3,658	86	56	47	22	125	48	2174	f_g	
18	3,824	95	56	54	22	132	44	Jagger	f_g	
SED	271	8					13			

SED: Standard error of the difference between two equally replicated means.
Ethephon applied at Feekes 9 at 0.42 kg ai ha^{-1}.
f_g: forage + grain production system.
KH_2PO_4 applied at anthesis at 10 kg material ha^{-1} in water carrier (2 L).

Table 6. Total Forage Yield, N Uptake and Efficiency for Forage-Only Treatments

Treatment	Total Forage Yield kg ha^{-1}	Total N Uptake kg ha^{-1}	kg Forage Yld / kg N Applied	Variety
		Stillwater, 1999		
16	7,785	249	74	Jagger
18	951	22	7	Jagger
		Haskell, 1999		
15	4,277	130	44	2174
16	5,640	189	71	Jagger
17	103	4	1	2174
18	412	12	5	Jagger
		Tipton, 1999		
15	7,121	183	56	2174
16	9,950	262	61	Jagger
17	482	21	4	2174
18	1,530	57	10	Jagger
		Stillwater, 2000		
15	7,565	197	95	2174
16	5,854	153	87	Jagger
17	1,770	75	18	2174
18	1,303	46	19	Jagger
		Haskell, 2000		
15	2,516	86	30	2174
16	2,392	74	27	Jagger
17	561	20	7	2174
18	584	23	7	Jagger
		Tipton, 2000		
15	3,982	147	63	2174
16	4,476	170	75	Jagger
17	1,589	71	24	2174
18	1,544	64	26	Jagger
		Stillwater, 2001		
15	1,283	87	14	2174
16	1,012	85	12	Jagger
17	687	33	20	2174
18	1,138	61	19	Jagger

(*continued*)

Table 6. Continued

Treatment	Total Forage Yield kg ha^{-1}	Total N Uptake kg ha^{-1}	kg Forage Yld / kg N Applied	Variety
		Haskell, 2001		
15	241	5	45	2174
16	242	5	48	Jagger
17	243	6	41	2174
18	244	5	47	Jagger
		Tipton, 2001		
15	4,822	226	22	2174
16	5,208	218	24	Jagger
17	687	38	18	2174
18	1,139	59	19	Jagger

Crop Year 1999

At the Stillwater site in 1999, we found no significant response to applied N. The block planted to 2180 experienced germination problems due to poor seed quality and could not be harvested. The Jagger plots were harvested and some high yields (3.2 Mg ha^{-1}) were noted for treatment nine (a 3-way split application with 34 kg ha^{-1} applied pre-plant, topdress N applied based on INSEY and 22 kg N ha^{-1} applied at flowering). The N uptake values for this plot were also indicative of good production conditions (Table 3). Forage dry matter yields and N uptake values for forage-only plots were much greater than those for forage + grain (FG) system plots (Table 7). The lack of harvest data for the 2180 plots eliminated the possibility of comparison of the two varieties for grain yield on those plots. When FG plots were compared to the grain-only plots at the same fertility and management levels, yields of grain-only plots were found to be significantly higher.

The Haskell site also experienced poor germination for the 2180 plots, thus, those plots were not harvested. Due to dry conditions in mid-spring and a very wet harvest, grain yields were highest in the 0-N check. Losses from lodging of high biomass producing plots where higher N rates were applied were significant as well as shattering losses from the heads. The greatest N uptake was from a 112 kg ha^{-1} pre-plant application (Table 3). Forage yields were greatest for the forage-only (two-cut) system (Table 6). We were unable to compare the two varieties for yield (FG treatments), but did note higher grain yields for the grain-only system when compared to the FG plots.

Table 7. Total Forage Yield, Total Grain Yield, and Total Biomass Yield, N Uptake and Efficiency for Forage and Grain Combination Treatments

Treatment	Grain Yield, kg ha^{-1}	Grain N Uptake, kg ha^{-1}	Forage Yield, kg ha^{-1}	Forage N Uptake, kg ha^{-1}	Total N Uptake, Forage + Grain, kg ha^{-1}	Topdress N Rate, kg ha^{-1}	Pre-plant N Rate, kg ha^{-1}	Flowering N Rate, kg ha^{-1}	Total N Rate, kg ha^{-1}	kg DM Yield/kg N Applied	Variety
					Stillwater, 1999						
18	1,832	57	951	22	79	76	56	22	154	7	Jagger
					Stillwater, 2000						
17	3,031	87	1,770	75	162	22	56	22	100	18	2174
18	2,911	74	1,303	46	120	12	56	22	90	19	Jagger
					Stillwater, 2001						
17	1,809	48	687	33	81	41	56	22	119	21	2174
18	2,303	62	1,138	61	123	42	56	22	120	29	Jagger
					Haskell, 1999						
17	1,059	35	412	12	47	34	56	22	112	5	Jagger
					Haskell, 2000						
17	1,439	37	561	20	57	28	56	22	106	19	2174
18	572	16	584	23	39	27	56	22	105	11	Jagger
					Haskell, 2001						
17	1,491	38	243	6	44	26	56	22	104	17	2174
18	957	24	244	5	29	28	56	22	106	11	Jagger

(*continued*)

Table 7. Continued

Treatment	Grain Yield, kg ha^{-1}	Grain N Uptake, kg ha^{-1}	Forage Yield, kg ha^{-1}	Forage N Uptake, kg ha^{-1}	Total N Uptake, Forage + Grain, kg ha^{-1}	Topdress N Rate, kg ha^{-1}	Pre-plant N Rate, kg ha^{-1}	Flowering N Rate, kg ha^{-1}	Total N Rate, kg ha^{-1}	kg DM Yield/kg N Applied	Variety
					Tipton, 1999						
17	2,568	76	482	21	97	81	56	22	159	4	2174
18	1,774	56	1,530	57	113	105	56	22	183	10	Jagger
					Tipton, 2000						
17	1,983	58	1,589	71	129	10	56	22	88	24	2174
18	1,825	54	1,544	64	118	4	56	22	82	26	Jagger
					Tipton, 2001						
17	3,658	86	687	38	124	47	56	22	125	35	2174
18	3,824	95	1,138	59	154	54	56	22	132	38	Jagger

The 1999 data from the Tipton experiment did include the 2180 plots so the entire experiment was harvested. Yields for the pre-plant only N application were lower than the 3-way split application system (3.8 vs. 3.0 Mg ha^{-1}) for the 2180 plots. The same treatments applied to the Jagger plots had no effect on grain yield. No significant difference in NUE was noted for either pre-plant or split applications for either variety (Table 3). The highest NUE for this site was found for the 3-way INSEY split application to Jagger (101%). This response could be due to near ideal conditions for fall growth in 1998. Wheat plants would have taken up a large amount of N early in the season and plots with sufficient N applied early would have had the opportunity to accumulate N during more favorable conditions than those experienced later in the season. Less than ideal environmental conditions occurred in the spring of 1999 at this location with warm and dry conditions favoring volatilization of topdress and flowering applications. A late-season hailstorm also damaged yields at this site. Yields for the forage-only Jagger plots were significantly higher compared to 2174 (Table 6). Again, total dry matter yields for the forage-only (two harvest) plots were higher than the yields from the combination plots. There was no difference in yield between varieties within the FG plots.

Crop Year 2000

In the 2000 crop year, due to lack of availability of quality seed, the wheat variety 2174 was substituted for 2180 at all locations. At Stillwater, the highest yields were obtained when 78 kg N ha^{-1} was applied topdress in the spring with an additional flowering application of 22 kg ha^{-1} (Trt. 7, Table 4). The highest NUE was 59% for trt. 9, receiving N as a 3-way split with winter topdress N applied based on INSEY for a total N rate of 70 kg ha^{-1}. Nitrogen use efficiency values for the 3-way split application using INSEY adjusted topdress rates were both greater than 47%. There was no difference in forage yield for the forage only plots between varieties in 2000. The forage-only system had higher dry matter yields than the single cutting from the FG plots (Table 7). Total N uptake values for these plots were also higher than those for FG plots. Grain yields from the grain-only vs. the FG plots were not significantly different (Table 4).

At Haskell in 2000, the highest yielding treatment was 2174 with 34 kg N ha^{-1} applied pre-plant, topdress N applied based on INSEY and another 22 kg ha^{-1} N applied at flowering (Trt. 8) (Table 4). Comparison of the treatments receiving chemical applications and those otherwise treated the same revealed no differences in final yield. Grain N uptake was the highest for the 2174 plot receiving the 3-way split application of fertilizer. This plot also had the highest NUE. The fixed topdress plots also had high NUE at this location. The three-way split application produced one of the better NUEs even for the lower yielding Jagger plots (8% for trt 9, Table 4). Grain yield for the grain-only plots were greater than yields from FG plots. Forage yields from forage-only plots with two harvests were significantly higher when compared to FG plots. There was no difference of variety using either system.

At Tipton, the Jagger plots receiving a 3-way split application gave the highest yields and NUE values (Table 4). The 2174 plots receiving no pre-plant N and 78 kg ha^{-1} topdress out yielded plots employing INSEY N rates at this site (2895 vs. 2196 kg ha^{-1}). At the 40 kg ha^{-1} fixed topdress rate, yields were not different than those from the INSEY plots. This seems to indicate that those treatments where N rates were based on INSEY were not high enough to maximize yields or that the plots fertilized based on the INSEY index were penalized by not having enough pre-plant N applied and thus yields were underestimated when compared to plots with pre-plant N applied. Nitrogen use efficiency was highest for the pre-plant only applications. It seems that at the Tipton site, pre-plant fertilization is necessary to produce high N use efficiency. Forage-only plots had higher dry matter yields than those from the forage + grain system. Values for N uptake were also higher for forage-only plots. Grain yields were higher for grain-only plots when compared to forage + grain treatments.

Crop Year 2001

Yields at the Stillwater site, in 2001 were greatest with Jagger and 112 kg N ha^{-1} applied pre-plant (2721 kg ha^{-1}). This same yield level was achieved when Jagger was fertilized based on INSEY and 22 kg N ha^{-1} applied at flowering for a total N rate of 64 kg ha^{-1}, 48 kg N ha^{-1} less than that required to achieve the same yield using only a pre-plant application (Table 5). Nitrogen uptake was greatest for this same treatment (71 kg N ha^{-1}). Maximum values for NUE were 14 and 20% for 2174 fertilized with variable rates based on INSEY and 22 kg N ha^{-1} applied at flowering and Jagger fertilized based on INSEY and 22 kg N ha^{-1} applied at flowering, respectively.

At Haskell, yields were highest for 2174 fertilized based on INSEY with no other applications (1755 kg ha^{-1}). The 0-N check was the next highest yielding at 1739 kg ha^{-1}. This indicates a minor response to applied N at this site potentially due to large amounts of available soil NO_3. Uptake of N was greatest for 2174 receiving 34 kg N ha^{-1} pre-plant, topdress N based on INSEY and 22 kg N ha^{-1} applied at flowering (Table 5). The highest NUE of 28 % was found with Jagger fertilized based on INSEY.

At Tipton, maximum yields of 3824 and 3775 kg ha^{-1} were achieved when Jagger was fertilized with 56 kg N ha^{-1} plus an INSEY based topdress rate, plus 22 kg N ha^{-1} at flowering, and when 2174 was fertilized with 34 kg N ha^{-1} and a fixed topdress rate of 45 kg N ha^{-1}, respectively. These yields were more than double those of the 0 N check and when comparing the 3-way split (total N rate of 101 kg ha^{-1}) to 112 kg N ha^{-1} applied pre-plant, yield was increased 125 kg ha^{-1}. Jagger fertilized with a 3-way INSEY split application and 2174 with a 3-way split N application also produced maximum values for N uptake (Table 5). The highest NUE was found with an INSEY based topdress N application to 2174 (Table 5). In fact, 2174 with INSEY based 3-way split N produced an NUE of 81% compared to 45% for pre-plant N and 46% for 78 kg N ha^{-1} as a fixed topdress rate.

CONCLUSIONS

Overall, the highest grain yields were achieved with 34 kg N ha^{-1} pre-plant, winter topdress applications based on INSEY, and 22 kg N ha^{-1} applied at flowering. Limited differences were noted between varieties. Maximum NUE values were obtained with different treatment combinations in different years. Various combinations where INSEY was used to determine N rates were always among the best, as well as Jagger with a 112 kg N ha^{-1} pre-plant application. The high average NUE for this treatment appears mainly due to the results from the Tipton site. While residual nitrate from soil tests were not lower than the other locations, the effects of pre-plant N seems to be much greater at Tipton. This may be due to the warmer temperatures and lower rainfall generally experienced in the spring, as compared to the other sites, placing more importance on early season growth and N assimilation. As expected, forage dry matter yields for the two-cut forage-only system were greater than those from the combination grain and forage plots. In addition, grain yields for the grain-only plots were higher than yields for the forage + grain plots. In some instances, like those with both forage and grain removal, large values for yield led to large values for NUE, sometimes over 100%. These results are consistent with those found by Thomason et al.[5] where NUE values over 100% were often noted following years with low potential for utilization of N fertilizer. The advantage of this forage + grain system is to use the forage biomass for grazing without significantly damaging final grain yields, thereby increasing nutrient use efficiency. Problems with forage harvest methods and timing limited final grain yields in some instances and therefore NUEs observed may be lower than normally expected. Choosing efficient varieties and the application of low rates, or even 0 N, at planting, basing in-season topdress rates on INSEY recommendations, and applying foliar N at flowering seems to be the most efficient way to supply N when grain production is the goal.

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