NITROGEN SOURCE, PLACEMENT, AND TIMING INFLUENCE NITRATE LEACHING IN IRRIGATED MAIZE

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ABSTRACT

Nitrate (NO_3-N) leaching below the crop root zone contributes to groundwater contamination. This concern is particularly relevant in Nebraska, where approximately 85% of residents rely on groundwater for drinking water. Adoption of 4R nutrient stewardship practices may reduce nitrate losses while maintaining farm profitability. This three-year study (2023-2025) evaluated the effects of nitrogen (N) fertilizer source, placement, and application timing on NO_3-N leaching and profitability under irrigated maize grown on coarse-textured soil. Eleven fertilizer management programs included injected anhydrous ammonia (AA), broadcast urea and polymer-coated urea (ESN), and urea ammonium nitrate (UAN) applied by broadcast (UAN-B) or injection (UAN-I) under preplant or split programs, plus an unfertilized control. UAN-I consistently had lower NO_3-N concentrations relative to UAN-B across all three years without reducing return to N (RTN). ESN had greater RTN than urea in 2024. Split application at V6 lowered NO_3-N concentrations relative to preplant application, particularly when early-season precipitation was greater. Preplant programs resulted in lower RTN than split programs by 18.0% (2024) and 14.6 % (2025). Overall, subsurface UAN placement and split application lowered NO_3-N concentrations while maintaining or improving economic returns, demonstrating opportunities to protect both farm profitability and groundwater quality.
Keywords: Nitrate leaching, 4Rs, economics, EEF, NUE

INTRODUCTION

Nitrogen (N) is essential for plant growth, but crops take up 30-50% of applied synthetic N fertilizer. The remainder is lost to the environment through various pathways, lowering nitrogen use efficiency (NUE). Improving NUE especially matters in Corn because it uses nearly 68% of the total N fertilizer used in the United States (Monaco et al. 2025), and Nebraska ranks third in U.S. corn production (2026). Annual N fertilizer use in the state has grown more than 20-fold since 1955, reaching 870,897 Mg in 2019, along with a shift in fertilizer source from Anhydrous ammonia (AA; 70-75%) in 1980 to Urea ammonium nitrate (UAN; 57%) in 2022 (Ferguson et al., 2024)

Decades of heavy N fertilization and irrigation on well-drained soils have made NO_3-N leaching the main cause of groundwater contamination in Nebraska (Ferguson et al., 2015). Groundwater supplies drinking water to over 85% of Nebraskans, and 15% of private drinking wells exceed the U.S. EPA safe limit of 10 ppm NO_3-N. So, the problem reaches into both public health and municipal budgets (NDEE, 2024). Long-term exposure to elevated nitrate has been linked to infant methemoglobinemia, certain cancers, and adverse birth outcomes (Ward et al., 2018).

The 4Rs nutrient stewardship framework (right source, right rate, right time, right place) is a practical way to reduce NO_3-N leaching while keeping yields up. But we still

know little about how 4R practices perform across different N sources, timing, and placement. Most leaching studies have tested only one or two fertilizer sources (Maharjan et al., 2014; Peng et al., 2015; Struffert et al., 2016), and field-scale comparisons of fertilizer placement are rare. Because Nebraska has shifted from anhydrous ammonia to UAN as its main N source, comparing surface-broadcast and subsurface-injected UAN is a logical next step for understanding root-zone nitrate dynamics. Therefore, a 3-year field study at the Haskell Agricultural Laboratory (HAL) in Concord, Nebraska was conducted. Our objectives were to (i) compare pore-water NO_3-N concentrations below the corn root zone across N fertilizer sources, application timings, and placement strategies, and (ii) evaluate how these management combinations affect corn grain yield and NUE.

MATERIAL AND METHODS

The experiment was conducted at a farm located near the Haskell Agricultural Laboratory (HAL), Concord, NE (42° 23.613' N, 96° 56.673' W), with a Thurman fine sand texture (sandy, mixed, mesic Udorthentic Haplustolls). The experiment was laid out in a randomized complete block (RCBD) design with 4 blocks, and each block had eleven management programs (Table 1), including an unfertilized control. The four N sources were AA, ESN, Urea, and UAN. UAN was broadcast (B) as well as injected (I). Five N source/placement systems were subjected to two timing scenarios: preplant (P) and split (S). In the preplant program, the full dose of fertilizer was applied before corn sowing, and in the split program, 40% of the dose was applied before planting, with the remaining 60% at V6. Grain yield in each site-year was determined from the two center rows of each 8-row plot harvested from the plot. Two suction cup lysimeters were installed in each plot at a depth of 1.2 m to measure nitrate leaching losses, following protocols by Singh et al. (2024) and Maharjan et al. (2014).

Table 1. Fertilizer treatments used in the experiment from 2023-2025 at a farm near Haskell Agricultural Laboratories (HAL)

Treatments			[&]Stage of fertilizer application	N rate (% of [#]RDF)
N-source	**Placement**	**Time**		
Anhydrous Ammonia (AA)	Injected	Preplant	PP	100% at PP
	Injected	Split[±]	PP + SD at V6	40% at PP + 60% at SD
Urea Ammonium Nitrate (UAN)	Broadcast	Preplant	PP	100% at PP
	Broadcast	Split[±]	PP + SD at V6	40% at PP + 60% at SD
	Injected	Preplant	PP	100% at PP
	Injected	Split[⊥]	PP + SD at V6	40% at PP + 60% at SD
Environmentally Smart Nitrogen (ESN)	Broadcast	Preplant	PP	100% at PP
	Broadcast	Split[⊥]	PP + SD at V6	40% at PP + 60% at SD

Urea	Broadcast	Preplant	PP	100% at PP
	Broadcast	Split[⊥]	PP + SD at V6	40% at PP + 60% at SD
Control	-	-	-	-

Note: UAN was applied at the V6 stage in each split treatment for side-dress. [‡]UAN was injected for AA and UAN-I Split treatments, and [⊥]UAN was broadcast for the Urea, ESN, and UAN-B split treatments

[&]PP = prior to planting; SD = side dress

[#] RDF (recommended dose of fertilizer) was calculated using the UNL-N Algorithm.

RESULTS AND DISCUSSION

Grain Yield

N-fertilizer application increased yield by an average of 5.6 Mg ha^{-1} above the unfertilized control across each study year.

Split programs had higher grain yield than preplant in 2024 and 2025 (Table 2). Similarly, Maharjan et al. (2014) also showed the advantage of splitting N than one-time preplant applications of even EEFs in coarse-textured soils. Fertilizer placement did not affect yield in either year. The N-fertilizer source did affect grain yield. AA treatments had marginally lower yields in 2023 and 2024 than the average of other sources. Further, ESN (regardless of application time) resulted in higher yield than UAN-B in 2024 and 2025 (Table 2). Maharjan et al. (2016, 2017) also showed a yield advantage for ESN in coarse-textured soil; it prevents early-season N loss, thereby increasing plant assimilation and yield.

Table 2. Effect of different nitrogen fertilizer sources and their application timing on mean agronomic efficiency (AE), partial factor productivity (PFP), grain yield, and seasonal average nitrate leaching (NO3-N) concentrations from corn at HAL in 2023,2024 and 2025

Treatments	AE (kg grain kg N^{-1})			PFP (kg grain kg N^{-1})			Grain Yield (Mg ha^{-1})			Seasonal average NO3-N concentrations (mg L^{-1})		
	2023	2024	2025	2023	2024	2025	2023	2024	2025	2023	2024	2025
Control	-	-	-	-	-	-	7.30c	9.90d	9.50c	7.35d	2.81de	12.3c
AA-P	41.6	27.5	32.0	81.5	95.6	92.7	12.8b	14.5c	14.5ab	14.3ab	2.02e	19.1b
AA-S	35.8	27.3	30.6	81.9	95.4	91.2	12.9b	15.4bc	14.3ab	16.0ab	4.24bcd	19.4b
UAN-B-P	47.0	23.1	27.6	76.0	91.1	88.3	13.0b	14.9bc	13.8b	19.0a	7.27a	30.1a
UAN-B-S	43.4	30.1	31.9	89.5	98.2	92.5	15.2a	15.9b	14.5ab	12.4abc	5.42ab	24.7ab
UAN-I-P	45.2	25.0	30.3	91.6	98.1	90.9	13.9ab	15.1ab	14.3b	10.4bcd	5.33ab	23.3ab
UAN-I-S	41.4	30.2	35.7	87.5	98.3	96.4	14.3ab	15.9ab	15.1ab	8.66cd	3.36cd	19.5b
ESN-P	39.1	31.1	33.7	85.2	99.2	94.3	13.4b	15.6b	14.8ab	15.7ab	4.98abc	26.7a
ESN-S	37.4	37.6	38.9	85.1	107	99.5	13.6ab	17.1ab	15.6a	12.2abc	2.87de	23.7ab
Urea-P	36.4	28.5	29.3	82.6	96.5	90.0	13.4ab	14.9bc	14.1b	17.6a	3.17de	29.4a
Urea-S	31.8	28.4	35.0	78.0	96.5	95.6	13.4b	15.1bc	15.0ab	14.2ab	3.62bcd	23.7ab
	ANOVA (Pr > F)											
Treatments	0.68	0.21	0.22	0.74	0.51	0.21	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	Contrast Estimate (Pr > |t|)											
Control vs Other	-	-	-	-	-	-	<0.01	<0.01	<0.01	<0.01	0.03	<0.01
Preplant vs Split	0.27	0.23	0.04	0.79	0.23	0.04	0.15	0.001	0.05	0.08	0.27	0.05
AA vs others	0.73	0.40	0.51	0.57	0.40	0.51	0.06	0.07	0.57	0.37	<0.01	<0.01
ESN vs Urea	0.43	0.04	0.15	0.43	0.12	0.15	0.91	<0.01	0.15	0.43	0.44	0.66
UAN-B vs Urea	0.06	0.60	0.39	0.67	0.61	0.39	0.28	0.32	0.57	0.86	<0.01	0.78
UAN-B vs ESN	0.24	0.01	0.03	0.70	0.04	0.03	0.33	0.03	0.03	0.54	<0.01	0.48
UAN-B vs UAN-I	0.74	0.78	0.25	0.28	0.40	0.25	0.99	0.81	0.27	0.01	0.01	0.03

Least significant difference at the 95% confidence level; Treatments in a column followed by the same letter are not significantly different. Columns that do not contain letters indicate no significant difference between treatments.

Overall, AE and PFP were not affected by fertilization treatments, but contrast estimates showed differences between specific management programs (Table 2). Split management programs had higher AE and PFP in 2025 than preplant programs. There was no effect of placement on either AE or PFP. The fertilizer source effect was limited on these efficiency indices. ESN, regardless of application timing, had higher AE (in 2024 and 2025) and PFP (2025) than UAN-B.

Pore-water nitrate concentrations

The N-fertilizer treatments interacted with sampling days (water sample collection) in all three years for NO_3-N leaching concentrations (Figure 1). In 2023, a series of precipitation events (exceeding the 30-year average) occurred in May, resulting in early-season peaks (Figure 1). Precipitation then declined, peaked again around mid to late June, and remained high through mid-July, with frequent precipitation events. In 2024, above-30-year-average precipitation in April and May delayed planting and fertilization until mid-May. Later in the season, it remained dry (50% of the 30-year average), resulting in lower NO_3-N concentrations throughout the season. Pawlick et al. (2019) and Waring et al. (2022) also noted reduced leaching under high summer crop evapotranspiration. In 2025, concentrations were low earlier in the season, with higher concentrations at the end of June, when we start getting frequent rain. Eventually, at the end of the season in all studies, when canopy-mature evapotranspiration peaked and root uptake drew soil moisture, lowering drainage and pore-water NO_3-N concentration, a buffering pattern Singh et al. (2024) also described.

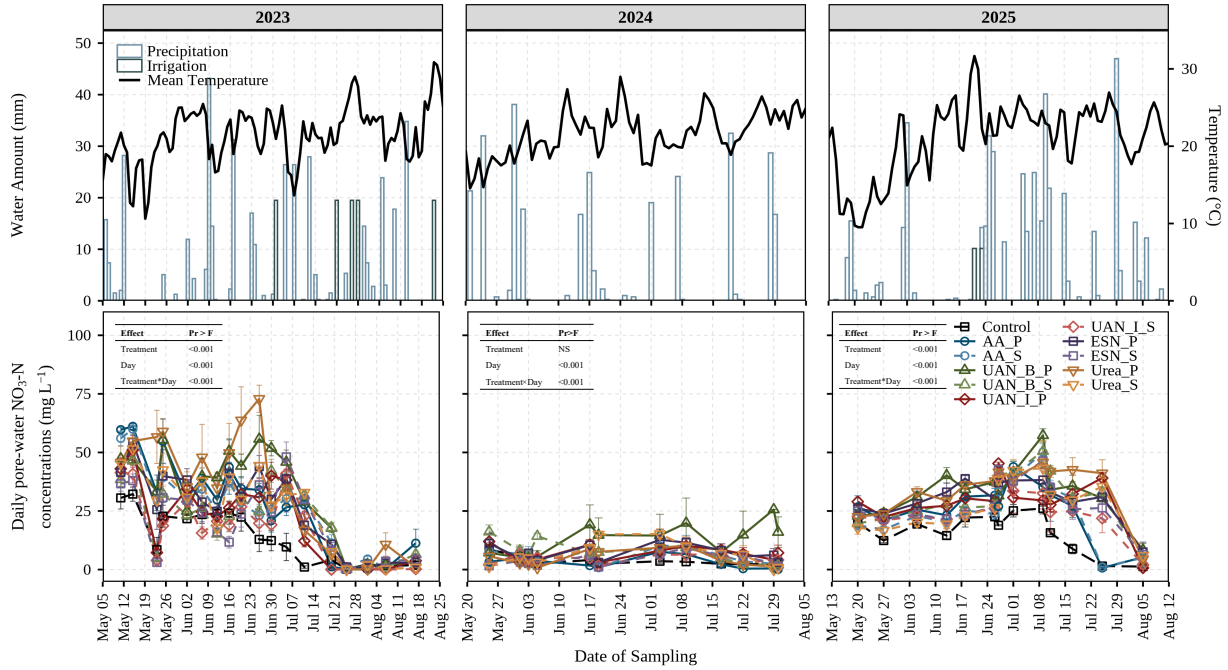


Figure 1. Temporal Dynamics of daily pore-water nitrate nitrogen (NO_3-N) concentrations (mg L^{-1}) under different nitrogen fertilizer sources, application timings (preplant, P; split, S), and placements (broadcast, B; subsurface injection, I) in irrigated maize at a farmer's field near the Haskell Agricultural Laboratory, from 2023-2025. The upper panel shows daily precipitation (mm), irrigation (mm), and mean air temperature (°C). The lower panels show concentrations

over time for anhydrous ammonia (AA), Urea Ammonium Nitrate (UAN), and Environmentally Smart Nitrogen (ESN)/urea treatments compared with the control. Inset values are P-values from two-way repeated-measures ANOVA. Error bars show standard error of the mean.

Across each study year, the average NO_3-N concentrations in fertilized treatments were more than 50% higher than their respective unfertilized control (Table 2). This baseline difference confirms the contribution of soil organic matter mineralization, but N inputs applied were the main source of leaching losses in coarse-textured soils (Peng et al., 2015; Singh et al., 2024). Split programs had lower average NO_3-N concentrations in 2025 and marginally lower in 2023. Fertilizer placement had the most consistent effect, with UAN-I resulting in lower concentrations than UAN-B by 64.6% (2023), 46.1% (2024), and 28.0% (2025). Fertilizer sources did not differ, except AA, which had a 30% (2024) and 23.4% (2025) lower concentration than the average of all other sources.

Economics

RTN differed among N-fertilizer treatments only in 2024 (Figure 2), and there was no difference in 2023 and 2025. There was no effect of placement on RTN; UAN-I had the same returns to nitrogen as UAN-B across all study years. Fertilizer source effects were limited on net returns. ESN had higher RTN than urea by \$192 ha^{-1} (2024). Unlike source and placement effects, timing management programs had a more consistent effect on RTN. Preplant programs had lower RTN than split programs by \$152 ha^{-1} (18%) in 2024 and \$101 ha^{-1} (14.6%) in 2025. Preza-Fontes et al. (2023) also showed early-season leaching losses result in economic penalties under pre-plant treatments.

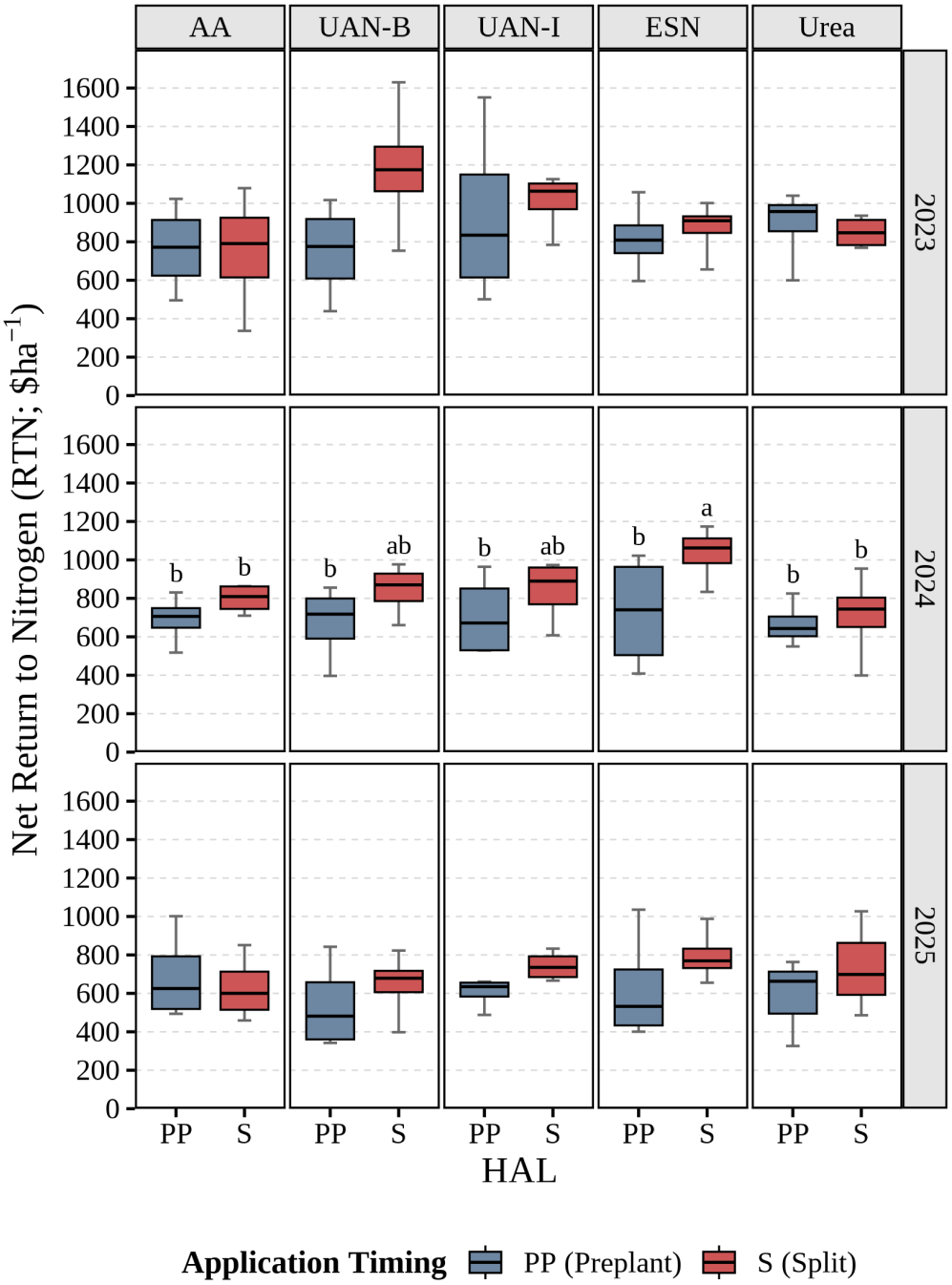


Figure 2. Annual Net Return to Nitrogen (RTN) as affected by nitrogen fertilizer source, placement, and application timing in irrigated maize during 2023-2025 at farms near the Haskell Agricultural Laboratory (HAL), Concord, NE. Fertilizer sources/placement systems include anhydrous ammonia (AA), broadcast UAN (UAN-B), injected UAN (UAN-I), Environmentally Smart Nitrogen (ESN), and urea. Timings: preplant (PP) versus split application (S). Within each year, means followed by different lowercase letters differ significantly according to Fisher's LSD (α=0.05). Error bars denote standard error of the mean.

CONCLUSIONS

Over three years of field data on irrigated maize, nitrate leaching below the root zone depends on how often the timing of rainfall coincides with N fertilization and not just on total rainfall. Another factor is whether rain fell while the crop was actively using water (transpiration) in later corn growth stages, which results in lower nitrate concentration. Rainfall early in the season (2023), before the canopy closed, drove deep drainage and high NO_3-N concentrations in the pore water. When heavy pre-season rain delayed planting and fertilization, peak crop demand during mid-summer rain transpired it, and little water drained through. A long dry spell early on, followed by mid-summer rain, was the worst case for a different reason: the nitrogen that had piled up in the soil came out in short, concentrated pulses. The fertilizer placement effect was consistent across all years. Injecting UAN below the surface reduced seasonal average NO_3-N concentrations compared with UAN-B, in every weather pattern, and it did not penalize net return to nitrogen. Among the sources, AA had higher yield than the average of the other sources in 2024 and 2025. ESN had higher yield than UAN-B in 2024 and 2025. But ESN had higher RTN in 2024 than urea. Applying 40% pre-plant and 60% at V6 reduced NO_3-N leaching concentration, particularly by avoiding early-season drainage. Broadcasting nitrogen on the surface, or putting it all down in a single pre-plant pass, had economic penalties. Subsurface injection and splitting fertilizer into early applications keep more of the crop's profit and reduce the nitrate that reaches groundwater.

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