THE THREE-LEGGED STOOL: NITROGEN, ENVIRONMENT, AND CROP PRODUCTION

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ABSTRACT

Nitrogen (N) loss reduces production and soil health. The objectives of this 3-yr continuous corn (Zea mays L.) US Midwest study were to evaluate traditional and advanced N management on corn N content, grain yield and economic returns; soil N content; and N losses [nitrate (NO_3^-), nitrous oxide (N_2O), and ammonia (NH_3)]. Treatments were: single pre-plant applications of 180 lb N ac^{-1} urea (U) or polymer coated urea ESN (E), and split with 60 lb N ac^{-1} pre-plant applications of either urea (U/U+) or ESN (E/U+) and 120 lb N ac^{-1} as urea+NBPT [N-(n-Butyl) thiophosphoric triamide] at V6. Split and E produced similar grain yield (177 bu ac^{-1} mean) and total N uptake (TNU) (140 lb N ac^{-1} mean) and were greater than treatment U (162 bu ac^{-1} and 119 lb N ac^{-1}). Net economic returns decreased: E/U+>U/U+>E>U, and splits and U had similar losses. The yearly mean sum of N_2O, NH_3, and NO_3^- was 47 to 49% lower with E vs. U, U/U+ and E/U+ (12.9 vs. 25.4, 24.2, and 24.6 lbs ac^{-1}, respectively). Consistent lower N losses for E and better grain yield than U or similar to split treatments indicate that E may be a valuable tool.

INTRODUCTION

Nitrogen, crop production, and environment are interrelated. Overemphasizing one component or underemphasis another creates instability, just like adding or cutting a piece of a leg in a three-legged stool. For brevity reasons, this proceedings article will focus on one particular study to illustrate points, but the oral presentation will discuss several projects aimed at finding where each of the three components (Nitrogen, crop production, and environment) are harmonized to produce a sustainable productive and environmentally-sound system. The results presented here are a summary of results published elsewhere (Menegaz et al., 2024).

The objectives of this continuous corn (*Zea mays* L.) US Midwest study over 3-yrs were to evaluate traditional and advanced N management on soil N content; N uptake, grain yield and economic returns of corn; and N losses as nitrate (NO_3^-), nitrous oxide (N_2O), and ammonia (NH_3).

MATERIALS AND METHODS

A field experiment was conducted from 2018 to 2020 in a continuous corn cropping system established in 2014 at the University of Minnesota Southwest Research and Outreach Center (SWROC) near Lamberton, MN (44°14’11.0” N 95°18’41.7” W), on a poorly drained Webster-Canisteo clay loam soil.

There were four treatments: single pre-plant applications of 180 lbs N ac^{-1} urea (U) or polymer coated urea ESN (E), and split with 60 lbs N ac^{-1} pre-plant applications of either urea (U/U+) or ESN (E/U+) and 120 lbs N ac^{-1} as urea+NBPT [N-(n-Butyl) thiophosphoric triamide] at V6.

Plant and soil samples were collected at various times during the growing season for nitrogen analysis. N losses were monitored throughout the growing season for nitrate (NO_3^-) and nitrous oxide (N_2O), and for approximately the first 60 days of the study for ammonia (NH_3).

Using local service supplier prices at the time the study, net economic return for the treatments was calculated by subtracting fertilizer and application costs from corn revenue. Corn revenue was calculated by multiplying corn yield by corn price of US$3.50 bu^{-1}. The following prices were used to calculate fertilizer costs: urea US$0.34 lb-N^{-1}, ESN US$0.54 lb-N^{-1}, and urea with Agrotain US$0.39 lb-N^{-1}. The pre-plant application cost was US$4.49 ac^{-1} and the side-dress application cost was US$11.01 ac^{-1}. All other costs were the same regardless of treatment and were not considered.

All the results were statistically analyzed. For more details on methodology, see Menegaz et al. (2024).

RESULTS AND DISCUSSION

Plant N uptake and grain yield

Total nitrogen uptake was lower for U compared to the other treatments in 2019, 2020 and for the 3-year mean, and a similar trend was observed in 2018 (Table 1). Averaged across years, TNU was 13 to 16% lower for U compared to the other treatments. The results highlight a clear advantage with the advanced N management practices, especially ESN combined with a side-dress application, to supply N during the entire growing season.

Although treatment differences in grain yield occurred only in 2020, all years showed consistently a similar trend, which was reflected in the differences observed for the 3-yr mean where the traditional treatment U resulted in lower yield (162 bu ac^{-1}) than the three advanced management treatments (Table 1). These results reflect the fact that advanced practices were better able to supply N through the season, as previously discussed for TNU. Further, net return calculations showed a clear advantage to using advanced management practices instead of a single pre-plant application with urea. Even though ESN is more expensive than urea, E instead of U increased net returns by US$18 ac^{-1} above the US$499 ac^{-1} revenue generated with U averaged across the three years of the study (Table 1). The split treatments were even more advantageous (despite the added cost of a side-dress application) generating an additional US$31 ac^{-1} (U/U+) and US$38 ac^{-1} (ESN/U+) compared to U.

Table 1. Mean plant total nitrogen uptake (TNU), grain yield, and net return from yield for 2018 to 2020 and 3-year mean as affected by treatment (Urea and ESN applied pre-plant at 180 lb N ac^{-1}; Urea/Urea+ and ESN/Urea applied pre-plant at 60 lb N ac^{-1}as urea or ESN followed by an application of 120 lb N ac^{-1} as Urea+NBPT [N-(n-Butyl) thiophosphoric triamide] at V6 corn development stage).

Year	Treatment	TNU‡	Grain Yield	Net Return§
		lb N ac^{-1}	bu ac^{-1}	US$ ac^{-1}
2018	Urea	129	147	447
	ESN	140	172	501
	Urea/Urea+	145	163	487
	ESN/Urea+	149	167	492
2019	Urea	107b†	163	503
	ESN	129a	167	484
	Urea/Urea+	131a	177	537
	ESN/Urea+	135a	179	531
2020	Urea	122b	175b	548
	ESN	143a	191a	568
	Urea/Urea+	142a	185ab	565
	ESN/Urea+	145a	194a	587
3-year Mean	Urea	119b	162b	499
	ESN	138a	177a	517
	Urea/Urea+	139a	175a	530
	ESN/Urea+	143a	180a	537

† Means within columns and year followed by different letters are significantly different ($P < 0.05$).

‡ Total nitrogen uptake (TNU) is the sum of plant N uptake at R6 and harvest grain N.

§ Calculated by subtracting fertilizer and application costs from corn revenue (corn price US\$3.50 bu^{-1}; urea US\$0.34 lb-N^{-1}; ESN US\$0.54 lb-N^{-1}; urea with Agrotain US\$0.39 lb-N^{-1}; pre-plant application US\$4.49 ac^{-1}; split application US\$11.01 ac^{-1}). All other costs were the same regardless of treatment and were not considered.

Nitrous oxide emissions

Although only the year total cumulative N_2O data are shown (Table 2), it is valuable to review some of the highlights of individual years, which are not presented here. The yearly fluxes averaged across treatments were greater in the wetter years, 2018 (40 µg N_2O-N m^2 h^{-1}) and 2019 (35 µg N_2O-N m^2 h^{-1}), than in the drier 2020 (23 µg N_2O-N m^2 h^{-1}), which highlight the large influence of weather conditions on environmental outcomes from N management strategies. While the magnitude of emissions varied between years and treatments, the temporal patterns of daily mean fluxes and resulting cumulative N_2O losses were generally similar across the growing seasons. Soil N_2O fluxes were low at the beginning of each season immediately before and after planting. Substantial emissions occurred within a few days after N application and continued for approximately 6 weeks during June and July. In fact, there were nine very high daily mean N_2O fluxes that occurred soon after the side-dress applications or after application of the U treatment in conjunction with precipitation events. Fluxes typically returned to baseline levels and remained low from August to October. These data support the finding that N fertilization is the primary contributor of N_2O in agriculture.

Table 2. Least square means and significance of F values for fixed sources of variation and their interactions for area scaled N_2O emissions (aN_2O) and yield-scaled N_2O emission (yN_2O) calculated by dividing aN_2O by grain yield.

	Direct aN_2O emission	yN_2O
	lb N ac^{-1}	lb N bu^{-1}
Year (Y)		
2018	2.7	0.015
2019	2.6	0.013
2020	1.8	0.009
Treatment (T)†		
Urea	3.4	0.022
ESN	1.4	0.008
Urea/Urea+	2.3	0.013
ESN/Urea+	2.2	0.013
Interaction		
Y*T	<0.05	<0.05

† Treatments were Urea and ESN applied pre-plant at 180 lb N ac^{-1}; Urea/Urea+ and ESN/Urea applied pre-plant at 60 lb N ac^{-1} as urea or ESN followed by an application of 120 lb N ac^{-1} of Urea+NBPT [N-(n-Butyl) thiophosphoric triamide] at V6 corn development stage.

The significant year by treatment interaction for *a*N_2O and *y*N_2O (Table 2) illustrates that N_2O emissions were impacted by the amount and distribution of precipitation after fertilizer application regardless of when it was applied (pre-plant or V6). Potential for N_2O loss was high for both application times in 2018 and pre-plant in 2019 and was low for both applications in 2020 and side-dress time in 2019. The interaction for *a*N_2O and *y*N_2O was explained by ESN substantially lowering emissions relative to treatments with urea during wet conditions soon after the pre-plant application (2018 and 2019) while no differences occurred when it was drier than normal in 2020, though a trend for more loss with U was also observed. Within 30 days after the pre-plant fertilizer application there were 16 days with 7.4 inches of precipitation in 2018 and 14 days with 4.7 inches in 2019, whereas there were only 9 days with 3.1 inches in 2020. Further, the year by treatment interaction clearly showed that split treatments might produce no benefit relative to U if substantial precipitation follows the side-dress application, as was the case in 2018 but not in 2019 and 2020. Within 30 days after the side-dress application, there were 15 days with 8.9 inches of precipitation in 2018, compared to only 10 days with 3.8 inches in 2019 and 10 days with 4.4 inches in 2020. Even closer to the time of application, within 7 days, it was observed that 5 days of precipitation totaling 2.8 inches in 2018 was sufficient to induce greater N_2O loss relative to 2019 (0.7 inches over 3 days of precipitation) and 2020 (0.8 inches during 1 day of precipitation). While logistically in commercial farming it is not always possible to side-dress at the best time, guiding the application based on a 5-to-7-day weather forecast can be an effective management strategy. Although E was not as profitable as the split treatments (U/U+ and ESN/U+) (Table 1), the fact that E consistently had low N_2O emissions regardless of weather conditions indicates that this management strategy could be viable for environmental-stewardship incentive programs. Further, since E maintained high grain yield levels, this management represents a win-win situation in the context of protecting the environment while maintaining agricultural productivity to meet the demands of a growing global population.

Ammonia volatilization

As with N_2O, although only the year total cumulative NH_3 data are shown (Table 3), it is valuable to review some of the highlights of individual years, which are not presented here. Ammonia emissions followed a similar temporal pattern between 2019 and 2020, but the magnitude was greater in 2019 likely due to differences in weather conditions that favored loss (Table 3). Compared to 2020, in 2019 the air temperature was 57°F warmer between days 1 to 5 and 45°F warmer between days 6 to 10 after the pre-plant application. Also, in 2019, 0.4 inches of precipitation three days after side-dress applications was likely sufficient to solubilize but not incorporate the fertilizer into the soil, thus increasing substantially the potential for NH_3 fluxes and cumulative loss. Whereas in 2020, 0.8 inches of precipitation five days after side-dress likely solubilized and incorporated the fertilizer deep enough in the soil to minimize NH_3 volatilization.

Table 3. Cumulative NH_3 loss for two 28-day periods after pre-plant and side-dress fertilizer applications and as a total across measurement periods for 2019, 2020, and the 2-year mean as affected by treatment (Urea and ESN applied pre-plant at 180 lb N ac^{-1}; Urea/Urea+ and ESN/Urea applied pre-plant at 60 lb N ac^{-1}as urea or ESN followed by an application of 120 lb N ac^{-1} as Urea+NBPT [N-(n-Butyl) thiophosphoric triamide] at V6 corn development stage).

Treatment	28 days after pre-plant application			28 days after split application			Total NH_3†		
	2019	2020	Mean	2019	2020	Mean	2019	2020	Mean
	lb ac^{-1}								
Urea	1.61a‡	1.16a	1.43a	0.09b	0.09b	0.09b	1.96b	1.16a	1.43a
ESN	0.45b	0.09b	0.27b	0.09b	0.09b	0.09b	0.63b	0.18b	0.27b
Urea/Urea+	0.27b	0.18b	0.18b	4.73a	0.89a	2.05a	5.18a	1.07a	2.32a
ESN/Urea+	0.27b	0.09b	0.09b	5.80a	1.07a	2.50a	6.07a	1.07a	2.59a

† Total NH_3 is the sum of cumulative emissions collected during the two sampling periods. In 2019, the final sampling was 30 days after side-dress application.
‡ Means within columns followed by different letters are significantly different ($P < 0.05$).

In 2019 and 2020, cumulative NH_3 emissions for U increased rapidly after fertilizer application for approximately 28 days until they plateaued. On the other hand, the full N fertilization rate with E showed a small amount of NH_3 accumulation, similar to the split treatments that had received only one-third of the fertilizer N. At 28 days after the pre-plant application, compared to U, the advanced treatments (E, U/U+, and E/U+) lowered cumulative NH_3 loss by approximately 80% in 2019 and 90% in 2020 (Table 3). After the side-dress application, although the magnitude was greater in 2019, both years displayed a rapid increase in cumulative NH_3 emissions during the entire sampling period for split treatments (U/U+ and E/U+), but little accumulation occurred for U and E. The cumulative NH_3 loss during the 58 days of measurement were on average 4.3 times greater for the split treatments (U/U+ and E/U+) than the single pre-plant treatments (U and E) in 2019, and in 2020 U and the split treatments produced 6 to 6.5 times greater loss than E (Table 3). As explained earlier, different weather conditions in the two years resulted in distinct treatment outcomes.

While only in 2020 U resulted in greater total NH_3 emissions than E, 2019 showed a similar trend with approximately the same difference between the treatments (Table 3). Further, the combined analysis across the years clearly shows that E lowered NH_3 emissions by 81% compared to the traditional practice (U). In addition, E was consistently superior in lowering total NH_3 emissions by 88 to 90% compared to the advanced practice of split applications (Table 3). Further, over the two years, the split treatments produced no advantage compared to U, and in 2019, split treatments actually significantly increased emissions. Agronomists often view split applications as superior to pre-plant applications to lower the risk of N loss in typical wet springs. These results clearly show that, while the N loss is nominal in agronomic terms (only a few pounds) and not reflected in grain yield (Table 1), the negative environmental impact of surface applications in-season can be substantial when there is insufficient precipitation to incorporate fertilizer in the soil. This is true even when applying a urease inhibitor as a recommended best management practice. These results highlight how challenging it is to manage N in the field under unpredictable weather conditions. However, these findings also point out, as described for N_2O, that E can be a viable alternative to meet both agricultural productivity- and environmental protection-goals.

Nitrate leaching

Nitrate loads were lower for E than the other treatments in 2019, and a similar trend was observed in 2018 during the two above-normal precipitation years of the study (Table 4). Conversely, loads were similar between all treatments and much lower during the drier-than-normal 2020 growing season that produced only a few episodic N loss events (Data not shown). As already discussed for N_2O and NH_3, E also shows promise as a management strategy to lower NO_3^- loading and mitigate the environmental footprint of N fertilizers in agriculture, especially when adverse weather conditions increase N loss potential. Unfortunately, the advanced N management practice of split applications showed no benefit compared to the traditional U application.

Drainage amounts as well as daily nitrate loads (data not shown) were greatly influenced by precipitation amounts and distribution, but there were no drainage differences due to treatment. However, during 2019, the wettest year of the study where daily NO_3^- loads were as high as 13 lb N ac^{-1}, there was a trend for less drainage with E (Table 4). Because NO_3^- load is greatly influenced by drainage amounts, flow-weighted NO_3^- concentration, are often used to account for differences in drainage. While there were no treatment differences for flow-weighted NO_3^- concentration, the trend for lower concentrations with E during the wet years as well as the average across years was consistent with the load data already discussed. The lack of treatment difference could be the result of compounded variability as drainage and concentration measurements, each with their inherent variability, were combined in the calculation. This is a common challenge for these kinds of studies. Furthermore, NO_3^- concentrations were below the maximum drinking water standard of 10 mg L^{-1} set by USEPA. Since the N rate used was within the MRTN rate recommended by university guidelines, these results highlight that when the right rate of N is applied, other N management practices, such as source or time of application, might provide limited additional benefit to lower NO_3^- concentrations in drainage water.

Table 4. Mean annual sub-surface drainage water, NO_3^- load leached, and flow-weighted NO_3^- concentration for 2018 to 2020 and 3-year mean as affected by treatment (Urea and ESN applied pre-plant at 180 lb N ac^{-1}; Urea/Urea+ and ESN/Urea applied pre-plant at 60 lb N ac^{-1}as urea or ESN followed by an application of 120 lb N ac^{-1} as Urea+NBPT [N-(n-Butyl) thiophosphoric triamide] at V6 corn development stage).

Treatment	NO_3^- Load				Drainage				Flow-weighted			
	2018	2019	2020	Mean	2018	2019	2020	Mean	2018	2019	2020	Mean
	-------------lb ac^{-1}-------------				-------------inch-------------				-------------mg L^{-1}-------------			
Urea	18	29a†	5	17a	8.8	20.3	2.7	9.7	8.8	6.3	8.0	7.8
ESN	13	16b	4	11b	8.9	13.0	1.8	7.4	6.9	5.9	8.6	7.2
Urea/Urea+	20	31a	4	16a	10.6	18.0	1.9	9.2	8.4	8.1	8.2	8.2
ESN/Urea+	20	29a	5	16a	11.0	17.1	2.8	10.1	8.1	7.4	6.6	7.4

† Means within columns followed by different letters are significantly different ($P < 0.05$).

CONCLUSIONS

Finding N management tools that increase or at least maintain crop productivity and profitability while improving N utilization and lower of N loss is fundamental to meeting the growing global demand for agricultural products in an environmentally minded way. Field conditions are challenging to meet these goals as our ability to forecast weather accurately, especially precipitation, extends only a few days into the future. Split applications, which in theory are considered best management practices to address both production and environmental protection goals, only produced crop production benefits without lowering N loss compared to the traditional U application. Clearly, one of the biggest challenges in lowering N loss is related to weather conditions following N fertilization regardless of when the application is done. While it might not be possible to obtain the full benefit of a given practice every year, favoring practices that have a higher frequency of producing gains, or at least not resulting in drawback, is appropriate given the uncertainty of growing season conditions that extend past the time of fertilization. Application of E can be a robust tool because it consistently maintained high productivity and net economic benefits while protecting against the different N loss pathways throughout the growing season regardless of different weather conditions. The combined direct measurements of aN_2O, NH_3, and NO_3^- showed an annual loss of

N that was 47 to 49% lower with E (12.9 lb ac^{-1}) than U, U/U+ and E/U+ (25.4, 24.2, and 24.6 lb ac^{-1}, respectively). While E represents a more complete solution because it meets both goals to maintain productivity and profitability and lower N loss to the environment, there are still costs with this practice. There is an added cost in the form of lower net returns compared to the most profitable production strategy tested, and N losses are lowered but not eliminated, which highlights the fact that even when using the best available practices there is an environmental cost to agricultural production. While profitability is key to farmers, incentive programs that pay for loss of revenue due to lower grain yields are often met with greater resistance than if the incentive is to pay for the implementation of an improved management practice that maintains or increases grain yield. As a management practice, E has a high potential for implementation success. This is because it does not require fundamental changes in equipment or logistics for farmers, and the difference in net profit compared to the most profitable scenario is relatively simple to calculate for compensatory measures given that the costs are related to inputs (fertilizer and application costs) and not do to reduction in grain yield. Although these results are promising, this study is limited to a single location and three years. Additional studies are needed before broad adoption of these results can be encouraged beyond the local conditions of this study.

REFERENCES

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