FINAL REPORT

PROJECT TITLE: Nutrient Management Dynamics in Northwest Minnesota Corn Production
PROJECT NUMBER: 6103-23DD
PRINCIPAL INVESTIGATOR AND CO-INVESTIGATOR(S): Lindsay Pease

ABSTRACT

Recent increases in corn production in Northwest Minnesota (NW MN) means that additional soil fertility information is needed to ensure that recommendations are accurate for the soil in this region. The overall goal of this project was to evaluate how nutrient management decisions impact nitrogen (N) and phosphorus (P) dynamics in Northwest Minnesota soils. To meet this goal, we conducted a two-year field trial and a complementary laboratory experiment to evaluate the potential agronomic benefits and environmental tradeoffs of three different P fertilizer sources (MAP, MESZ, struvite), and three rates of P fertilizer (single rate, double rate, none) ahead of corn in a corn-soybean rotation. Field trials demonstrated that phosphorus rate and proper soil fertility management were more important than P fertilizer source when managing corn ahead of soybeans. We saw some evidence that MESZ improved zinc uptake at higher P levels, but this did not translate to greater harvested yields. Factors outside of soil fertility likely affected corn yields in 2022 and 2023. We observed dry soil conditions and net nitrogen immobilization in the soil, particularly during the early growing season. Although sufficient N was present in the soil, it was not necessarily in a form that the crop could use. Our laboratory analysis simulating flooded soil conditions showed that it took approximately three weeks to see dissolved P release from soil to water.

Based on our findings, we recommend that Northwest Minnesota farmers continue to follow University of Minnesota's current fertility guidelines. The current guidelines appear to provide sufficient fertility given that enough moisture is present in the soil to support the corn crop. Double rates provided little agronomic benefit over single rates during the corn phase. We recommend that Minnesota farmers avoid applying double rates of P fertilizer on fields that experience prolonged spring flooding. For these fields, the limited agronomic benefit gained by applying a double rate of fertilizer is unlikely to outweigh increased risk of P loss to surface water.

INTRODUCTION

With more farms adopting corn into their rotations in the coming decades, supporting growers with research-based recommendations will help promote both more profitable corn production systems and improved soil and water quality. One potential fertility strategy for corn-soybean rotations is to apply a two-year application of phosphorus (P) fertilizer while nitrogen (N) fertilizer is applied for corn. Because triple super phosphate fertilizer is not widely available, this strategy means that farmers need to choose a P fertilizer that may contain other nutrients. Two common P fertilizers in NW MN are monoammonium phosphate (MAP, 11-52-0) and MicroEssentials SZ (MESZ, 12-40-0-10S-1Zn). A newly available P fertilizer, struvite, is manufactured from recycled sources. Adding N above the UMN recommended maximum return on nitrogen rate to reach P application goals may cause small changes in the soil environment, affecting microbial activity, carbon (C) pools, and nutrient cycling. One potential concern with applying a two-year application of P fertilizer is that the timing of application will not be aligned with crop uptake. Spring snowmelt is a critical time of the year when excess soil moisture and flooding has the potential to move soil and nutrients off-site and into waterways. This project explored the combined effects of fertilizer source and rate decisions on N, P, and C dynamics from multiple perspectives: corn grain production, soil nutrient availability, and water quality.

OBJECTIVE AND GOAL STATEMENTS

The overall goal of this project was to evaluate how nutrient management impacts N, P, and C dynamics. Our goal was met by achieving the following objectives:

1. Comparing the effect of fertilizer source and rate on corn yield/production metrics
2. Monitoring soil N, P, and C availability in response to fertility treatments, soil moisture levels, and soil temperature in a two-year, corn-soybean rotation
3. Measuring post-harvest N and P losses in snowmelt runoff in relation to residual soil nutrient concentrations

MATERIALS AND METHODS

Site Description/Experimental Design

Field trial

Field trials were established at the University of Minnesota's Northwest Research and Outreach Center in Crookston, MN, which is in the Red River Valley in 2022 and 2023. Field treatments in the fertility field trials were applied to plots by hand broadcast then incorporated by plough in randomized complete block design with four replicates in the spring prior to planting. Treatments included the following commonly used fertilizers: monoammonium phosphate (MAP, NPK: 11-52-0), MicroEssentials SZ (MESZ, NPK-Zn: 12-40-0-10S-1), and 25% Struvite/Crystal Green (NPK: 5-28-0) with 75% MAP. Treatments were split by single rates (meeting the corn requirement only) and double rates (meeting the corn requirement and soybean requirements) (table 1). The fertilizer rates used were selected based on University of Minnesota recommendations for corn and soybeans. Plot sizes for both fields and all years were 11 x 30 feet (330 ft^2, 0.00758 acres). Early RM field corn (76 RM) was planted in 6 rows per plot with 22 inch spacing, for a target seeding rate of 35,000 seeds per acre. Urea was applied at a blanket rate to the ranges to meet university recommendations.

Table 1 Field Trial Phosphorus-Based Fertilizer Treatment Names and Rates

Phosphorus-Based Fertilizer Treatment	Rate	
	Year 1 (corn)	Year 2 (soybean)
	lbs P_2O_5 ac^{-1}	
MAP 1x/1x	100	80
MAP 2x/0x	180	0
MAP 1x/0x	100	0
MAP + Struvite 1x/1x	100	80
MAP + Struvite 2x/0x	180	0
MESZ 1x/1x	100	80
MESZ 2x/0x	180	0
None (Control)	0	0

Field Sample Collection

Each summer corn stand counts were taken on 6-22-2022 and 6-12-2023. Crops were staged and sampled for biomass nutrient testing on 7-6-2022 (V2) and 6-14-2023 (V5). At harvest, corn grain and biomass were tested for total N, P, K, S, Ca, Mg, Na, Zn, Fe, Mn, Cu, and B. Harvest dates were 10-10-2022 and 10-17-2023. Soil fertility tests were taken prior to or at planting for all field trials and a standard fertility analysis was conducted to test for N, P, K, S, and Zn. Nitrate mineralization data was collected by collecting final and initial soil samples in the same plot location contained in schedule 40 PVC cores on a biweekly basis. At the initial time point, soil was sampled at the initial location for the "initial sample" and then cores were hammered at least 15 cm into each plot in the center of the plot in a representative row and covered with a PVC plastic cap to isolate the soil in the column from precipitation and crop material. After 2 weeks, the cores were removed for soil testing the final sample. The initial and final samples allow us to see the change in nitrate and ammonia as mineralization occurs, without interference from environmental disturbance. Soils were homogenized by hand in the field, then air-dried, and ground through a 2 mm sieve and stored for in-house testing in the winter and analyzed for NO_3 and NH_3. Nitrate mineralization methods were based on established methods (Balkcom et al., 2009; Fernández et al., 2017). Soil moisture and temperature were collected on 8/31/2022, 9/14/2022, 9/28/2022, 10/13/2022. In 2023, they were measured biweekly at nitrate mineralization sampling then until harvest. Soil moisture was measured with a ML3 ThetaProbe Soil Moisture Sensor, and soil temperature was measured with a Taylor 3519 thermometer. Nitrification and ammonification rates were determined by calculating the change in inorganic nitrogen between the samples over two weeks, and ammonification were summed to determined mineralization rates.

Laboratory Analysis

Laboratory flood simulation study

Soil samples collected from Fall 2022 following corn harvest were used to explore the environmental tradeoff of single and double rates of P fertilizer. Lab-grade plastic 50 ml centrifuge tubes were packed with 15 g soil ground to < 2mm (0% moisture, ~1.0 g cm^{-3}) for each of the eight fertilizer treatments, at the two depths, with three replicates. This was done eight times, to pull off samples over eight weeks of the trial. 30ml deionized water was added to each at the initial sampling time to create the mesocosms. Mesocosms were kept gently covered with caps to prevent evaporation and were refrigerated to simulate the cool environment of early spring snowmelt flooding. Upon collection, times were recorded, and pH was measured with a glass probe (Fisher Scientific ACCUMET AR15 PH/MV/TEMP KIT), and refrigerator temperature was recorded. This study was conducted initially in January 2023 and repeated in October 2023 with the samples from the same field sampling date. Water levels were maintained at 30ml prior to sampling with deionized water. The refrigerator temperature was an average of 5.6 °C in Trial 1 and 5.5°C in Trial 2 and ranged from 4.5°C to 8°C. This is comparable to NOAA monthly climate normals (1991-2020) for April (4.83°C) and May (12.3°C) in the Grand Forks, ND & MN region ("U.S. Climate Normals," 2021). Supernatant water was sampled and tested for dissolved P at the initial date of the study and weekly for eight weeks, for a total of nine time points. At each sampling time point, the supernatant was collected (~10ml) using syringes off three replicates of each treatment on each sampling day, then discarded, so that each sample at all time points had not been previously disturbed or drained of water. Samples were analyzed immediately upon collection from the mesocosms. A deionized water blank was analyzed with each collection date run.

Soil and water sample analysis

All in-house soil nutrient analysis at the Pease Lab was done on an AQ400 Automated Discrete Analyzer (SEAL Analytical, Mequon, WI). Soil NO_3 and NH_3 were tested with the AGR-231-A method, which has a detection limit of 0.03 mg N L^{-1} for nitrate and 0.011 mg N L^{-1} for ammonia. These are reported as N species. Samples not tested in-house were sent to Agvise Laboratories (Benson, MN), for analysis.

Water samples were tested for dissolved P via EPA-118-C Rev. 2, *o-Phosphate–P in Drinking, Saline and Surface Waters, and Domestic and Industrial Wastes* on an AQ400 Automated Discrete Analyzer (SEAL Analytical, Mequon, WI). This method has a detection limit of 0.01 mg P L^{-1}.

<u>Statistical analysis</u>

Corn yield and production metrics

Corn production metrics were analyzed by site-year with a linear mixed effects model with "block" as a random effect. Post-hoc testing was done via multiple comparisons with Least Square means using the *Tukey-HSD* test. All statistical analysis was completed using JMP Pro 17.0.0 (JMP Statistical Discovery LLC, 2022) at α=0.10.

Laboratory flood simulation study

Raw data were not normally distributed via the Shapiro-Wilks test at α=0.05. Dissolved P data were log-transformed. A constant was added to perform the analysis, and non-parametric statistical tests were implemented. Data were analyzed with a restricted maximum likelihood linear mixed effects model with time series and with replicates as a random effect and a repeated measures ANOVA, using the *lme4* and *stats* packages. Estimated marginal means were obtained with the *emmeans* package in R (R Core Team, 2022). Statistics and preparation were done with base R, *stats*, *reshape2*, and *outliers* packages. Spearman's rank correlation coefficient was used to assess relationships between dissolved P and pH, and total P and pH on log-transformed nutrient concentrations.

RESULTS AND DISCUSSION

Corn yield and production metrics

Pre-treatment soil testing in Fall 2021 showed that field plots were "low" in P (3 ppm Olsen), "very low" in zinc (0.31 ppm), and sufficient in potassium (226 ppm) and sulfur (24 lb ac^{-1}). In Fall 2022, field plots tested "low" for P (6 ppm), but were sufficient in zinc (0.83 ppm), potassium (171 ppm), and sulfur (84 lb ac^{-1}). We saw a significant yield response to treatment in 2022 but not in 2023 (Figure 1). The observed treatment responses are in line with university recommendations. The improvement in yield for the "2x MESZ" and "2x MAP" treatments compared to the "1x MESZ" and "1x MAP" treatments shows that rate may be a stronger factor than source when soil fertility is a limiting factor. Prior fertility work on corn in Minnesota estimates that a yield response to P fertilizer application will be seen about 87% of the time at "very low" fertility levels, but soils testing at 6 ppm Olsen-P are nearing a threshold level where P fertility response may not be seen (Kaiser et al., 2023). University of Minnesota guidelines recommend broadcasting 10 lb Zn ac^{-1} based on our Fall 2021 soil test. Even at our "2x MESZ" rate which applied about 2 lb ac^{-1}, soils were likely deficient in zinc during the 2022 growing season. Comparing between site years, both P and zinc content in corn grain were lower in 2022 than 2023, providing further evidence that zinc deficiency impacted corn yields in 2022.

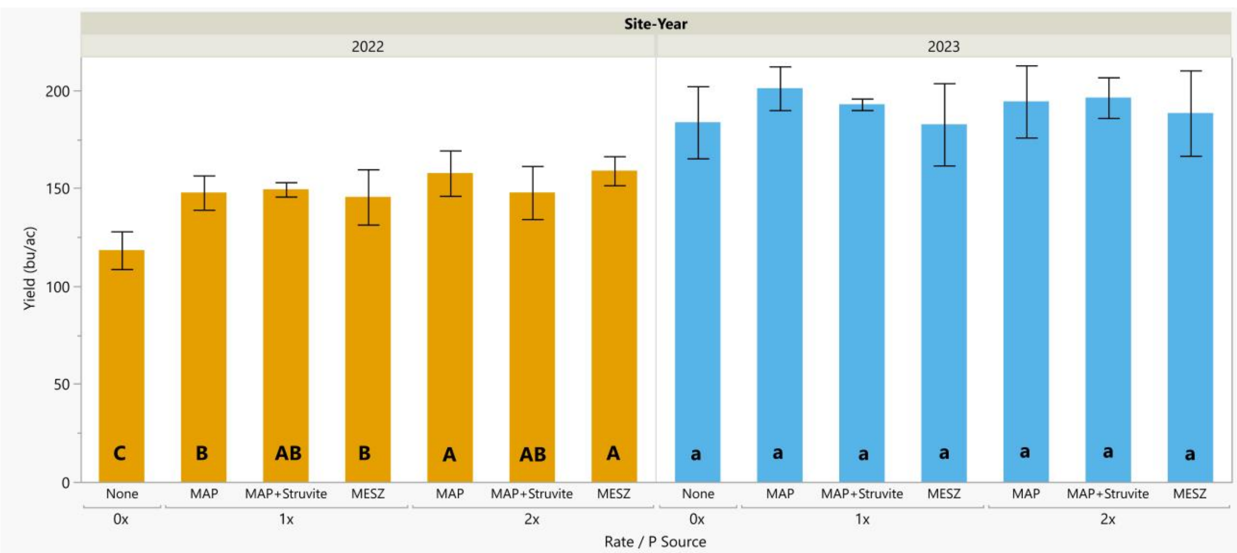

Figure 1: Average corn yield by treatment. Error bars indicate standard deviation from the mean. Yields are averaged by treatment and reported by site-year (2022 and 2023). Different uppercase or lowercase letters indicate treatment means are significantly different ($p<0.10$).

We observed inconsistent benefits from specialized P products between the two years. In 2022, zinc uptake by corn grain was greater in the "2x MESZ" treatment than the "2x MAP" treatment. This suggests that MESZ at least partially alleviated reduced Zn uptake with rates of P as intended. Zinc has a complex relationship with phosphorus, as both can bind together and P can reduce zinc release to plants (Safaya, 1976; Singh et al., 2020). While MESZ appeared to provide some benefit to P uptake, this was not translated into a yield gain between these two treatments. In 2023, the "1x MAP+Struvite" treatment exhibited greater P content in corn grain than the "0x" control and greater P content in corn stover than both the "0x" control and the “1x MESZ” treatment. Also in 2023, the “2x MESZ treatment exhibited greater sulfur uptake in corn stover than both the control and the “1x MAP” treatment. However, similarly as in 2022, these nutrient uptake differences did not translate to differences in grain yield. No other treatment differences in nutrient uptake or stand count were statistically significant by site year. This implies that a nutrient management plan that targets specific nutrient deficiencies may provide a better return on investment than specialized products when fertilizing corn.

Nitrogen Mineralization

In 2022, net mineralization began the growing season through midsummer with negative rates across treatments, which means immobilization was occurring and N was converted to organic N (Figure 2). Then in August 2022, rates climbed as N switched to a mineralization process and produced inorganic N. This corresponded with a slight decrease in temperature, and higher precipitation rates (Table 2).

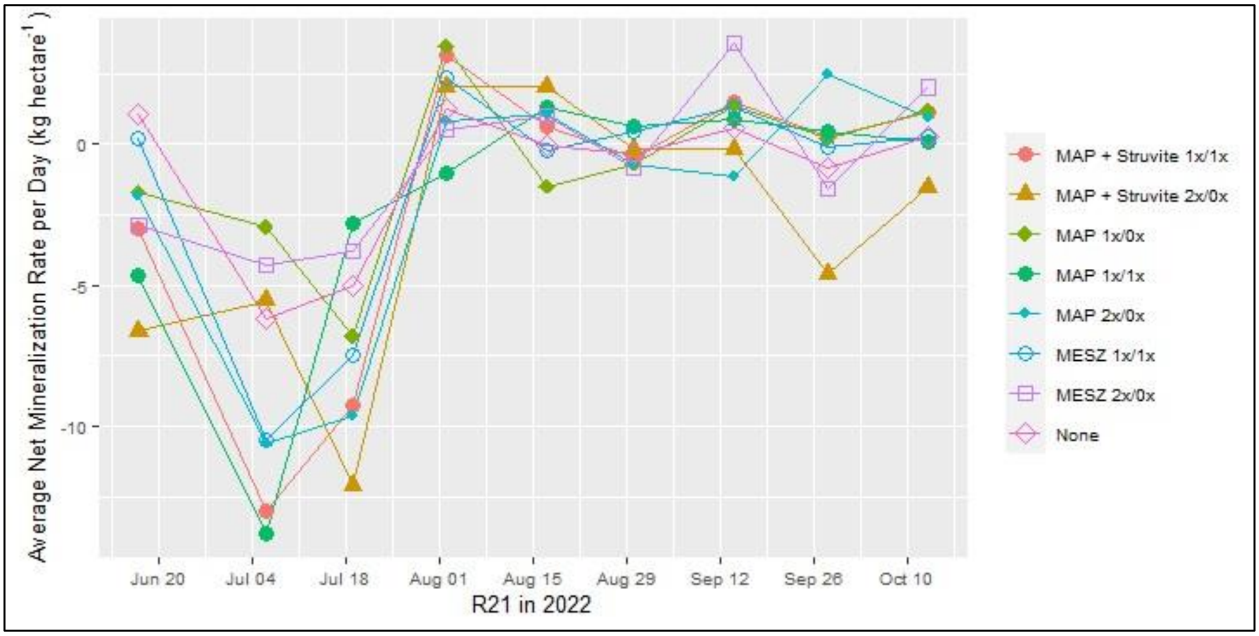

Figure 2: Average net mineralization per day during the 2022 growing season

Table 2: Weather Averages for 2022 and 2023, NOAA (Grand Forks, ND).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
Precipitation (mm)													
2022	15.7	22.4	7.6	138.9	129.3	54.9	116.6	36.1	13.5	4.3	13.2	39.9	592.3
2023	3.0	7.1	26.7	46.5	28.4	56.4	47.5	29.0	66.0	55.1	2.5	23.6	391.9
Average Temperature (℃)													
2022	-17.4	-17.2	-5.6	-0.1	12.7	19.3	21.7	20.6	15.7	8.2	-3.6	-13.1	3.4
2023	-12.6	-12.5	-10.8	0.7	16.9	22.0	19.7	20.2	17.6	7.5	-0.7	-3.1	5.4
Maximum Temperature (℃)													
2022	1.1	3.3	11.1	12.8	28.9	37.8	34.4	32.8	32.2	26.1	20.6	1.7	20.2
2023	2.2	3.9	2.8	13.3	32.2	37.8	36.1	35.6	36.1	33.3	14.4	13.3	23.0

In 2023, the season began with high immobilization, then climbed closer to rates of zero (equilibrium between mineralization and immobilization), but for the most part hovered on the side of immobilization (Figure 3). In both years, temperatures were highest June through August, and precipitation declined from July to August, with August being the driest of the months from April to August (Table 2) (National Oceanic and Atmospheric Administration, 2022-2023).

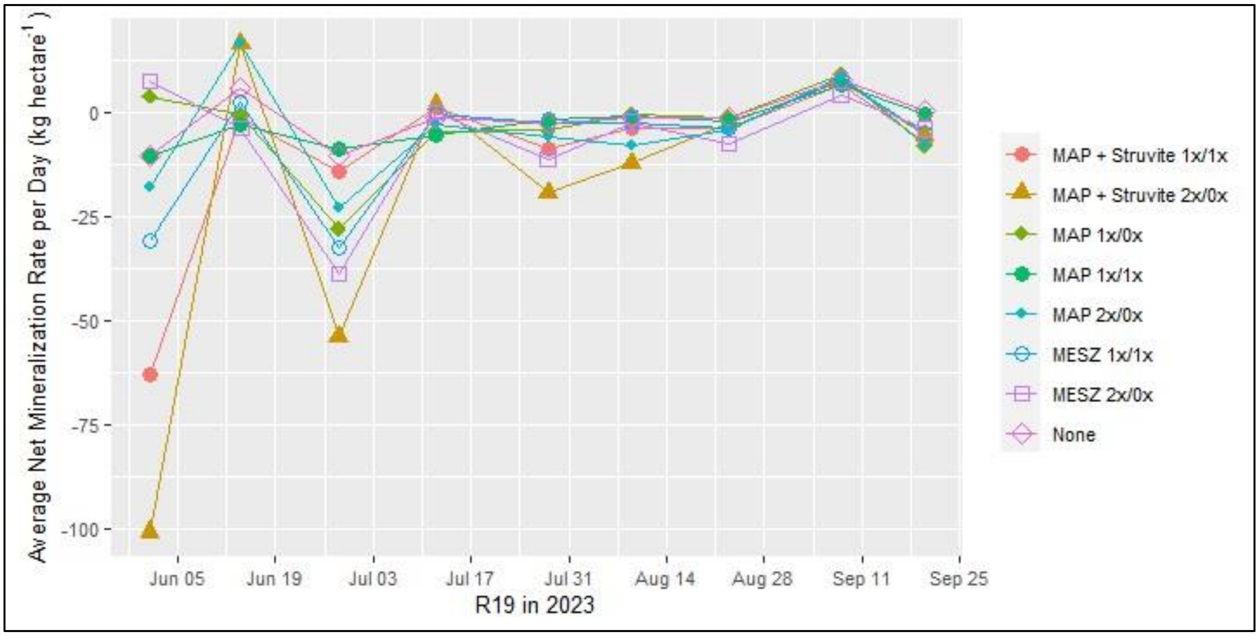

Figure 3: Average net mineralization per day during the 2023 growing season

Nitrogen mineralization showed weather-based variation and as both seasons were dry, with periods of drought, the primary process was N immobilization, as seen by the negative rates. In these dry conditions, N uptake was likely more impactful on crop growth than P. Nitrogen is often the primary limiting nutrient for corn, but P can be as well, depending on the nutrient interactions, soil nutrient concentrations, and climate conditions (Ziadi et al., 2007; Khan et al., 2014). The N mineralization results provide insight into the corn's growth and production metrics dynamics and indicate that although the crop had sufficient fertilizer applied, the crop was likely N-limited. This also may have obscured P-based treatment results. While sometimes increased temperature, with increased moisture, can increase mineralization via accelerating biological activity, conditions that are too dry reduce mineralization rates. This may continue to occur on a large scale in drier regions of the Northern Great Plains due to climate change (Morgan et al., 2008; Zhang et al., 2020; Deng et al., 2021) and is important to monitor these changes from the historic record as the regional climate shifts.

Laboratory flood simulation study

Dissolved P was released from soil to waters at consistent times, approximately 3 weeks since submergence. Several factors influence the timing of dissolved P release from soils. The alkalinity of simulated flood water samples tended to increase over time, but this did not differ by treatment. As the flooded environment becomes anaerobic and redox potential decreases, pH increases (Pierzynski et al., 2015). The time between submergence and dissolved P release is the amount of time that it takes for soil microbes to go through oxygen reduction, become anaerobic, and go through nitrification at close to biological zero (Bartlett and Ross, 2005; Vepraskas and Craft, 2016). While the period required for dissolved P release was about 3 weeks based on these laboratory trials, the Red River Valley region of Minnesota often sees spring snowmelt flooding last for four to seven weeks (Rannie, 2016; Stadnyk et al., 2016).

We observed a greater release of dissolved P from "2x MESZ" and "2x MAP+Struvite" than other treatments. Double rates, intended to reach the second-year crop rotation, will be at a higher risk of loss to floodwaters via P-release in extended flood conditions. The presence of the micronutrients sulfur, zinc, and magnesium in MESZ and Struvite may account for their greater release relative to MAP. Several complex interactions exist in the soil between these micronutrients and clay minerals, hydrous oxides, organic matter, calcium carbonate, and phosphorus (Safaya, 1976; Singh et al., 2020; Havlin, 2013). Several fertilizer studies have shown P-release increases with the addition of Mg (Mam Rasul et al., 2011; Al-Marsumy and Jarallah, 2019; Fattah et al., 2022; Lu et al., 2022). However, magnesium sulfate applications reduced P release in a 2021 flood simulation study on similar soils from southern Manitoba (Vitharana et al., 2021), and Mg additions to MAP had no impact on P-solubility in a 2022 study (Lu et al., 2022). Interestingly, a 2024 study in a corn rotation (Kokulan et al., 2024) showed decreased Olsen soil test and soil water P with Struvite and MAP applications when compared to MAP alone, which was not apparent in this study.

It is important to note that this study measured dissolved P concentrations in water, but not the overall P load moving off the field. These values, which would be considered dangerously high in a lake or stream, are not fully indicative of the values that would reach surface water bodies. Nutrients from the soil-water medium are filtered by soil, root material, and vegetative buffers on their way from field to ditch, decreasing concentrations. These concentrations may be further diluted by snowmelt water, rainfall, or other soil water. This path of overland flow, leaching, filtration, and dilution further transforms nutrient concentrations before reaching surface waters (Smith et al., 2005; Dunne et al., 2007; Daly et al., 2017; Pease et al., 2018; Kokulan et al., 2019; Macrae et al., 2019).

CONCLUSIONS

Field trials demonstrated that phosphorus rate and proper soil fertility management were more important than P fertilizer source when managing corn ahead of soybeans. We saw some evidence that MESZ improved zinc uptake at higher P levels, but this did not translate to greater harvested yields. Factors outside of soil fertility likely affected corn yields in 2022 and 2023. We observed dry soil conditions and net nitrogen immobilization in the soil, particularly during the early growing season. Although sufficient N was present in the soil, it was not necessarily in a form that the crop could use. Our laboratory analysis simulating flooded soil conditions showed that it took approximately three weeks to see dissolved P release from soil to water. We recommend that farmers avoid applying double rates of P fertilizer on fields that experience prolonged spring flooding. For these fields, the limited agronomic benefit gained by applying a double rate of fertilizer is unlikely to outweigh increased risk of P loss to surface water.

EDUCATION, OUTREACH, AND PUBLICATIONS

Conferences, Workshops, Field Days

1. Pease, L. "Minnesota Drainage & Water Quality Update," Conservation Drainage Network Annual Meeting, Columbus, Ohio. (April 4, 2024).

2. Pease, L. "Nutrient Management Dynamics in Northwest Minnesota Corn Production," Minnesota Ag Expo, Mankato, Minnesota. (January 17, 2024).
3. Malone, R., Pease, L., Loss, P., Reitmeier, H., Fleischer, C. "Phosphorus Fertilizer Source & Rate Impacts on P-Release in Simulated Flooded High pH Soils of the Northern Great Plains," ASA, CSSA, SSSA International Annual Meeting, St. Louis, Missouri. (October 31, 2023).
4. Pease, L. "Minnesota Drainage & Water Quality Update," Conservation Drainage Network Annual Meeting, Easton, Maryland. (April 6, 2023).

Publications

1. Malone, R. Characterizing phosphorus impacts on crop yields, soil nutrient profiles, and water quality in soils at risk of flooding for several phosphorus-based fertilizers of varying source and rate. 2024. University of Minnesota Twin Cities, M.S. Thesis.
2. Malone, R., Pease, L., Reitmeier, H., Fleischer, C., & Loss, P. Phosphorus release in alkaline calcareous soils under simulated floodwater conditions by fertilizer source and rate. Journal of Environmental Quality. [In Review]

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