Final Project Report to Calcium Products and The Leopold Center for Sustainable Agriculture

Reducing Dissolved and Total Phosphorus Loss with Surface Runoff by Using Gypsum as a Soil Amendment

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Introduction and Review of Objectives

The goal of this two-year project was to evaluate the use of gypsum amendments to reduce phosphorus (P) loss with surface runoff in no-tilled fields. The project was possible with funding by Calcium Products and complementary funding by The Leopold Center for Sustainable Agriculture. The objectives and treatments were selected after careful consideration of costs, that the most common P fertilization practice in Iowa is to broadcast fertilizer in the fall before corn (soybean residue), and important issues for meaningful and cost-effective field rainfall simulations since the budget did not allow for research under natural rainfall. The field work for the study was conducted on one site from fall 2016 through spring 2017 and at another site from fall 2017 through spring 2018. The chemical analyses of soil and surface runoff samples were finished in 2019. The data management and summarization of results took much longer time than expected due to the limited budget for qualified personnel and complications due to the COVID-19 pandemic.

The specific objectives were: (1) Use a field rainfall simulation technique to study how different gypsum forms and application rates affect dissolved and particulate P loss with surface runoff from harvested soybean ground managed with no-tillage. (2) Evaluate how the timing of the first runoff event after P and gypsum application influences P loss. (3) Determine if soil analysis for water-extractable P could serve as a surrogate to estimate potential dissolved P loss with surface runoff for no-tillage.

Summary of Procedures

Procedures for the First Year

The field work began in early October 2016 by setting up field rainfall simulation plots in a field located at an Iowa State University research farm in central Iowa (Boone County) with Clarion loam soil where soybean had been harvested. Before the treatments were applied, soil of the experimental area was sampled from depths of 0-2 and 2-6 inches. These initial samples were analyzed for P by the commonly used methods in Iowa and the North Central Region for crop production and the P index - Bray-1, Olsen, and Mehlich-3 all with colorimetric P determination of extracted P; extractable cations potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) by the ammonium-acetate routine method; extractable Fe and Al by the Mehlich-3 method; extractable soil sulfate (SO_4^{2})by the mono-calcium phosphate method; pH (1/1 soil/water ratio); Sikora buffer pH; organic matter from carbon measured by the combustion method; and estimated cation exchange capacity (CEC). The analyses procedures used were those described by the NCERA-13 (North Central Extension and Research Activities) committee for soil testing and plant analysis (NCERA-13, 2015). Soil water-extractable P with a colorimetric P determination of extracted was measured by the method described by Pote et al. (1996). Table 1 summarizes the soil test results.

Table 1. Initial soil properties of the first-year site.

	Sampling Depth (inches)	
Measurement	0-2	2-6
Bray-1 P (ppm)	7	4
Mehlich-3 P (ppm)	8	5
Olsen P (ppm)	6	4
Water extractable P (ppm	0.8	0.9
K (ppm)	117	103
Ca (ppm)	2432	2715
Mg (ppm)	260	255
Na (ppm)	16	13
Al (ppm)	780	829
Fe (ppm)	124	123
SO_4-S (ppm)	0.8	1.0
pH	6.6	6.8
Organic matter (%)	3.5	3.1
CEC (meq/100 g)	14.3	14.6

The rainfall simulator and technique used were developed before for a multi-state runoff P project (NPRP, 2002). For each simulation plot, a soil area 30 square-feet in size was enclosed on three sides by galvanized steel walls 6 inches in height. A collecting trough was installed in the downslope side with the upper edge levelled with the soil surface that was covered with a canopy to exclude simulated rainfall, and a PVC pipe routed runoff to a collecting vessel downslope. A nozzle was placed 10 feet above the center of the plot supported by a 100 square-foot aluminum frame (larger than the plots) and plastic curtains were wrapped around the frame to avert wind effects. Simulated rainfall was applied at 3 inches/hour and runoff occurring during 30 minutes was weighed and a 1-L sample was taken to measure total solids (APHA, 1998) and total P with the alkaline-oxidation digestion method using sodium hypobromite for soils (Dick and Tabatabai, 1977) modified by Cihacek and Lizote (1990) for an aluminum block and adapted to runoff by Allen and Mallarino, (2008). A runoff subsample was filtered through 0.45 um filter to measure dissolved reactive P (DRP) colorimetrically (Murphy and Riley, 1962).

Treatments replicated three times were selected combinations of P fertilization (granulated diammonium phosphate, DAP) and finally ground or granulated mined gypsum rates and different times to runoff since the materials application to the soil. The DAP was a commercially available source. The granulated and finely ground gypsum sources were provided by Calcium Products, were from the same Iowa quarry, and had similar composition except for the granulating agent in the granulated source. For the granulated source 3, 62, 35, and 0% of the material passed standard Tyler mesh screens 4, 8, 20, and 60, respectively. For the ground gypsum source 0, 1, 4, 7, 17, and 71% of material passed standard Tyler mesh screens 4, 8, 20, 60, and 100, respectively.

Eight gypsum/P treatments for 30 square-foot plots were no gypsum or P (1), only P (2) and gypsum rates of 500, 1000, and 2000 lb/acre of granulated or ground gypsum with 100 P_2O_5/acre (6). Three sets of these same eight treatments were randomized to plots of three sections within each of three blocks (replications) needed for the runoff timing treatments. The materials were broadcast by hand in the fall and there was no tillage or incorporation of the materials into the soil. Soybean residue cover and slope were measured on each plot. Residue cover average across plots was 66% (40 to 80% and the average slope was 2.4% (1.7 to 5.5%). Four runoff timing treatments were (1) runoff within two days of the materials application, (2) runoff 15 days after the application to different plots, (3) a second runoff event

15 days after the 24-hour event to the same plots, and (4) natural snowmelt runoff collection from winter to early spring after application to different plots followed by a final rainfall simulation in spring 2017 on the same plots. A final rainfall simulation was not planned but it was done because there was little or no snowmelt runoff from several plots. Therefore, there were 72 plots because three sets of the same eight gypsum treatments were applied to each of three replications. Treatments and replications were arranged as a split-plot randomized complete-block design with runoff timing in large plots, gypsum/P rates in subplots, and blocking along the slope gradient.

The gypsum/P treatments for two sets of plots within each block for the 2-days and 15-days rainfall simulations were broadcast by hand on 17 October 2016. The first single rainfall simulation was on October 17-18 for plots of the 2-days runoff event. Fifteen days later, on November 1-2 (before snowfall or soils froze), simulated rainfall was applied to the same plots used for the 2-days event and to the second set of plots within each block that did not receive a 24-hour event. The plots were temporarily covered with wood planks during the 15-days period when the weather forecast predicted rainfall that could produce runoff. On November 3 (before snowfall or soils froze) the gypsum/P treatments were spread to the third set of plots within each block to evaluate treatment effects on P loss with natural snowmelt runoff. A small amount of simulated rainfall (0.25 inches) that did not produce runoff was applied immediately after spreading the materials for the snowmelt runoff plots. There was no runoff from for 78 days after the materials application, there were four small snowmelt events seldom from all plots from 20 January to 29 March 2017, and the final spring rainfall simulation to these snowmelt plots was conducted on April 10.

New soil samples were taken from depths of 0-2 and 2-6 inches in fall 2016 three to four days after the 15-days rainfall simulations from plots with a single runoff event and plots with two runoff events (about 20 days after the materials application). New soil samples were also taken from the same soil depths in spring 2017 three to four days after the final rainfall simulation on plots from which we collected snowmelt runoff (about five months after the materials application). These new soil samples were tested for the same chemical properties as for the initial samples using similar procedures, except that buffer pH, organic matter, and CEC were not measured.

Procedures for the Second Year

The second-year experiment site had similar soil type and crop residue (Clarion loam, soybean) as in the first year but with higher soil-test P and slightly steeper slope of 2.9% on average (2.0 to 5.0% across plots). Residue cover was 95% on average (90 to 100%). As in the first year, there was no tillage since the soybean harvest. The soil sampling and analysis procedures before applying the treatments were the same as in the first year. Table 2 shows the initial soil-test results.

Since the first-year results showed no difference between the ground or granulated gypsum sources, for second year experiment we used only granulated gypsum, which is the most common and practical source in production agriculture. We also changed some gypsum/P treatments and added a measurement of soil aggregate stability that had not been included in the proposal. Since this soil tested very high in P, two new P treatments were used for the same set of granulated gypsum application rates used the previous year. The P treatments were no P or 100 lb P_2O_5/acre using granulated monoammonium phosphate fertilizer (MAP) broadcast while the gypsum was applied. The materials were applied in the fall without incorporation into the soil. Therefore, eight gypsum/P treatments were 0, 500, 1000, and 2000 lb/acre each with or without P application. There were three replications arranged as blocks along the slope gradient. As in the first year, there were 72 plots because three sets of the eight treatments needed for the runoff event treatments were randomized to three sets of plots within each of three blocks. The treatments and replications were arranged as a split-plot randomized complete-block design with runoff times in large plots and the gypsum/P treatment combinations in subplots.

Table 2. Initial soil properties of the second-year site.

	Sampling Depth (inches)	
Measurement	0-2	2-6
Bray-1 P (ppm)	65	11
Mehlich-3 P (ppm)	64	11
Olsen P (ppm)	35	8
Water extractable P (ppm)		
K (ppm)	99	78
Ca (ppm)	1592	1968
Mg (ppm)	247	261
Na (ppm)	74	79
Al (ppm)	882	823
Fe (ppm)	158	125
SO4-S (ppm)	4.2	3.8
pH	5.6	6.0
Organic matter (%)	3.4	3.3
CEC (meq/100 g)	12.0	13.8

The runoff timing treatments were the same as for the first year but there was no final rainfall simulation in spring 2018 because this time there was much more snowmelt runoff. Runoff timing events were (1) within 2 days of the materials application, (2) 15 days after the application to different plots, (3) a second event 15 days after the 2-days event to the same plots, and (4) natural snowmelt runoff collection from winter to early spring after fall application of the materials to different plots.

The first gypsum/P treatments were spread by hand on 25 October 2017 onto two sets of 24 plots within each block. The first rainfall simulation was on October 25-26 on one set of plots for the 2-days runoff event. Fifteen days later (on November 8-9) with no snowfall or frozen soil, simulated rainfall was applied for a second time to the same plots that had been rained earlier and to the other set of 24 plots for the 15-days runoff treatment. The plots were covered temporarily with wood planks during the period between the two simulations when the weather forecast predicted rainfall that could produce runoff. On November 22 (before snowfall that persisted on the soil surface or soil froze) the gypsum/P treatments were applied to the third set of 24 plots within each block to evaluate treatment effects on P loss with natural snowmelt runoff. A small amount of simulated rainfall (0.25 inches) that did not produce runoff was applied immediately after spreading the materials for the snowmelt runoff evaluation. There was no surface runoff from natural rainfall or snowmelt for 59 days after the materials application, and there were six snowmelt events (several with runoff from all plots) from January 19 to March 28.

New soil samples were taken from depths of 0-2 and 2-6 inches in fall 2017 three to four days after the 15-days rainfall simulations from plots with a single runoff event and plots with two runoff events (about 20 days after the materials application). New soil samples were also taken from the same soil depths on 14 April 2017 (spring), three days after the final rainfall simulation on plots from which we collected snowmelt runoff (approximately five months after the materials application). The new soil samples were tested for the same chemical properties as for the initial samples using similar procedures, except that buffer pH, organic matter, and CEC were not measured.

In addition, in spring 2018 soil samples also were collected for aggregate stability analysis on 24 April 2018, which was 27 days after the last snowmelt runoff and after the soil had thawed and drained. Undisturbed field-moist samples were collected from the top 6-inches of soil from selected treatments.

The aggregate stability analysis was performed following the procedures described by Guzman and Al-Kaisi (2011) who slightly modified procedures first suggested by Kemper and Rosenau (1986). The field-moist soil samples were sieved gently through a screen with ¼-inch openings and subsequently let the soil dry at room temperature and subsamples were taken to determine soil moisture of the air-dried samples by drying in an oven at 105 °C. Another 100-g portion of air-dried soil was sieved using a wet sieving apparatus through seven screen sizes to measure different soil aggregate sizes (>4, 2-4, 1-2, 0.5-1, 0.25-0.5, 0.053-0.25, and <0.053 mm). The sieved soil was dried at 65 °C, weighed, and the weights were adjusted to the oven-dried soil moisture content. The aggregate stability results were expressed as mean weight diameter (MWD) and as the percentage of aggregates with a diameter of 1.0 mm or larger. Larger numbers indicate better aggregate stability and soil structure for both forms of expression.

Results and Discussion

Results for the First Year - Fall 2016 to Spring 2017

The observed total P and DRP concentrations or loss with surface runoff in all events were much lower for the untreated control without P applied than for all other treatments which received 100 lb P_2O_5/acre with or without gypsum, which was expected. For example, the P loss for this control treatment was equal to or smaller than 2 and 3.7% for runoff within 24 hours of applying the materials and runoff for the single simulation 15 days after the application, respectively. Therefore, results for this control without P are not shown to simplify the presentation and discussion of the results. It is noteworthy that the seven treatments for which results are shown received the same P fertilizer rate of 100 lb P_2O_5/acre.

Figure 1 summarizes the results for DRP and total P concentrations in runoff from the fall simulations. There were no statistically significant differences among the gypsum sources or application rates at the 0.10 probability level for any runoff fraction or runoff event. The runoff DRP concentration for the control receiving only P and the average across all plots receiving gypsum and P were 13.5 and 12.5 mg/L for runoff within 24 hours of the application, 8.25 and 7.88 mg/L for runoff delayed 15 days after the application, and 0.72 and 0.76 mg/L for the second runoff 15 days after the first one. The runoff total P concentration for the control receiving only P and the average across all plots receiving gypsum and P were 15.3 and 14.8 mg/L for runoff within 24 hours of the application, 9.41 and 9.47 mg/L for runoff delayed 15 days after the application, and 3.19 and 2.72 mg/L for the second runoff 15 days after the first.

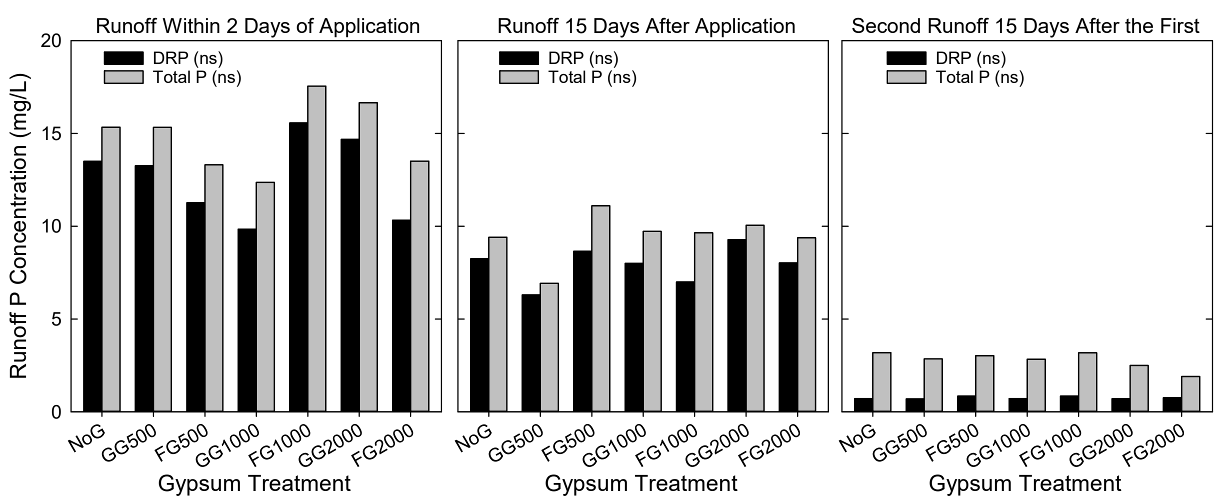


Figure 1. First-year trial: Effects of no gypsum (noG) and 500, 1000, and 2000 lb/acre of granulated (GG) or finely ground (FG) gypsum on dissolved reactive P (DRP) and total P concentrations in runoff for three events. ns, no statistically significant differences ($P \leq 0.10$).

Therefore, as was observed in previous work by our group, a runoff event delay of just 15 days significantly reduced the concentration of DRP and total P in runoff compared with runoff with 24 hours of the materials application (about 63 and 64%, respectively). This has been explained by P retention by surface soil with delayed runoff events; which does not mean fixation as not plant-available P forms. The P losses from a second runoff event after a 24-hour event were much lower, which was explained by P loss in the first event and further retention of applied P by soil in between both events.

Figure 2 summarizes the results for the total P and DRP loss from the fall simulations, which combine effects on P concentrations and amount of runoff. The results were similar to those for concentrations in that there were no statistically significant differences among treatments. The ranking of the treatments was approximately similar for P concentrations and losses because runoff volume varied among the plots but was not affected by the treatments (not shown). It is important to remember that total P loss from field rainfall simulations is useful for comparing treatments but cannot be extrapolated to edge of field losses.

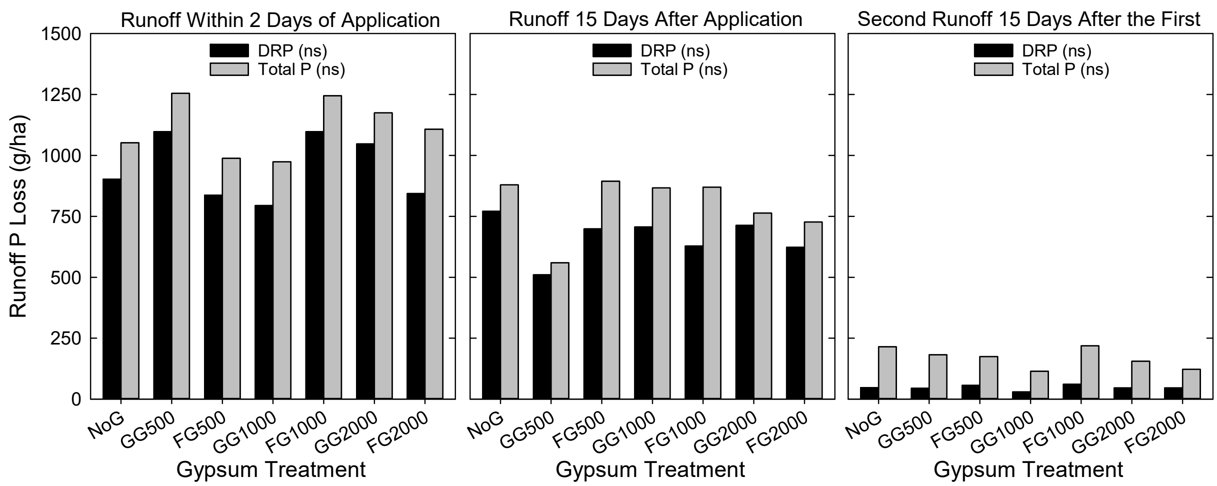


Figure 2. First-year trial: Effects of no gypsum (noG) and 500, 1000, and 2000 lb/acre of granulated (GG) or finely ground (FG) gypsum on dissolved reactive P (DRP) and total P losses with runoff for three events. ns, no statistically significant differences ($P \leq 0.10$).

Figure 3 summarizes results for average concentrations and cumulative losses of runoff DRP and total P across all snowmelt runoff events and the final early spring rainfall simulation (January 20 to April 10).

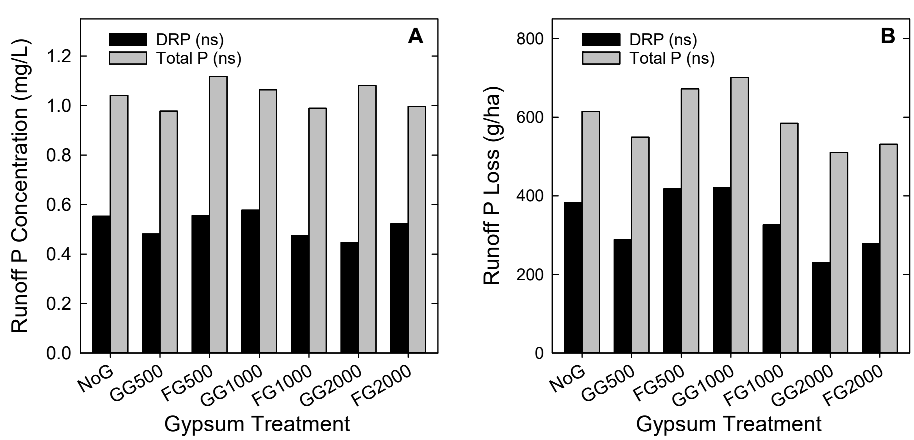


Figure 3. First-year trial: Average runoff P concentration (A) and cumulative loss (B) across snowmelt and a spring rainfall simulation events after fall-applied P fertilizer alone (NoG) or with three rates of granulated (GG) or finely ground (FG) gypsum. ns, no statistical differences ($P \leq 0.10$).

The runoff P concentrations and losses about five months after applying the treatments (Fig. 3) were much lower than for the fall runoff events (Figs. 1 and 3). This has been observed before, and less runoff P is explained by the longer time without runoff since the materials application and additional retention by the soil. There were no statistically significant differences ($P \leq 0.10$) for any runoff P fraction concentration (Fig. 3A) or loss (Fig. 3B). However, there was an apparent small DRP loss decrease for the highest gypsum rate (2000 lb/acre) of both sources (Fig. 3 B) that seems reasonable.

Knowledge of the DRP proportion of the total runoff P is important because DRP is the most active runoff P fraction at stimulating algae growth and eutrophication. Calculations from data in Fig. 2 showed that the percent DRP loss of the total P loss across all treatments did not change much for runoff events within 2-days and after 15-days of the treatment applications (85 and 84%, respectively). This result confirms that most of the P loss immediately after applying P is dissolved P and that a 15-day delay in runoff reduced both runoff P fractions by an approximately similar amount. Calculations from data in Fig. 3 showed that the percent DRP loss of the total P loss across all treatments for the winter snowmelt and early spring simulation was much lower (56%) than for single runoff events within 2-days and after 15 days. Therefore, a 78-days runoff delay after P application sharply reduced the DRP proportion in runoff.

Figure 4 shows that for the fall rainfall simulations, gypsum effects on soil concentrations in runoff and soil loss were statistically significant only for the single runoff event 15 days after applying the treatments and for reasons not understood, both gypsum sources increased both soil concentration and loss.

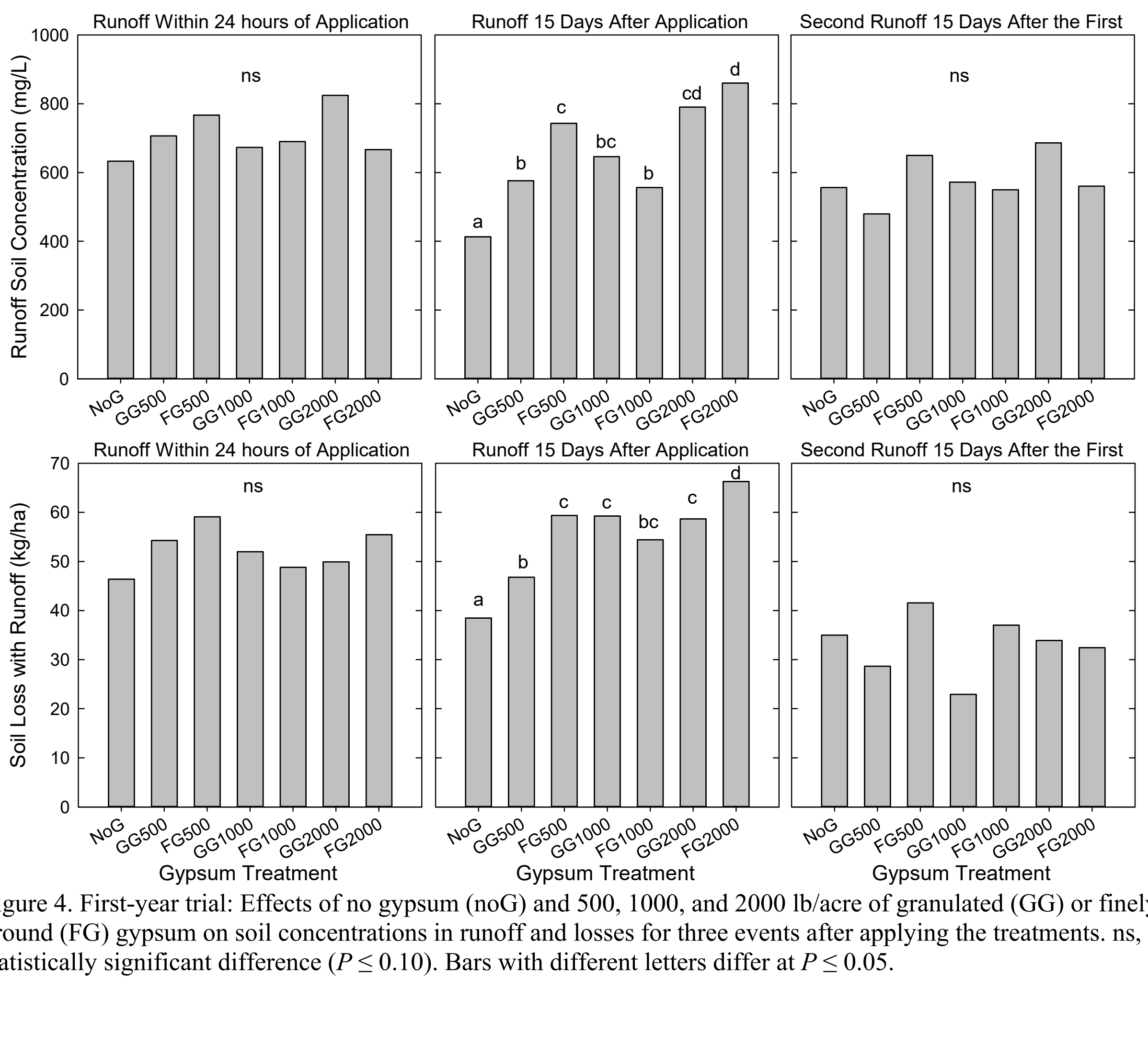


Figure 4. First-year trial: Effects of no gypsum (noG) and 500, 1000, and 2000 lb/acre of granulated (GG) or finely ground (FG) gypsum on soil concentrations in runoff and losses for three events after applying the treatments. ns, no statistically significant difference ($P \leq 0.10$). Bars with different letters differ at $P \leq 0.05$.

Figure 5 shows that gypsum also increased soil concentration in runoff and cumulative soil loss across all snowmelt runoff events and the final spring rainfall simulation but effects were more variable and less clear. Soil concentrations increased with the gypsum rate up to the 1000-lb rate with granulated or ground sources (Fig. 5A) whereas soil losses were the largest for the 1000-lb rate with either source (Fig. 5B). Increasing soil concentrations or losses with surface runoff cannot be explained satisfactorily. Soil concentrations in runoff for the control and the 500-lb with ground or granulated gypsum sources were statistically similar but slightly lower for the ground 500-lb rate (Fig. 5A). A similar comparison for soil losses (Fig. 5B) show highest loss for the granulated 500-lb rate. The runoff volume was statistically similar for all treatments (not shown) but random variability may explain these results since the two sources did not differ for the other gypsum rates.

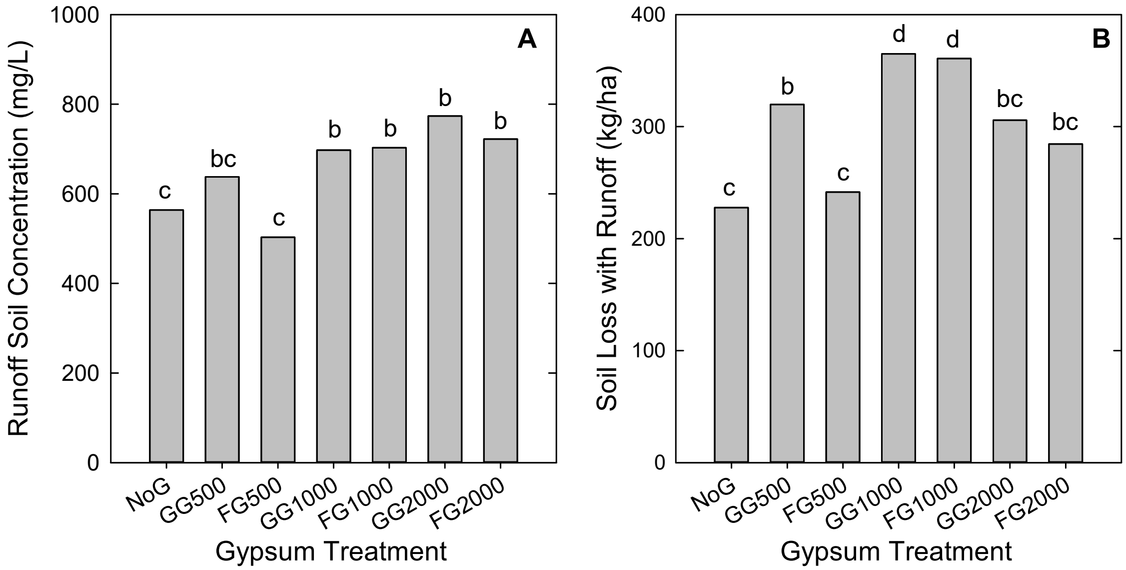


Figure 5. First-year trial: Soil concentration (A) and loss (B) in accumulated runoff from snowmelt events and an early spring rainfall simulation after applying no gypsum (NoG) or 500, 1000, and 2000 lb/acre of granulated (GG) or finely ground (FG) gypsum. Bars with different letters differ at $P \leq 0.05$.

Results of analyses of soil samples taken in fall 2016 a few days after the single 15-days runoff event and both the 2-days and 15-days events (about 20 days after applying treatments) and samples taken after the spring final rainfall simulation to plots where snowmelt was collected (about five months after applying treatments) showed mostly no statistically significant gypsum effects at $P \leq 0.10$ (not shown). Exceptions were effects on extractable sulfate, extractable Ca, and water-extractable P (WEP).

Figure 6 shows that gypsum always increased soil sulfate up to the highest rate applied but the ground and granulated sources did not differ. Soil sulfate in the top 2 inches of soils for the fall sampling after plots that received simulated rainfall twice were lower than for plots that received rainfall only once but the inverse happened for the depth of 2-6 inches, which indicates some sulfate leaching to the second depth with the additional rainfall. Results from a previous study with a wider range of gypsum rates that assessed effects on crop yield and soil properties showed significant sulfate leaching from the top 6-inches of soil to a depth of 6 to 12 inches with gypsum rates of 500 lb/acre or higher. Overall low sulfate five months after gypsum application may be explained by leaching or immobilization in organic matter.

Figure 7 shows that both gypsum sources increased soil Ca concentration up to the highest rate applied only at the top 2-inch depth, which is reasonable due to the no-till management. The increase was statistically significant for the fall soil sampling but not for the sampling after snowmelt and the spring rainfall simulation events 100 days after the treatment application.

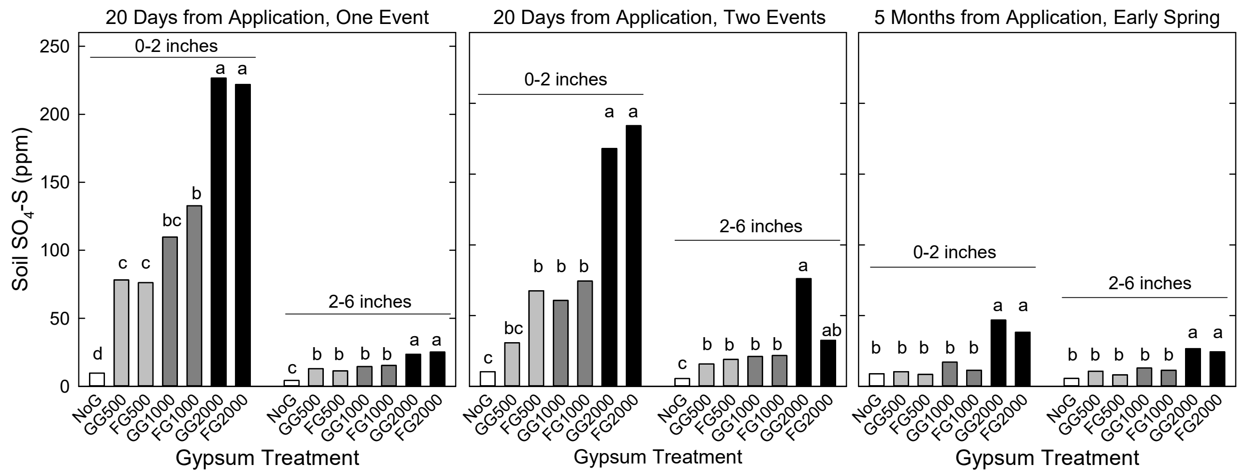


Figure 6. First-year trial: Soil sulfate as affected by no gypsum (noGyp) and 500, 1000, and 2000 lb/acre of granulated (GG) or finely ground (FG) gypsum for three combinations of days after application and runoff event. Bars with different letters within each sampling time or depth differ at $P \leq 0.05$.

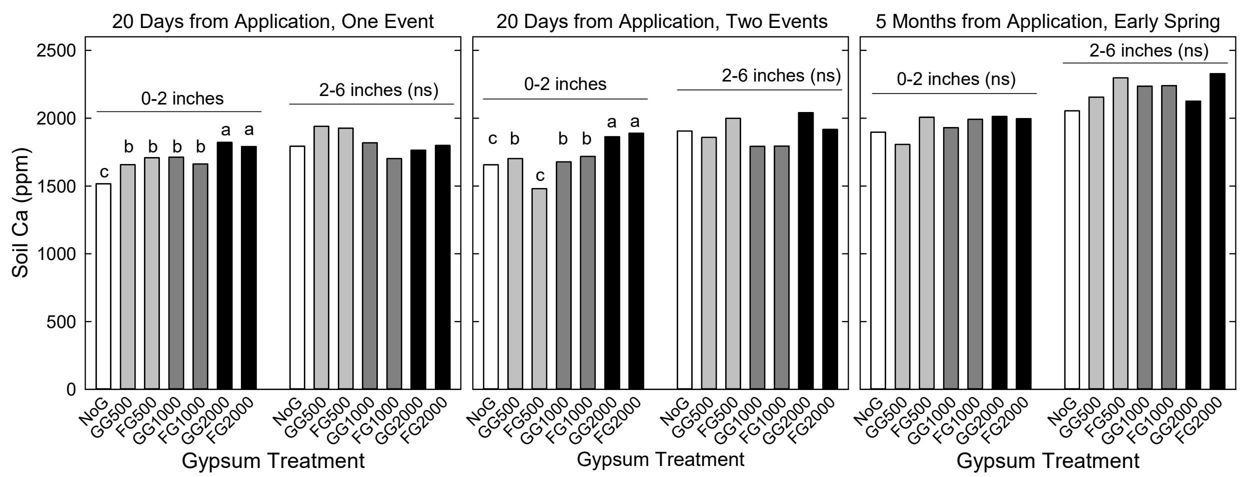


Figure 7. First-year trial: Soil calcium as affected by no gypsum (noGyp) and 500, 1000, and 2000 lb/acre of granulated (GG) or finely ground (FG) gypsum for three combinations of days after application and runoff events. Bars with different letters within each sampling time or depth differ at $P \leq 0.05$. sampling dates runoff events

Figure 8 shows that gypsum affected soil WEP only for the top 2-inch depth for the three combinations of sampling dates and runoff events. Unexpectedly, both gypsum sources increased soil water-extractable P although the increases were very small. Furthermore, the increases tended to be the largest for rates of 500 and 1000 lb/acre and smallest for the 2000-lb rate. This was especially consistent for the fall soil sampling 20 days after the materials application. The WEP levels in the top 2 inches of soil were much higher for the sampling about 5 months after the materials application, which may be explained by applied P retention by the soil with a longer reaction time. The differences among the gypsum application rates were less clear for the 5-months sampling date and apparent differences between the two sources were not consistent across the gypsum application rates.

Perhaps complex and difficult to predict interactions between the applied materials with soil constituents resulted in increased extracted soluble P instead of the decrease some may expect. The previous project mentioned before conducted in two sites using a wider range of gypsum application rates over three years did not show consistent effects of gypsum on water-extractable soil P.

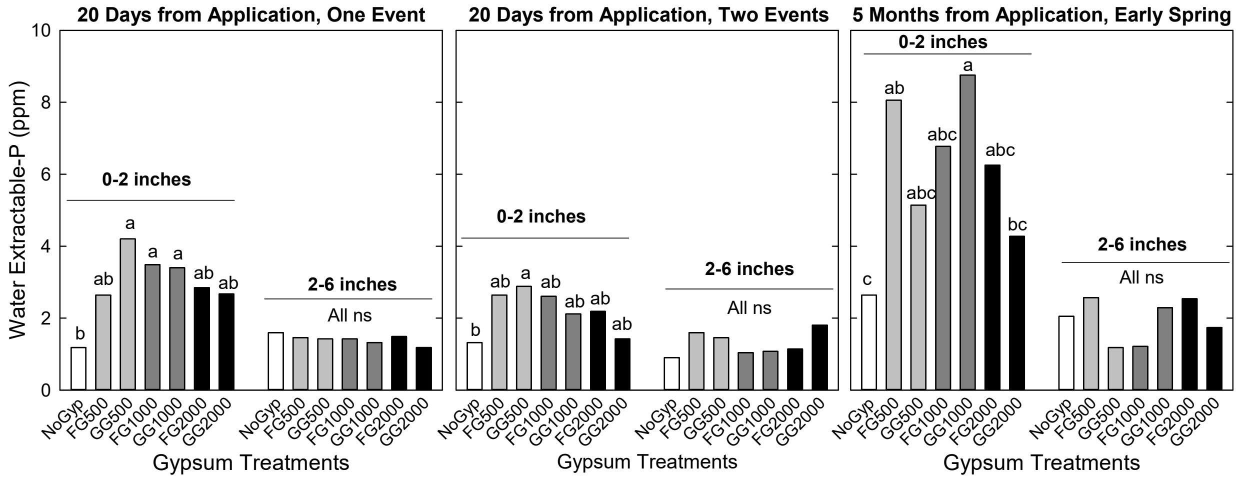


Figure 8. First-year trial: Water-extractable soil P as affected by no gypsum (noGyp) and 500, 1000, and 2000 lb/acre of granulated (GG) or finely ground (FG) gypsum for three combinations of days after application and runoff events. ns, no statistical differences ($P \leq 0.10$). Bars with different letters for each sampling depth differ at $P \leq 0.05$.

Results for the Second Year - Fall 2017 to Spring 2018

The first-year results showed generally similar treatment rankings for concentrations in runoff and losses of soil, DRP, and total P due to small and variable differences in runoff volume. Therefore, only results for losses with runoff are shown for the second-year experiment.

Figure 9 shows that soil loss for all runoff events of the second-year experiment were lower than in the first year. Apparent small soil loss increases with the higher gypsum for some events are not statistically significant ($P \leq 0.10$).

Figure 10 shows that there were no statistically significant gypsum effects ($P \leq 0.10$) on DRP or total P losses with runoff in any of the three runoff timing treatments. When P was applied with the gypsum there were no meaningful differences. As expected, the runoff P losses were many times higher with P applied than without P applied. As was observed in the first year, both DRP and total P losses were the highest for the runoff event shortly after the materials application. The difference, however, was much larger with P applied together with the gypsum than without P application. Although treatment differences were not significant, for the 2-days and 15-days events the P loss tended to be the largest with rates of 500 and 100 lb/acre than with the 2000-lb rate, which has no reasonable explanation and may have resulted from random variability.

Figure 11 summarizes results for the cumulative losses with runoff of soil, DRP, and total P across all snowmelt runoff events (from January 19 to March 28, 2018). The soil losses (Fig. 11A) were higher than for the fall rainfall simulation runoff events but apparent treatment differences were small and not statistically significant ($P \leq 0.10$). There was a very small increasing trend of soil loss with increasing gypsum rates without P applied, however, and with P applied there was an apparent soil loss increase with the 500-lb gypsum rate and an apparent decrease with the 2000-lb gypsum rate.

As expected, the losses of both runoff P fractions (Fig. 11B) were much less without P than with P applied. There were no statistically significant gypsum effects on runoff DRP or total P when no P was applied. With P and gypsum applied together, however, gypsum had no statistically significant effect on DRP loss (although there was an apparent small decrease with the 2000-lb gypsum rate) but the total P losses were significantly higher for gypsum rates of 0 and 500 lb/acre compared with the two higher gypsum rates of 1000 and 2000 lb/acre.

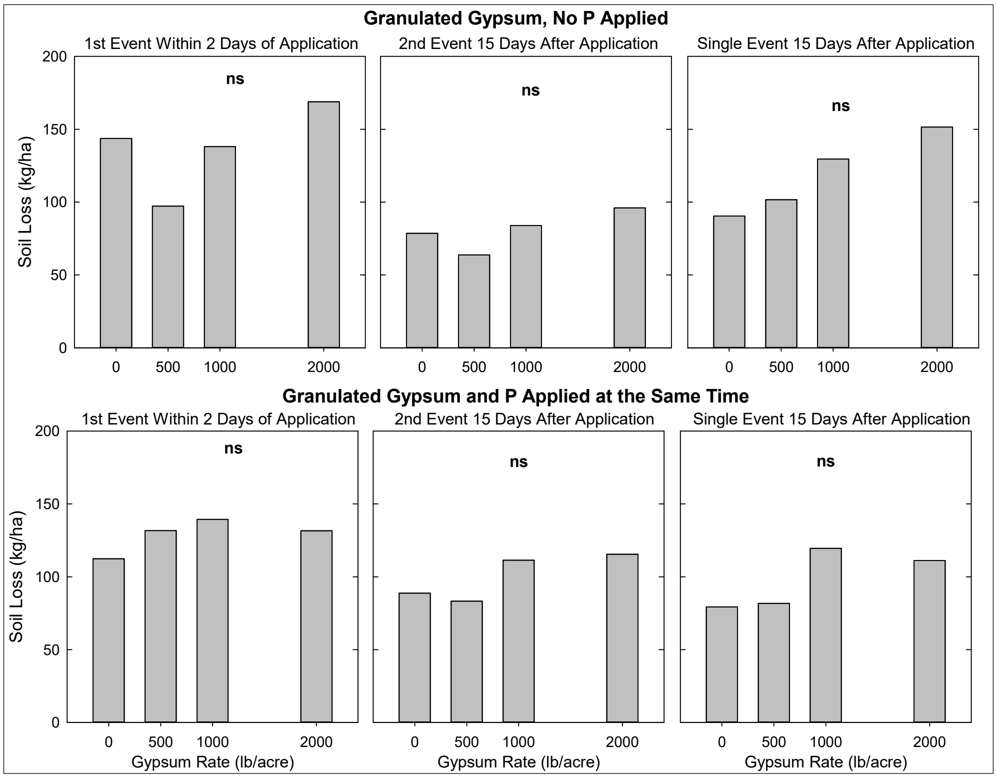


Figure 9. Second-year trial: Effects of 0, 500, 1000, and 2000 lb/acre of granulated gypsum with or without P on soil loss with runoff for three events after applying the treatments. ns, no statistically significant differences ($P \leq 0.10$).

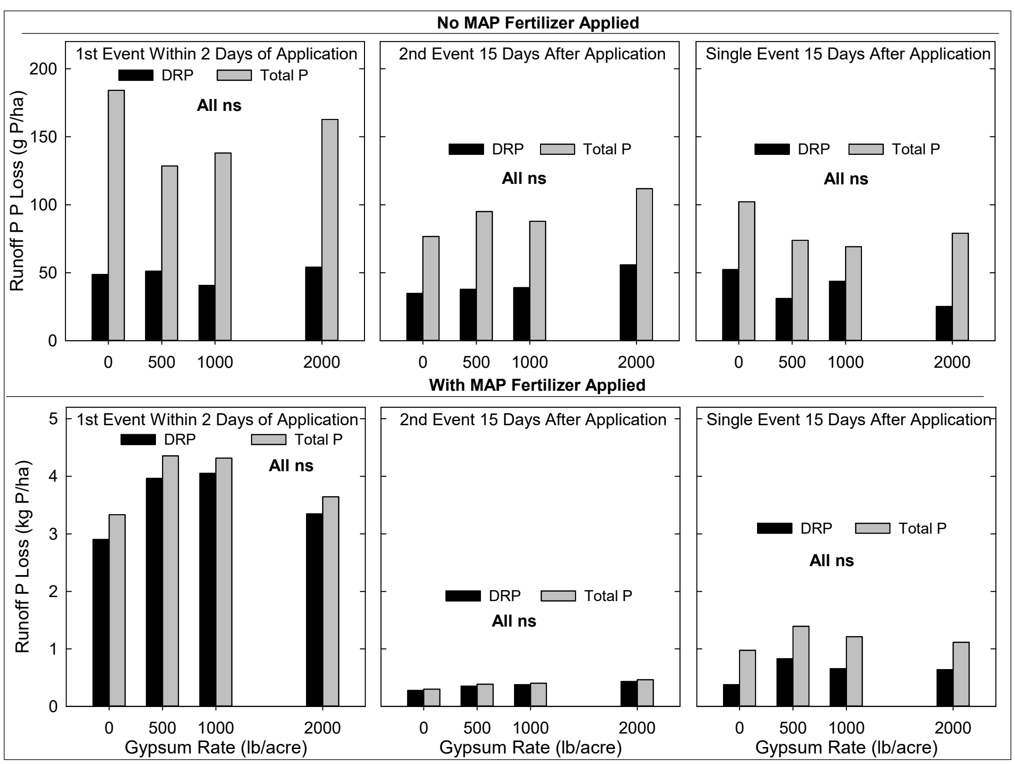


Figure 10. Second-year trial: Effects of 0, 500, 1000, and 2000 lb/acre of gypsum with or without P on dissolved reactive P (DRP) and total P losses with runoff for three events after applying the treatments. ns, no statistically significant differences ($P \leq 0.10$).

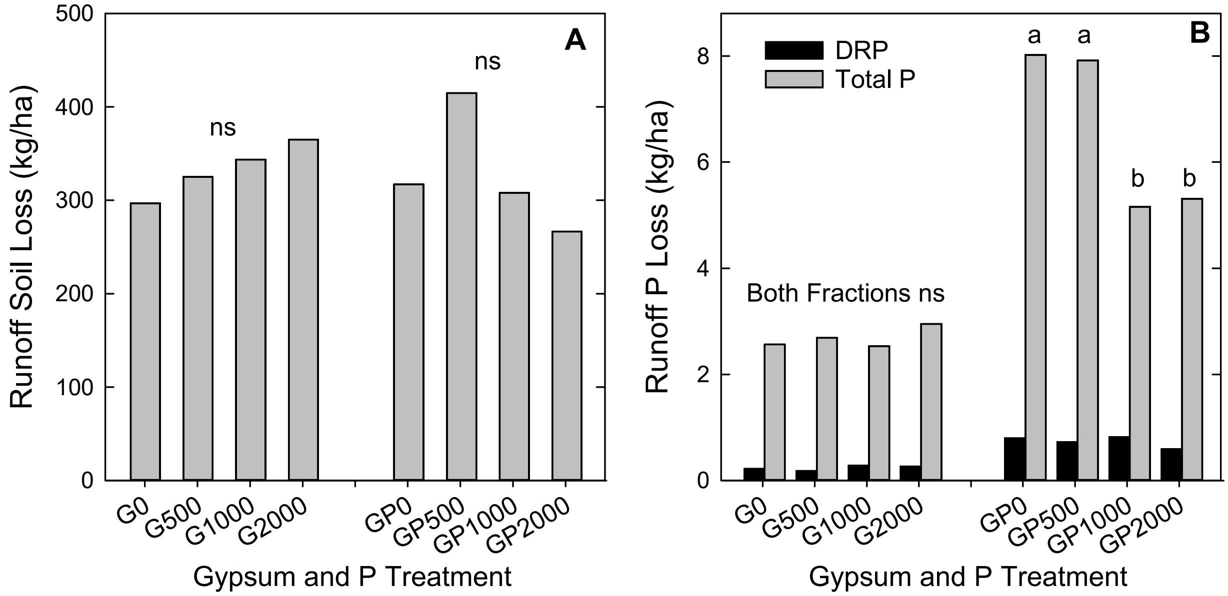


Figure 11. Soil loss (A) and dissolved reactive P (DRP) and total P losses (B) in accumulated snowmelt runoff events after applying granulated gypsum rates of 0, 500, 100, or 2000 lb/acre without (G) or with P fertilizer (GP). ns, no statistical differences ($P \leq 0.10$). Bars for total runoff P with different letters differ at $P \leq 0.05$.

We cannot explain well the results for total P in Fig. 11B because if were real (not a random difference) would mean that the two highest gypsum rates reduced particulate P loss since the DRP levels reduction do not account for the total P reduction. A not statistically significant but moderate soil loss reduction with the 2000-lb gypsum rate (Fig. 11A) could explain the particulate P loss reduction with this rate, but soil and P losses for the other gypsum rates do not relate in a reasonable way. Therefore, we believe observed gypsum effects on total or particulate P loss likely resulted from experimental variability.

Results of analyses of soil samples taken from depths of 0-2 and 2-6 inches in fall 2017 a few days after the single 15-days runoff event and both the 2-days and 15-days events (about 20 days after applying treatments) and samples from the same depths taken in spring 2018 from plots where snowmelt was collected (about five months after applying treatments) showed mostly no statistically significant gypsum effects at $P \leq 0.10$. Therefore, test results that showed no statistical differences among the gypsum treatments are not shown. The only exceptions were extractable calcium and soil extractable sulfate. The extractable calcium results are not shown, however, because although there were apparent increasing trends for the two highest gypsum rates for the top 2-inches depth and for the three combination of sampling dates and runoff events, differences attained statistical significance ($P \leq 0.10$) only for the spring 2018 sampling date.

Figure 12 shows the results for soil sulfate, for which there were statistically significant gypsum application effects for both sampling depths and for the three combinations of sampling dates and runoff events. Increasing gypsum rates greatly increased soil sulfate levels linearly or exponentially with decreasing increments to a maximum. As was observed in the first year, sulfate in the top 2-inch soil depth for the fall sampling after plots that received simulated rainfall twice were lower than for plots that received rainfall only once but the inverse happened for the depth of 2-6 inches. The results indicate sulfate leaching beyond the sampled second depth because at this depth levels were similar with one or two runoff events. Overall low sulfate five months after gypsum application only for the 2-inch depth may be explained by immobilization in organic matter or leaching further below a 6-inch depth.

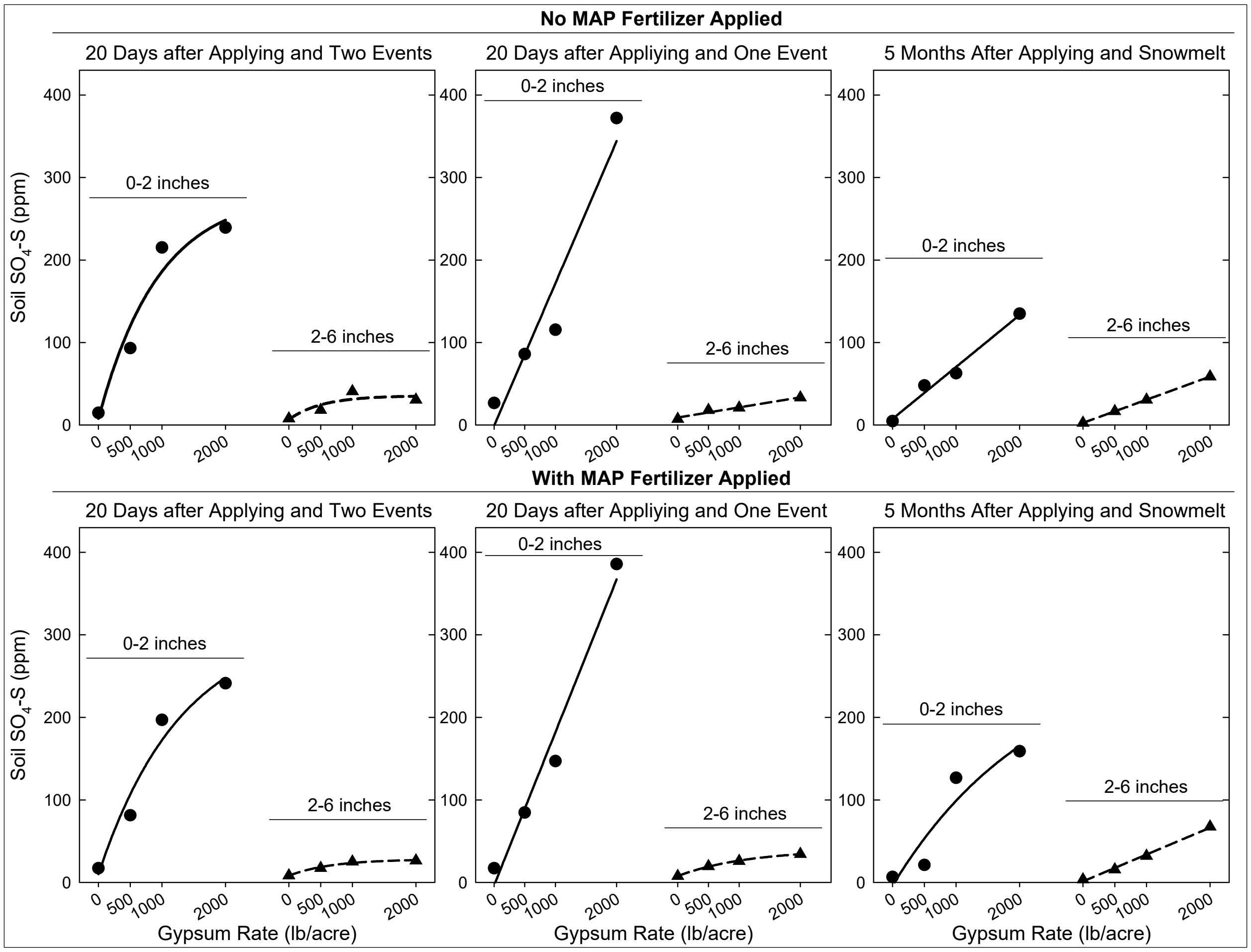
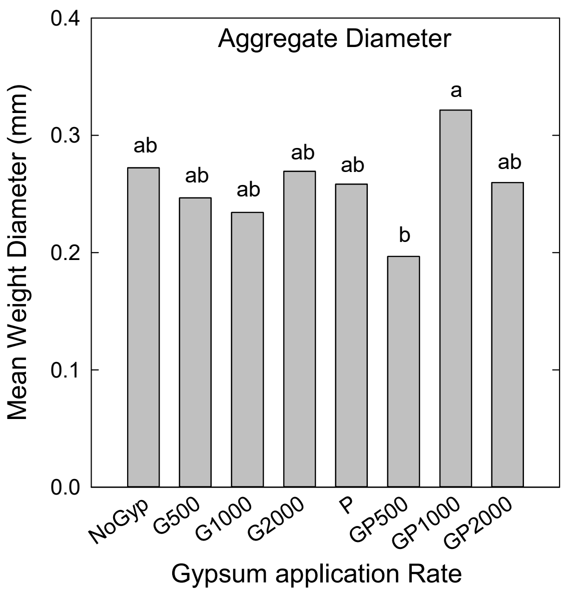


Figure 12. Second-year trial: Soil sulfate as affected by 0, 500, 1000, and 2000 lb/acre of granulated gypsum applied with or without P fertilizer for three combinations of days after application and runoff events. All sulfate increases were significant at $P \leq 0.05$.

Figure 13 summarizes gypsum application effects on two measurements of soil aggregate stability from soil samples collected in spring 2018 a few days after the last snowmelt runoff was collected (about five months after the treatments application the previous fall). No large gypsum effects were expected because of the short time to react with the soil and especially with no-till management. There were statistically significant differences only at $P \leq 0.10$ for both expressions of aggregate stability due to a decrease with the 500-lb gypsum rate and an increase with the 1000-lb rate only with gypsum and P fertilizer application at the same time. We believe, however, that these apparent differences among the treatments resulted from random variability because such a result is difficult to explain. It is also difficult to explain why there would be an aggregate stability difference with P applied but not without P in a study with no growing crop and a too short time for P to make any difference in soil physical properties. On average across the two P fertilizer treatments there were no statistical differences and the only apparent difference was a small decrease by the 500-lb rate (not shown). Therefore, we conclude that in this study with a short period of reaction with the soil, gypsum did not affect soil aggregate stability.



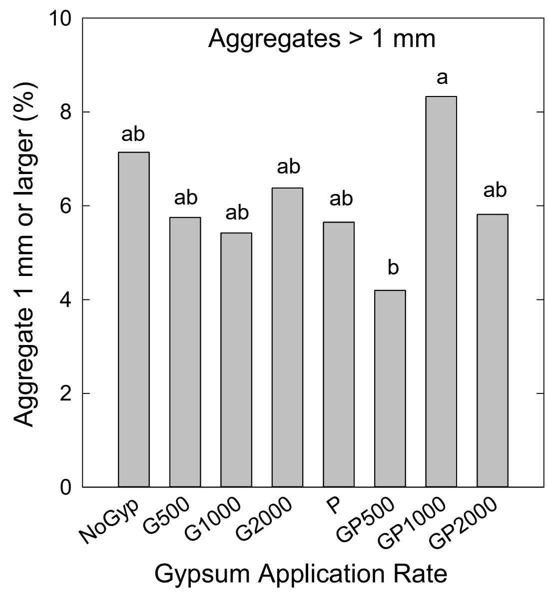


Figure 13. Second-year trial: Soil aggregate stability in spring 2018 expressed as mean weight diameter and aggregate size 1 mm or larger five months after applying no gypsum (noGyp), P fertilizer alone (P) and 500, 1000, and 2000 lb/acre of granulated gypsum without (G) or with P (GP). Bars with different letters differ at $P \leq 0.10$.

SUMMARY AND CONCLUSIONS

The study consisted of two trials established in different fields and years both with Clarion loam soil but with low-testing soil P in the first year and high-testing P in the second year. Both trials were conducted without tillage and with treatments applied in the fall between soybean harvest and before snowfall or soils a froze. For the first-year trial treatments were a no-gypsum control and granulated or ground gypsum at rates of 500, 1000, 2000 lb/acre broadcast at the same time that 100 lb P_2O_5/acre were broadcast across all plots. For the second-year trial treatments were 0, 500, 1000, and 2000 lb/acre of granulated gypsum broadcast with or without applying 100 lb P_2O_5/acre at the same time. In both trials additional treatments were four times to runoff that used three sets of the same gypsum and P treatments applied in the fall. Simulated rainfall was used for two of the treatment sets - one set was used for a first runoff event within two days of the materials application and a second runoff event after 15 days whereas the second set was used for a single runoff event 15 days after the application. The third treatment set was used to collect natural snowmelt runoff during five months from the materials application. Several soil chemical properties were measured in initial and final samples taken from depths of 0-2 and 2-6 inches. Measurements in runoff were soil, total P, and dissolved reactive P. Soil aggregate stability was measured at the end of the second-year trial in soil of plots from where snowmelt runoff had been collected.

First-year trial summary results:

- There were no dissolved P or total P differences between granulated or ground gypsum sources.
- Gypsum application rates did not affect runoff dissolved P or total P losses for any time to runoff events within two days, after 15 days, or after five months of the application.
- Several gypsum rates increased soil loss in the fall runoff event 15 days after the application and the 100-lb rate with granulated or ground gypsum also increased soil loss with snowmelt runoff. These effects have no reasonable explanation and probably resulted from random soil variability.
- Gypsum increased soil sulfate at soil sampling depths of 0-2 and 2-6 inches and also increased extractable calcium at the top 2-inch soil depth although small increases in snowmelt runoff did not attain statistical significance. Gypsum slightly increased or did not affect soil P measured by routine soil test methods nor water-extractable P.

Second-year trial summary results:

- Gypsum application rates with or without P applied at the same time did not affect runoff dissolved P or total P losses for times to runoff events within two days or after 15 days of the application.
- The two highest gypsum rates applied together with P fertilizer decreased runoff total P loss but did not affect dissolved P loss for snowmelt runoff. This result has no reasonable explanation and may have been caused by random site variability.
- Gypsum did not affect soil loss with runoff for any time to runoff event.
- Gypsum increased soil sulfate at sampling depths of 0-2 and 2-6 inches but small calcium increases at the top 2-inch soil depth by the two highest rates applied together with P fertilizer did not attain statistical significance. There were no gypsum effects on soil P measured by routine soil test methods nor water-extractable P.
- Soil aggregate stability was measured only in the second-year site five months after gypsum application and was improved only by the intermediate gypsum rates applied together with P fertilizer, which we could not explain satisfactorily and may have resulted from random site variability.

Overall, the study showed no significant effects of gypsum application on dissolved or total P loss with surface runoff. Gypsum did not clearly affect soil aggregate stability either, although improvements were not expected for this short-term study. Additional field research with natural rainfall and larger plots or at a watershed level would be desirable with a longer time of evaluation after gypsum is applied.

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