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# Decreasing Phosphorus Loss in Tile-Drained Landscapes Using Flue Gas Desulfurization Gypsum

K. W. King,* M. R. Williams, W. A. Dick, and G. A. LaBarge

## Abstract

Elevated phosphorus (P) loading from agricultural nonpoint-source pollution continues to impair inland waterbodies throughout the world. The application of flue gas desulfurization (FGD) gypsum to agricultural fields has been suggested to decrease P loading because of its high calcium content and P sorbing potential. A before–after control–impact paired field experiment was used to examine the water quality effects of successive FGD gypsum applications (2.24 Mg ha$^{-1}$; 1 ton acre$^{-1}$ each) to an Ohio field with high soil test P levels (>480 ppm Mehlich-3 P). Analysis of covariance was used to compare event discharge, dissolved reactive P (DRP), and total P (TP) concentrations and loadings in surface runoff and tile discharge between the baseline period (86 precipitation events) and Treatment Period 1 (42 precipitation events) and Treatment Period 2 (84 precipitation events). Results showed that, after the first application of FGD gypsum, event mean DRP and TP concentrations in treatment field tile water were significantly reduced by 21 and 10%, respectively, and DRP concentrations in surface runoff were significantly reduced by 14%; however, no significant reductions were noted in DRP or TP loading. After the second application, DRP and TP loads were significantly reduced in surface runoff (DRP, 41%; TP 40%), tile discharge (DRP, 35%; TP, 15%), and combined (surface + tile) discharge (DRP, 36%; TP, 38%). These findings indicate that surface application of FGD gypsum can be used as a tool to address elevated P concentrations and loadings in drainage waters.

## Core Ideas

- A paired field study demonstrated the water quality benefits of FGD gypsum.
- FGD gypsum improved aggregate stability and increased infiltration.
- FGD application reduced dissolved and total P concentrations.
- FGD gypsum reduced dissolved and total P loads.
- Significant reductions were realized in surface and tile drainage discharge.

Phosphorus (P) loading from agricultural landscapes and the resulting eutrophication of aquatic ecosystems remains one of the most pervasive surface water quality impairments globally. In the midwestern United States and other tile-drained regions, the risk of P loss from agricultural fields is dependent on several factors, including soil P concentration and the degree of hydrologic connectivity between fields and nearby surface waters (King et al., 2015; Williams et al., 2015a). Elevated soil P concentrations not only increase the risk of particulate and dissolved P loss in surface runoff (Pote et al., 1996) but also increase the risk of dissolved P loss from the subsurface drainage network (King et al., 2015). Many existing management practices have been shown to successfully decrease particulate P losses in surface runoff (e.g., no-till, grass buffer strips); however, relatively few management practices have the ability to control dissolved P losses (Sharpley et al., 2015). Increasingly, scientists and producers are investigating the application of P-sorbing materials that typically contain appreciable concentrations of aluminum, iron, or calcium to agricultural fields to decrease the solubility and mobility of soil P (Penn et al., 2007).

Flue gas desulfurization (FGD) gypsum ($CaSO_4{\cdot}2H_2O$), a by-product of coal-fired electricity-producing power plants, is a well-known soil amendment for reclaiming sodium-afflicted soils, for ameliorating subsoil acidity and aluminum toxicity, and for improving soil structure and reducing runoff and erosion (Chen and Dick, 2011; Norton and Dontsova, 1998; Shainberg et al., 1989; Truman et al., 2010). It has also been shown to be a quality source of gypsum due to its high purity (Chen et al., 2014; USEPA, 2008; Watts and Dick, 2014) and has been evaluated (Torbert and Watts, 2014) and approved for use as a soil amendment (USDA–NRCS, 2015).

Flue gas desulfurization gypsum has a calcium concentration as high as 23% and, as a result, has the potential to function as a P-sorbing material and reduce the risk of P loss when applied to soils with elevated P (Endale et al., 2014; Murphy and Stevens, 2010; Stout et al., 1998) or in conjunction with organic fertilizer sources (Watts and Torbert, 2016). Indeed, numerous laboratory incubation experiments and rainfall simulation studies have shown that FGD gypsum decreases soil P solubility and dissolved



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*Corresponding author (kevin.king@ars.usda.gov).

K.W. King and M.R. Williams, USDA–ARS Soil Drainage Research Unit, 590 Woody Hayes Dr., Columbus, OH 43210; W.A. Dick, Environment and Natural Resources, The Ohio State Univ., 101A Hayden Hall, 1680 Madison Ave. Wooster, OH 44691; G.A LaBarge, The Ohio State Univ., 222 W. Center St., Marion, OH 43302. Assigned to Associate Editor Laura Christianson.

**Abbreviations**: DRP, dissolved reactive phosphorus; FGD, flue gas desulfurization; TP, total phosphorus.

P losses in surface runoff compared with control treatments (Boruvka and Rechcigl, 2003; Callahan et al., 2002; Endale et al., 2014; Murphy and Stevens, 2010). A significant reduction in dissolved P leaching after application of FGD gypsum has also been observed in soil column experiments (Coale et al., 1994; Favaretto et al., 2012; Zhu and Alva, 1994). Although the potential of FGD gypsum to decrease P losses in surface runoff and subsurface leachate has been demonstrated, there is a paucity of research on P losses after application of FGD gypsum at larger spatial scales (except Cox et al., 2005; Ekholm et al., 2012). Thus, a critical next step in determining the effect of FGD gypsum on P losses is to examine its capacity to decrease P concentrations and loads in surface and subsurface discharge at the field scale.

In this study, we evaluated the effectiveness of FGD gypsum on decreasing P losses in surface runoff and tile discharge from fields with high soil P concentrations (>480 ppm Mehlich-3) using a before–after control–impact (Smith, 2002) study design. Surface runoff and tile discharge from two adjacent fields in western Ohio were measured for 4.5 yr. After a baseline period, FGD gypsum was surface-applied to one of the fields on two different occasions; the other field served as the control. The objectives of the study were (i) to determine the effect of FGD gypsum on surface runoff and tile discharge volume and (ii) to quantify the impact of FGD gypsum on P concentrations and loads in surface runoff and tile discharge.

# Materials and Methods

## Site Description

Two adjacent tile-drained fields located in Mercer County, OH, that are part of the USDA–ARS edge-of-field research network (Williams et al., 2016) were used to evaluate the effect of FGD gypsum on P losses in surface runoff and tile discharge (Fig. 1). One of the fields was randomly designated as the control and the other field as the treatment. The soil in both fields is a somewhat poorly drained Blount silt loam (Fine, illitic, mesic Aeric Epiaqualfs). The surface contributing areas for each field were delineated using 0.3-m contours generated from the 2006 Ohio Statewide Imagery Program (OSIP). The surface drainage areas were 3.7 and 5.2 ha for the control and treatment fields, respectively. Both fields have a mixture of systematic and random tile drainage, with tile laterals positioned at a depth of approximately 1 m. The subsurface drainage area for each field was determined using 2007 OSIP color orthophotos and site visits with the landowner. The estimated subsurface contributing areas were 3.7 ha for the control field and 4.5 ha for the treatment field.

The fields have historically been managed by the same producer in a corn (*Zea mays* L.)–soybean [*Glycine max* (Merr.) L.] rotation (Table 1). Before 2005, poultry litter was applied annually to both fields to meet crop N demands, which led to excess P application and elevated soil test P concentrations. Soil P concentrations in the top 20 cm of the profile averaged 481 and 498 ppm Mehlich-3 P in the control and treatment fields, respectively. Since 2005, no P has been applied to either field. Fertility-related management has primarily consisted of N applications and the use of cover crops. In October 2013 and January 2015, FGD gypsum was surface-applied to the treatment field at a rate of 2.24 Mg ha$^{-1}$ (1.0 t acre$^{-1}$) (Table 1).

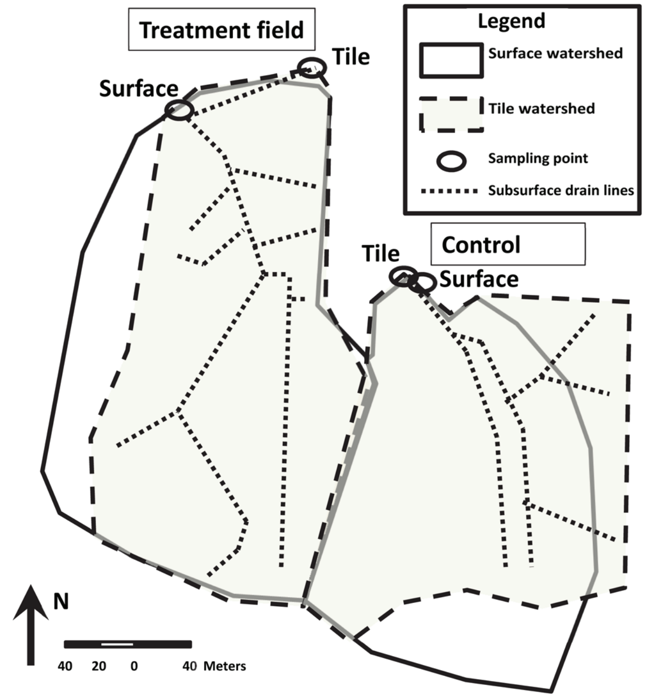


**Fig. 1. Layout of paired (control and treatment) fields showing surface delineation, tile lines identified from orthophotos and estimated subsurface drainage area, and surface and subsurface (tile) sampling locations.**

## Precipitation and Discharge Measurements

Precipitation, surface runoff, and tile discharge were measured continuously from 5 June 2011 through 1 Sept. 2015.

**Table 1. Management of study fields including planting and harvest dates, fertilizer and flue gas desulfurization gypsum applications, crop yield, and tillage.**

| Date | Operation |
|---|---|
| 25 Sept. 2010 | plant rye clover radish cover crop |
| 1 June 2011 | plant soybeans |
| 25 Sept. 2011 | plant rye clover radish cover crop |
| 20 Oct. 2011 | harvest soybeans (3.36 Mg ha$^{-1}$) |
| 17 Apr. 2012 | plant corn |
| 17 Apr. 2012 | fertilize corn (141 L ha$^{-1}$; 28% UAN) |
| 1 June 2012 | fertilize corn (328 L ha$^{-1}$; 28% UAN) |
| 14 Aug. 2012 | plant rye and radish cover crop |
| 7 Sept. 2012 | harvest corn (partial silage; remainder 3.14 Mg ha$^{-1}$) |
| 17 May 2013 | plant soybeans |
| 10 Sept. 2013 | plant clover and radish cover crop |
| 1 Oct. 2013 | harvest soybeans (2.89 Mg ha$^{-1}$) |
| 3 Oct. 2013 | apply gypsum to treatment field (2.24 Mg ha$^{-1}$) |
| 12 Oct. 2013 | tillage (vertical till) |
| 8 May 2014 | plant corn |
| 8 May 2014 | fertilize corn (141 L ha$^{-1}$; 28% UAN) |
| 14 June 2014 | fertilize corn (422 L ha$^{-1}$; 28% UAN) |
| 9 Nov. 2014 | harvest corn (10.0 Mg ha$^{-1}$) |
| 3 Jan. 2015 | apply gypsum to treatment field (2.24 Mg ha$^{-1}$) |
| 8 May 2015 | plant corn |
| 12 June 2015 | fertilize corn (281 L ha$^{-1}$; 28% UAN) |
| 28 Aug. 2015 | plant oats and clover cover crop |
| 14 Oct. 2015 | harvest corn (7.65 Mg ha$^{-1}$) |
| 22 Oct. 2015 | tillage (ripper) |

Precipitation was measured using an Isco 674 tipping bucket rain gauge (Teledyne Isco) and a standard rain gauge (NovaLynx 260–2510), which were located near the outlet of the treatment field. Surface runoff from each field was measured using a 0.61-m h-flume (Tracom Inc.). Wing walls were extended horizontally from the flume to channel surface flow through the flume. The original 10-cm-diameter tile outlets draining each field were cut and fitted with a 30-cm-diameter pipe that facilitated the installation of compound weir inserts (Thel-Mar LLC). To measure discharge, each control volume (i.e., flumes and compound weirs) was equipped with an Isco 4230 Bubbler Flow Meter that was programmed to record water depth at 10-min intervals. Each tile outlet was also instrumented with an Isco 2150 Area Velocity Sensor to aid in discharge measurement under submerged conditions.

## Water Quality Sampling and Analysis

All surface flumes and tile outlets were instrumented with Isco 6712 portable water quality samplers. Water quality samples for surface runoff were collected using a flow-proportional sampling strategy, with a 200-mL aliquot collected for every 1 mm volumetric depth of water that passed through the flume. Ten aliquots were composited into a single sample bottle. Water quality samples from the tile outlets could not be collected using flow-proportional sampling due to tile submergence; thus, samples were collected using a time-proportional strategy. A 200-mL aliquot was collected from each tile outlet every 6 h, and four aliquots were composited into a sample bottle (i.e., daily sample).

Water samples were retrieved from the field one or two times per week depending on the number and timing of precipitation events. After collection, water samples were refrigerated at 4°C and generally analyzed within 28 d. All water samples were analyzed according to USEPA method 365.1 for P analysis (USEPA, 1983). Briefly, samples were vacuum filtered (0.45 μm) before analysis of dissolved nutrients. Dissolved reactive P ($PO_4$–P) concentrations were determined colorimetrically by flow injection analysis using a Lachat Instruments QuikChem 8000 FIA Automated Ion Analyzer (Lachat Instruments Inc.). The concentration of $PO_4$–P concentration was determined by the ascorbic acid reduction method (Parsons et al., 1984). Total P (TP) analyses were performed on unfiltered samples after alkaline persulfate oxidation (Koroleff, 1983) with subsequent determination of $PO_4$–P. From this point forward, $PO_4$–P in the filtrate will be designated as dissolved reactive P (DRP).

## Statistics and Data Analysis

To evaluate the effect of FGD gypsum on discharge volume and P losses in tile-drained landscapes, data were first divided into three time periods. The baseline period was defined as the time between the beginning of data collection and the first application of FGD gypsum to the treatment field (Table 1; Fig. 2). Two treatment periods followed the baseline period and corresponded to the timing of FGD gypsum application. The first treatment period was from 3 Oct. 2013 to 2 Jan. 2015 (i.e., the date of the second FGD gypsum application), and the second treatment period included both FGD applications (3 Oct. 2013–1 Sept. 2015). The decision to include the first treatment period in the second treatment period was based on the anticipated continued effectiveness of the first FGD application. Separating the effects from the two different applications was not possible. During each of the three time periods, rainfall and associated discharge data were separated into individual events. Precipitation events were defined as at least 6.35 mm of rainfall in a 6-h period separated by at least 6 h from additional rainfall. Surface runoff events were defined as the period between initiation of precipitation and surface discharge returning to zero. Subsurface events were defined as the period between the start of precipitation and the lesser of the periods when discharge returned to within 5% of the initial discharge or 7 d. The 7-d threshold was selected based on observation and professional experience and permitted greater than 90% of total annual discharge to be used in the analysis. To calculate P loads, continuous (10 min) concentration data were constructed through linear interpolation between individual

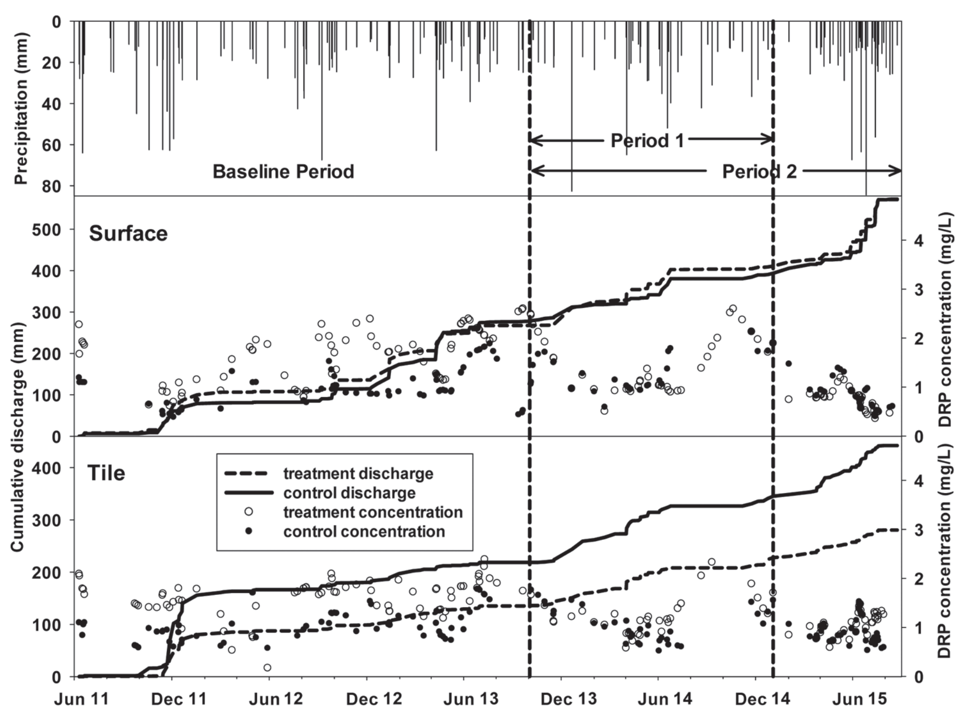


**Fig. 2. Time series of event precipitation, cumulative surface and tile discharge, and dissolved reactive P (DRP) concentrations for control and treatment fields during the baseline period and after gypsum applications.**

samples (Williams et al., 2015b). Event loads were calculated by multiplying the instantaneous discharge measured at the 10-min intervals by the concentrations determined for those same intervals and summing over the duration of the discharge event. Event mean concentrations were calculated as the event load divided by the event discharge. Combined (surface + tile) discharge and loads were calculated as the sum of the surface and tile contributions. Combined concentrations were calculated as the load divided by discharge.

Discharge, P concentrations, and P loads were evaluated using a before–after control–impact design (Smith, 2002). Event data were analyzed using analysis of covariance (ANCOVA) as outlined by Clausen and Spooner (1993) to determine if application of FGD gypsum significantly affected discharge and P transport. Normality was tested using the Shapiro–Wilk test, and equal variance was evaluated using the Levene statistic. However, even after transformation, normality and equal variance were not achieved for all data. Linear relationships between the control and treatment fields were established for each response variable for the baseline period (Table 2). The linear relationships were significant and the duration of the baseline period (>2 yr) was considered appropriate to determine a treatment response. After the treatment period, linear relationships were established between the control and treatment fields. Both slopes and intercepts between the control period and treatment periods were compared. Significantly different slopes or intercepts, when slopes were not significantly different, indicated a treatment effect. For the analysis, the factor or independent variable was set as the baseline/treatment periods, and the dependent variable was identified as the treatment field and the covariate the control field. When treatment means were different, post hoc analysis was completed using the Holm–Sidak method and a significance level of 0.05. All analysis was conducted using SigmaStat 3.4 statistical software (Systat Software, 2006).

Percentage reductions in discharge, concentrations, and loads were calculated by using the linear relationship established for the baseline period to predict discharge, concentrations, and loads for the treatment periods for the treatment field. That is, discharge, concentrations, and loads for the treatment field were predicted from the baseline period linear relationship (Table 2) and the parameter event values from the control field. Differences in the predicted values and measured values for each of the treatment periods were converted to percentage reduction to estimate the effect of FGD gypsum application.

**Table 2. Baseline regression coefficients and predicted and observed discharge, dissolved reactive P, and total P concentrations and loads for surface, subsurface, and combined pathways for the different treatment periods.**

| Parameter† | Baseline | | | Treatment period‡ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Treatment period 1 | | | | | Treatment period 2 | | | | |
| | Slope | Intercept | $R^2$ | Predicted | Observed | Difference | % Reduction | *P* value | Predicted | Observed | Difference | % Reduction | *P* value |
| | | | | | | | Surface runoff | | | | | | |
| Discharge, mm | 0.961 | 0.114 | 0.83 | 2.70 | 3.36 | 0.66 | 24.4 | 0.102 | 3.49 | 3.61 | 0.12 | 3.4 | 0.553 |
| DRP EMC, mg L$^{-1}$ | 0.711 | 0.953 | 0.29 | 1.53 | 1.32 | −0.21 | −13.7 | *<0.001*§ | 1.49 | 0.97 | −0.52 | −34.9 | *<0.001* |
| DRP load, g ha$^{-1}$ | 1.494 | 0.001 | 0.79 | 52.33 | 35.40 | −16.93 | −32.4 | 0.109 | 51.42 | 30.36 | −21.06 | −41.0 | *0.008* |
| TP EMC, mg L$^{-1}$ | 1.088 | 0.675 | 0.32 | 2.26 | 2.28 | 0.02 | 1.0 | 0.675 | 2.22 | 1.69 | −0.53 | −23.8 | *<0.001* |
| TP load, g ha$^{-1}$ | 1.307 | 0.004 | 0.76 | 91.94 | 62.93 | −29.01 | −31.6 | 0.298 | 90.05 | 53.72 | −36.33 | −40.3 | *0.038* |
| | | | | | | | Tile discharge | | | | | | |
| Discharge, mm | 0.366 | 0.645 | 0.58 | 1.71 | 2.11 | 0.40 | 23.4 | 0.085 | 1.61 | 2.09 | 0.48 | 29.8 | *0.004* |
| DRP EMC, mg L$^{-1}$ | 0.498 | 1.057 | 0.18 | 1.56 | 1.23 | −0.34 | −21.5 | *<0.001* | 1.54 | 1.15 | −0.39 | −25.3 | *<0.001* |
| DRP load, g ha$^{-1}$ | 0.773 | 0.008 | 0.62 | 34.42 | 24.42 | −10.00 | −29.1 | 0.153 | 30.08 | 19.59 | −10.49 | −34.9 | *0.020* |
| TP EMC, mg L$^{-1}$ | 0.521 | 1.112 | 0.19 | 1.80 | 1.61 | −0.19 | −10.3 | *0.010* | 1.85 | 1.66 | −0.19 | −10.4 | *0.008* |
| TP load, g ha$^{-1}$ | 0.797 | 0.008 | 0.51 | 35.23 | 30.79 | −4.44 | −12.6 | 0.223 | 30.75 | 26.26 | −4.49 | −14.6 | *0.040* |
| | | | | | | | Combined surface and tile | | | | | | |
| Discharge, mm | 0.694 | 0.681 | 0.86 | 4.57 | 5.48 | 0.91 | 19.9 | 0.119 | 4.96 | 5.34 | 0.38 | 7.7 | 0.419 |
| DRP EMC, mg L$^{-1}$ | 0.610 | 0.979 | 0.24 | 1.66 | 1.27 | −0.39 | −23.6 | *<0.001* | 1.57 | 1.07 | −0.50 | −31.8 | *<0.001* |
| DRP load, g ha$^{-1}$ | 1.094 | 0.010 | 0.74 | 84.98 | 59.80 | −25.18 | −29.6 | *0.005* | 78.17 | 49.90 | −28.27 | −36.2 | *<0.001* |
| TP EMC, mg L$^{-1}$ | 0.780 | 0.904 | 0.26 | 2.27 | 2.07 | −0.19 | −8.5 | 0.511 | 2.16 | 1.75 | −0.41 | −19.0 | *0.002* |
| TP load, g ha$^{-1}$ | 1.092 | 0.014 | 0.75 | 134.01 | 93.73 | −40.28 | −30.1 | *0.013* | 128.10 | 79.97 | −48.13 | −37.6 | *<0.001* |

† DRP, dissolved reactive P; EMC, event mean concentration; TP, total P.

‡ Baseline period: 1 June 2011–2 Oct. 2013 (*n* = 86); Treatment Period 1: 3 Oct. 2013–2 Jan. 2015 (*n* = 42); Treatment Period 2: 3 Oct. 2013–1 Sept. 2015 (*n* = 84).

§ Italicized *P* values indicate significance ($p < 0.05$) between baseline and treatment period.

# Results

## Precipitation and Discharge

There were 86 defined precipitation events during the baseline period, 42 precipitation events during Treatment Period 1, and 84 precipitation events during Treatment Period 2 (Fig. 2). Precipitation events ranged in size from 7.0 to 84.4 mm. Mean precipitation event size did not vary among periods, with mean event sizes of 22.8, 22.7, and 20.7 mm measured for the baseline period, Treatment Period 1, and Treatment Period 2, respectively. Precipitation during the nongrowing season was similar among periods; however, growing season precipitation was substantially greater during Treatment Period 2 compared with the baseline period and Treatment Period 1. During Treatment Period 2, measured precipitation amounts for June (253 mm) and July (212 mm) were approximately 100% greater than normal precipitation reported for nearby Fort Recovery, OH (NCDC, 2016). Not all precipitation events produced surface and/or tile discharge events (Fig. 2). In general, surface discharge generating events occurred during the winter and spring, whereas tile discharge was more prominent from fall through spring.

There was no significant ($P < 0.05$) difference in mean surface discharge between the baseline period and Treatment Period 1 or Treatment Period 2 (Table 2; Fig. 2 and 3). Similarly, no significant difference in mean tile discharge was measured between the baseline period and Treatment Period 1. Significant increases (approximately 30%) in mean event tile discharge, however, were measured between the baseline period (1.6 mm) and Treatment Period 2 (2.1 mm) (Table 2; Fig. 2 and 3). When combining the discharge from both surface and subsurface flow pathways, no significant differences in discharge were measured between the baseline and either treatment period. Thus, the measured increase in tile discharge after FGD gypsum application did not result in a statistical increase in cumulative discharge from the field.

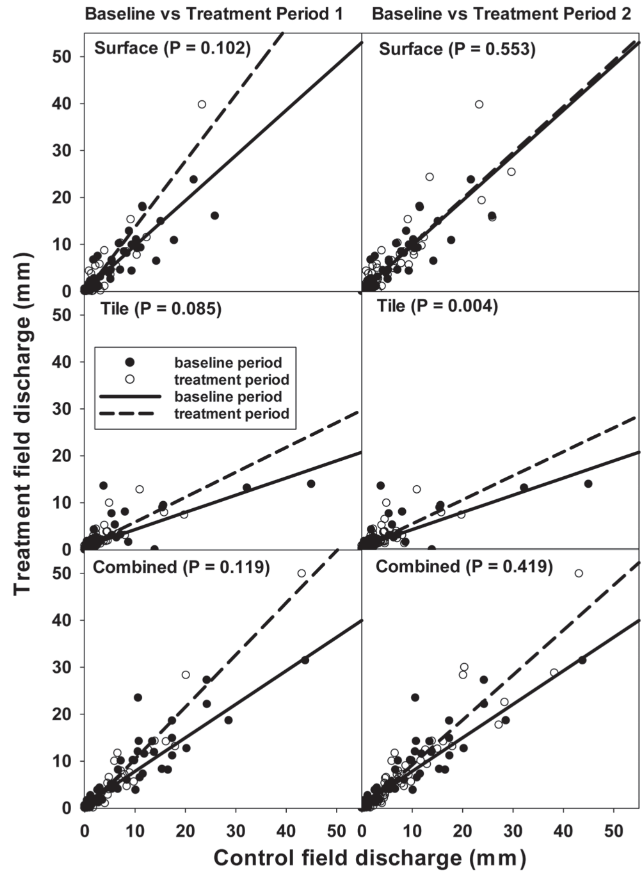


**Fig. 3. Discharge regressions for surface, tile, and combined discharge pathways between control and treatment fields for the baseline period (1 June 2011–2 Oct. 2013; *n* = 86) and Treatment Period 1 (3 Oct. 2013–2 Jan. 2015; *n* = 42) and for the baseline period versus Treatment Period 2 (3 Oct. 2013–1 Sept. 2015; *n* = 84).**

## P Concentrations and Loads

### Concentrations

Event mean DRP concentrations in surface runoff from both control and treatment fields ranged from 0.4 to 2.6 mg $L^{-1}$, and event mean TP concentrations in surface runoff ranged from 0.6 to 5.1 mg $L^{-1}$ (Fig. 2, 4, and 5). Surface runoff event mean DRP concentration in the control field did not vary significantly among periods (average, 1.04 mg $L^{-1}$), but significant differences were found among periods in the treatment field (Table 2). Average event mean DRP concentration in surface runoff from the treatment field during the baseline period was 1.65 mg $L^{-1}$, which was significantly greater than the average event mean DRP concentration observed during Treatment Period 1 (1.32 mg $L^{-1}$) and Treatment Period 2 (0.97 mg $L^{-1}$). Similar to DRP concentration, event mean TP concentration in surface runoff was not significantly different among periods in the control field, but a significant reduction (23.8%) in event mean TP concentration was found between the baseline period and Treatment Period 2 for the treatment field (Table 2).

Event mean DRP concentrations in tile drainage from both control and treatment fields were generally less than concentrations measured in surface runoff, with observed concentrations ranging from 0.2 to 2.4 mg $L^{-1}$ (Fig. 2, 4, and 5). No differences were measured in average event mean DRP concentrations among periods in the control field (average, 1.01 mg $L^{-1}$). Tile drainage event mean DRP and TP concentrations in the treatment field were significantly reduced after the first and second gypsum applications compared with the baseline period (Table 2; Fig. 4 and 5). Predicted average event mean DRP concentration in the treatment field was significantly greater during the baseline period (1.56 mg $L^{-1}$) compared with Treatment Period 1 (1.23 mg $L^{-1}$; 22% reduction) and Treatment Period 2 (1.15 mg $L^{-1}$; 25% reduction). Similar to DRP concentrations, tile drainage event mean TP concentration in the treatment field was significantly reduced after the first and second gypsum applications (Table 2; Fig. 4 and 5). Average event mean TP concentrations were reduced in the treatment field from 1.8 to 1.61 mg $L^{-1}$ (10.3% reduction) during Treatment Period 1 and from 1.85 to 1.66 mg $L^{-1}$ during Treatment Period 2 (10.4% reduction).

### Loading

Event mean DRP loads in surface runoff from both control and treatment fields ranged from 0 to 408 g $ha^{-1}$, and event mean TP loads ranged from 0 to 501 g $ha^{-1}$ (Fig. 4 and 5). In the control field, there was no difference in event mean surface DRP loads (32 g $ha^{-1}$) or TP loads (50 g $ha^{-1}$) across periods. After the first gypsum application, there was no difference in mean DRP loads between the baseline (52 g $ha^{-1}$) and Treatment Period

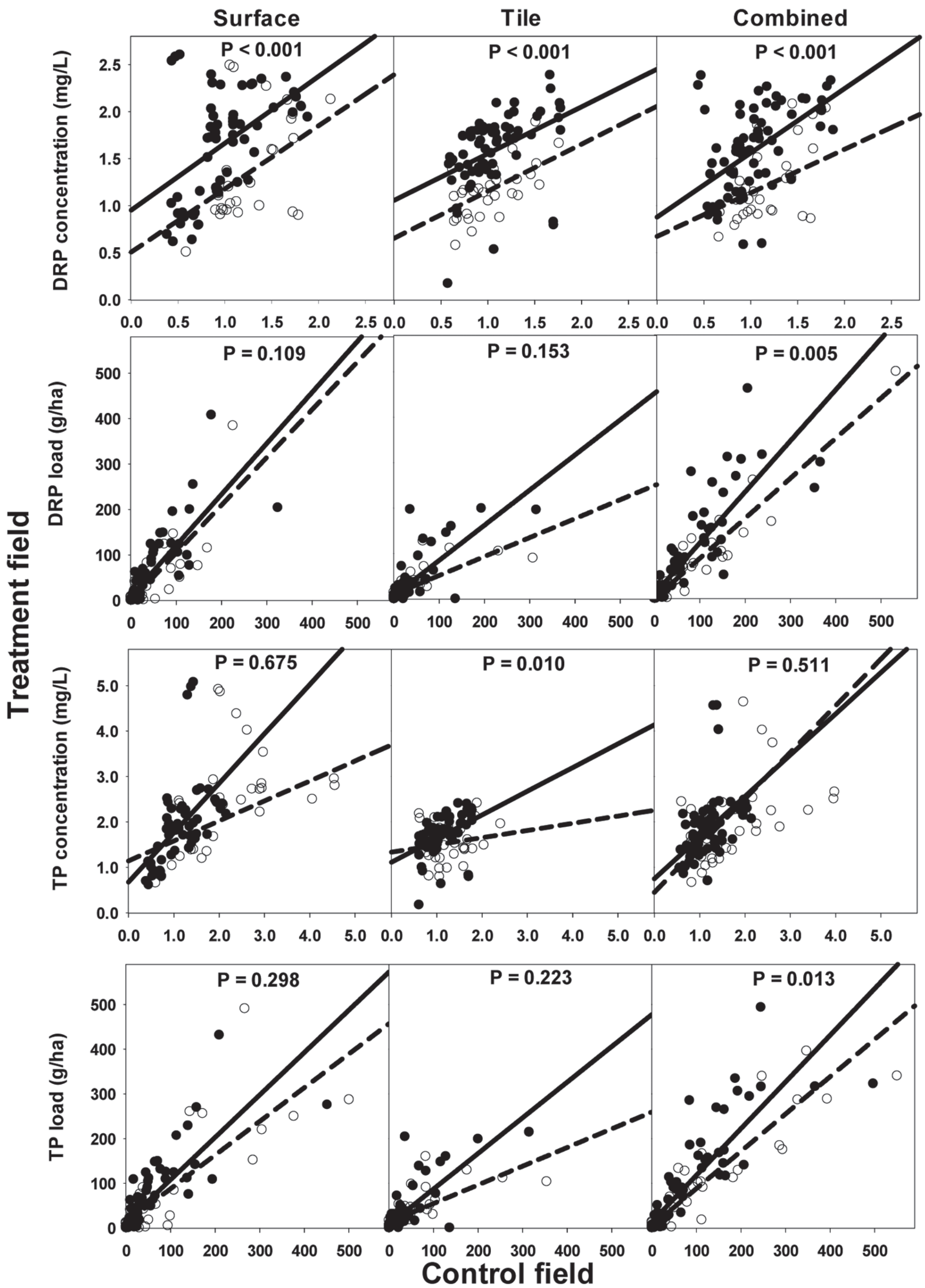


**Fig. 4. Regressions for surface, subsurface, and combined surface and subsurface dissolved reactive P (DRP) and total P (TP) concentrations and loadings during the baseline period (1 June 2011–2 Oct. 2013; *n* = 86) and Treatment Period 1 (3 Oct. 2013–2 Jan. 2015; *n* = 42). Solid lines and closed symbols are for the baseline period; and dashed lines and open symbols are for Treatment Period 1.**

1 (35 g ha$^{-1}$) in the treatment field (Table 2; Fig. 4). Similarly, there was no difference in surface TP loads between the baseline (91 g ha$^{-1}$) and Treatment Period 1 (63 g ha$^{-1}$) (Table 2; Fig. 4). However, after the second gypsum application, mean DRP surface loads were significantly reduced from 51 to 30 g ha$^{-1}$ (41% reduction) (Table 2; Fig. 5). Similarly, after the second application, event mean surface TP loads were reduced from 90 to 54 g ha$^{-1}$ (40% reduction) (Table 2; Fig. 5).

Event mean DRP loads in tile drainage, from both control and treatment fields, ranged from 0 to 308 g ha$^{-1}$; event mean TP loads ranged from 0 to 355 g ha$^{-1}$ (Fig. 4 and 5). Event mean DRP load in the control field was 25 g ha$^{-1}$ and was not different across periods. Predicted DRP load from the treatment field for Treatment Period 1 was 34 g ha$^{-1}$ and was not significantly reduced after the first gypsum application (Period 1 DRP load = 24 g ha$^{-1}$) (Table 2; Fig. 4). However, after the second gypsum application, the DRP load was significantly reduced from 30 to 19 g ha$^{-1}$ (35% reduction) (Table 2; Fig. 5). Similarly, mean TP load in tile drainage from the control field was 31 g ha$^{-1}$ and did not differ across periods. After the second gypsum application, predicted TP loads were significantly reduced from 31 to 26 g ha$^{-1}$ (14.6% reduction) (Table 2; Fig. 5).

# Discussion

Findings from the current study suggest that FGD gypsum increased tile discharge but did not result in significantly greater cumulative water yield (surface + tile) from the field. Calcium ions from gypsum have been shown to promote flocculation of clay particles, which results in increased aggregate stability and infiltration compared with soils high in magnesium where hydrated magnesium ions create dispersion of the clay particles, surface sealing, and reduced infiltration (Dontsova and Norton,

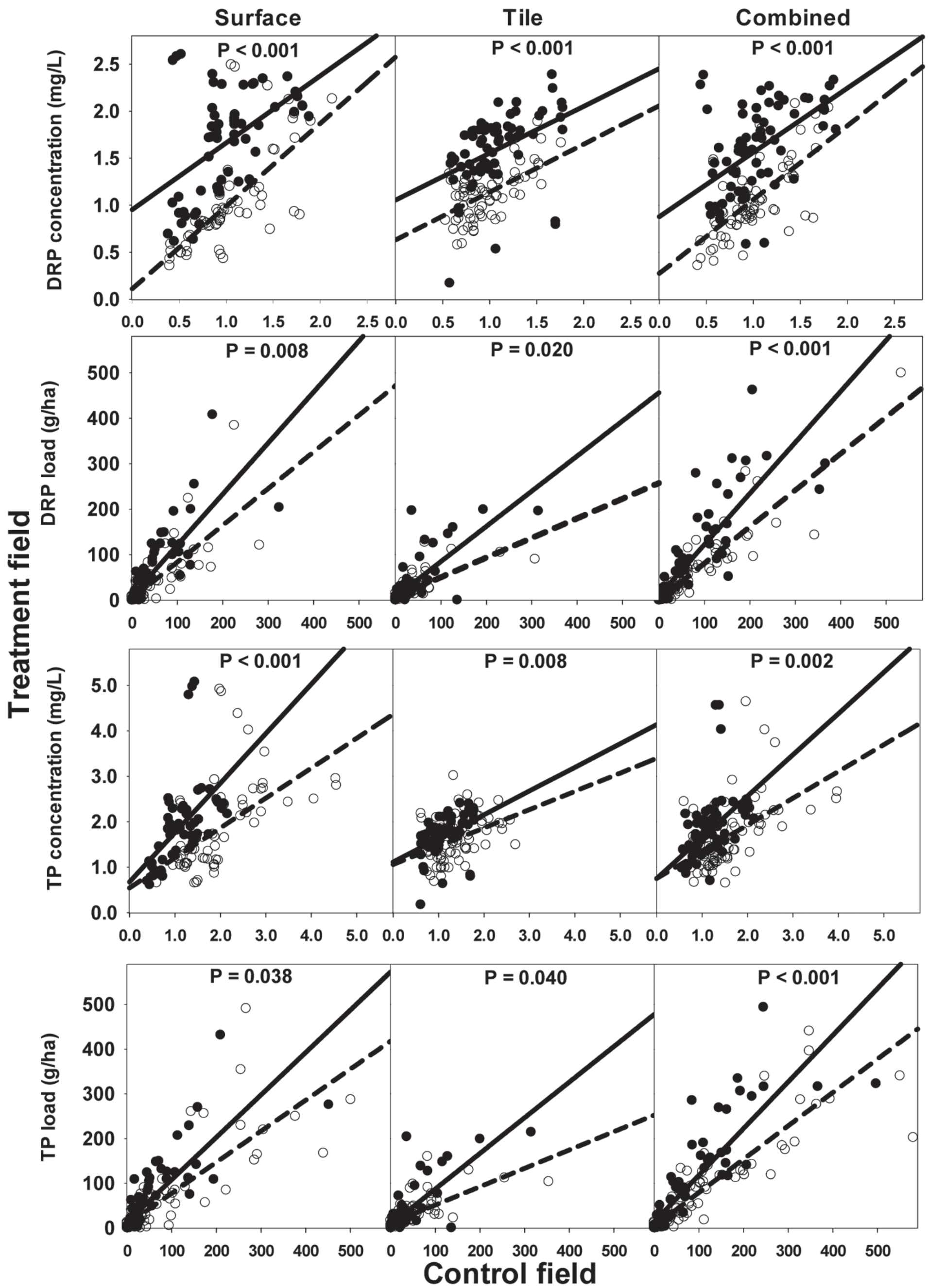


**Fig. 5. Regressions for surface, subsurface, and combined surface and subsurface dissolved reactive P (DRP) and total P (TP) concentrations and loadings during the baseline period (1 June 2011–2 Oct. 2013; *n* = 86) and Treatment Period 2 (3 Oct. 2013–1 Sept. 2015; *n* = 84). Solid lines and closed symbols are for the baseline period; dashed lines and open symbols are for Treatment Period 2.**

2002; Zhang and Norton, 2002). Soil magnesium concentrations at the study fields ranged from 275 to 697 ppm or 11.9 to 20.8% base saturation. The increased tile discharge after FGD gypsum application was thus likely due to enhanced aggregate stability and increased infiltration rates in the soil resulting from decreased magnesium levels due to calcium displacement. Although infiltration and aggregate stability were not measured in the current study, increased tile discharge after FGD gypsum application is in agreement with findings from previous laboratory and rainfall simulation studies. Using the same Blount soil series in a rainfall simulation experiment, Dontsova and Norton (2002) found that the infiltration rate of calcium-treated soils was nearly 2 times greater than that of magnesium-treated soils. Increases in infiltration rate with gypsum application have also been observed on silty loam and sandy clay soils (Yu et al., 2003). In the current study, successive FGD gypsum applications were needed before significant increases in tile discharge were observed, similar to findings reported by Truman et al. (2010). Truman et al. (2010) found that infiltration increased with increasing gypsum application rates from 1.1 to 9.0 Mg ha$^{-1}$.

Successive applications of FGD gypsum significantly reduced P concentrations in both surface runoff and tile drainage compared with the control field. After the first FGD gypsum application, event mean DRP concentration decreased by 21.5%, and event mean DRP concentration decreased by 25.3% after the second application. This finding suggests that successive or continued application of FGD gypsum may be necessary to achieve long-term water quality goals. However, it is unclear if the additional gypsum was required or if the effectiveness of gypsum is time dependent; that is, the effectiveness of gypsum may be slow, and its effects may not be fully manifested in the first year of application. Previous studies have also documented reductions of 10 to 50% in soil soluble P after gypsum application (Brauer et al., 2005; Murphy and Stevens, 2010; Phillips, 1998; Stout et al., 1998). Decreased DRP concentrations observed in the current study were likely due to enhanced P sorption through the dissolution of the calcium in the applied gypsum and the precipitation of Ca-, Al-, and Fe-phosphates. The average soil pH of the study fields was 6.5, which suggests that calcium from the FGD gypsum would either be available for Ca-phosphate formation (soil pH >6.5) (Havlin et al., 1999) or would be exchanged for Al and Fe on cation exchange sites and promote the formation of Al- or Fe-phosphate (soil pH <6.5) (Callahan et al., 2002; Cox et al., 2005; Stout et al., 1998).

Measured P concentrations in the current study were generally an order of magnitude greater than other reported surface and tile drainage concentrations (King et al., 2015) and were reflective of 40+ years of poultry litter application to the study fields and very high soil test P levels (>400 ppm in the plow layer). Field characteristics and the amount of FGD gypsum applied may potentially influence the effect of FGD gypsum on P concentrations as well as influence crop yields; thus, study results should be interpreted accordingly. For example, it is possible that the effect of FGD gypsum on event mean P concentration may be greater on fields with lower soil test P levels or on fields with higher gypsum application rates. Additionally, application of gypsum to a cover crop may alter its effectiveness as well as P transport. Because one of the goals of cover crops is to scavenge nutrients, the effectiveness of the gypsum may be masked by any P that was utilized by the cover crop. The first gypsum application was applied to a cover crop, whereas the second application was applied to bare soil and crop residue.

Stout et al. (2003) found that applying FGD gypsum to soils with high soil test P (228–367 ppm Mehlich-3) resulted in a 37 to 57% decrease in water-extractable soil P but resulted in minimal changes in Mehlich-3 P. If Mehlich-3 accurately assesses P availability to crops, FGD gypsum applied to fields does not negatively affect crop response by limiting crop-available P. Future research is needed to examine the effect of FGD gypsum application to fields with a range of soil test P levels and to determine if there is a soil test P threshold where FGD gypsum application would negatively affect crop yields.

Decreased P concentrations in surface runoff and tile drainage resulted in decreased P loading despite the observed increase in tile discharge after FGD gypsum application. The decrease in DRP concentrations was thus greater than the increase in tile discharge. Dissolved reactive P loading was reduced by 41% in the surface runoff and by 35% in tile drainage, and TP load was reduced by 40% in the surface runoff and 15% in tile discharge compared with the control field. If water quality is most negatively affected by DRP loads, the gypsum benefits noted in this study after only two treatments of 2.24 Mg ha$^{-1}$ each are indeed very significant. For example, the USEPA target for reducing soluble reactive P going into Lake Erie via the Maumee River is 40% (USEPA, 2015).

Similar P load reductions have been measured in previous laboratory and field studies (Ekholm et al., 2012; Favaretto et al., 2012; Murphy and Stevens, 2010). For instance, Favaretto et al. (2012) found that surface-applied gypsum (5 Mg ha$^{-1}$) decreased P leaching losses from soil columns with soil test P concentrations of 74 ppm Mehlich-3 by 2.8 times and that incorporation of gypsum to a depth of 2.5 cm decreased P losses by 2.3 times compared with the control.

In the current study, a vertical tillage tool was used after the initial FGD gypsum application (Table 1), which may have reduced the effectiveness of this first gypsum application on P loads. For fields that are continuously managed by no-tillage, the gypsum would certainly be spread and left on the soil surface, and a comparison of gypsum effects on reducing P concentrations and loads for a no-tillage field is needed. This is especially important because of stratification that occurs in no-tillage situations where available P is highly concentrated at the soil surface (Dick et al., 1991).

At the watershed scale, DRP reductions of 33% have been measured after a 4 Mg ha$^{-1}$ gypsum application to approximately one third of the contributing drainage area (Ekholm et al., 2012). Results from the current study together with previous findings indicate that applying FGD gypsum at moderate rates to fields with high soil test P levels can significantly reduce the amount of P loss in surface runoff and tile drainage. However, no single practice or technology currently available can achieve the total percentage and mass reduction targets after only a single year of application. It is thus most appropriate to consider the long-term, cumulative benefits of FGD gypsum application and the need to combine this practice with other upland and edge-of-field management practices such as 4R nutrient stewardship and drainage water management to reduce loadings to acceptable levels in the shortest time possible.

## Conclusions

Applications of FGD gypsum to artificially drained agricultural fields increased tile discharge but also decreased P concentrations and loadings in both surface runoff and tile drainage. Although a single application of FGD gypsum resulted in decreased P concentrations, it was not until after the second application that P loading was statistically significantly decreased. The effects of the first application may not have been optimized because the gypsum was tilled into the soil instead of being left on the surface where it could more readily react with P being solubilized into surface and/or tile water. Results from the current study were consistent with laboratory studies of FGD gypsum because FGD gypsum likely increased aggregate stability and infiltration of precipitation into the soil and increased P retention through the formation of Ca-, Al-, and Fe-phosphates. Transferring the findings from the current study to other fields or soils is likely to depend on both field characteristics (e.g., soil test P level) and the number and rate of FGD gypsum applications. Results suggest that applying FGD gypsum is an effective practice to reduce P losses in tile-drained landscapes but will be most effective if coupled with other upland and edge-of-field practices to meet nutrient reduction goals. Future research is needed to further examine (i) the effect of FGD gypsum rates on P losses as well as productivity and crop P stress from fields with varying soil test P levels, (ii) the persistence of P concentration and loading reductions after a single FGD gypsum application, and (iii) the frequency of repeat applications of gypsum to maintain reduced P concentrations and loadings, at least until soil drawdowns of P have been achieved.

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