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Effectiveness of Nutrient Management for Reducing Phosphorus Losses from Agricultural Areas

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Abstract

Dissolved reactive phosphorus (DRP) export from agricultural areas is a leading cause of nutrient pollution in freshwater systems (e.g., the North American Great Lakes). A potential solution to mitigate the excessive release of DRP is the use of nutrient management. To evaluate the effectiveness of nutrient management for phosphorus (P) in the United States, we conducted a review to synthesize P management and DRP export data from peer-reviewed articles published between 2000 to 2022. We identified 15 publications and extracted 113 and 90 observations from plot- and field-scale studies, respectively. At the plot scale, mean DRP concentrations were approximately 60% lower when P application rates were below the maximum recommended rate. In addition to the lower mean value, more extreme DRP export events occurred when the P fertilization rate was greater than the maximum recommended rate. In terms of application method, subsurface placement reduced mean DRP concentrations during rainfall simulations by 88% relative to surface placement (i.e., broadcasting). For fertilizer sources, mean DRP concentrations were similar between inorganic and organic fertilizers. However, at high application rates, organic fertilizers had a greater potential to produce extreme DRP export events. At the field-scale, organic fertilizers applied at high rates had the potential to produce extreme DRP export events. However, field-scale results for the other nutrient management techniques were generally inconclusive due to a limited number of studies and confounding factors. Overall, these results displayed the potential adverse impacts of overfertilization and the surface application of P fertilizers and highlighted the need for further research into the influence of nutrient management on P losses.

Keywords

4R management; Agricultural runoff; Conservation practice; Phosphorus export

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SUPPLEMENTAL MATERIAL

The supplemental materials mentioned in this article are available for download from the ASABE FigShare repository at: https://doi.org/10.13031/24088365

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This article is part of a collection that provides a systematic review and evaluation of the performance and cost-effectiveness of selected agricultural conservation practices on nutrient and sediment reduction.

Nutrient management (NRCS Code 590) is defined by the USDA Natural Resources Conservation Service (NRCS) as “managing the rate, source, placement, and timing of plant nutrients and soil amendments while reducing environmental impacts” (NRCS, 2019). Here, we focused on the specific use of nutrient management practices to reduce phosphorus (P) losses in agricultural areas of the United States. Applying P to agricultural fields allows for increased crop yields and a subsequent increase in overall agricultural production, which can benefit producers by increasing farm profit. However, applying P fertilizers also creates the potential for excess P to be transported from agricultural lands to receiving water bodies and propel an increase in algal production and a subsequent decline in water quality (Alexander et al., 2008; Conley et al., 2009; Crain, 2006; Kane et al., 2014; Ni et al., 2020; Sharpley, 1995; USEPA, 2016, 2017). In particular, P has been identified as the primary limiting nutrient for algal growth in most freshwater systems and a secondary limiting nutrient, along with nitrogen, in coastal marine systems (Howarth and Paerl, 2008; Smith and Schindler, 2009). Within the United States, excess P has been identified as a main driver in the eutrophication of local streams, rivers, and reservoirs, and at a larger scale, portions of the Great Lakes and the Gulf of Mexico (USEPA, 2017). Specifically, agricultural P losses from the Corn Belt, which includes 13 Midwestern states, have come under increasing scrutiny as a primary source of the excess P (Alexander et al., 2008; Annex 4, 2015; Baker et al., 2014; Dougherty et al., 2020; Duncan et al., 2017; Hanrahan et al., 2019; Jarvie et al., 2017; Kane et al., 2014; Kast et al., 2021; Pease et al., 2018; Scavia et al., 2014; Schilling et al., 2020; Smith et al., 2015; Smith et al., 2017; USEPA, 2017, 2022).

To quantify P export to downstream waterbodies, P can be measured as total P (TP) or it can be broken down into its component dissolved and particulate forms. Notably, the dissolved reactive form of P (DRP), also known as soluble reactive phosphorus or SRP, is often measured because, out of all P forms, it has the greatest potential to cause eutrophication (Baker et al., 2014). In fact, the recent re-eutrophication of the Western Lake Erie Basin has been linked to an increase in DRP loads released from agricultural areas in the basin (Michalak et al., 2013; Scavia et al., 2014). In recognition of this link, the Great Lakes Water Quality Agreement was revised in 2016 to include a target 40% reduction of DRP loads entering Lake Erie by 2025 (USEPA, 2016). Additionally, Baker et al. (2014) stressed that agricultural conservation practice effectiveness should be determined based on their ability to decrease DRP export because this highly bioavailable form is a primary driver of algal production. As a result, this study focused on the effectiveness of nutrient management to reduce DRP export.

Nutrient management plans are typically developed based on guidance from land grant universities to account for crop nutrient requirements and fertilizer costs. Nutrients are managed based on the 4Rs of nutrient stewardship: apply the right nutrient source, with the right rate, at the right time, and in the right place (NRCS, 2019). Nutrient management can be applied in tandem with other agricultural conservation practices, such as residue and tillage management (e.g., no till and reduced till practices), conservation crop rotation, filter strips, cover crops, contour farming, and contour buffer strips, to create a comprehensive conservation plan.

Previous reviews have attempted to define and understand the management of agricultural P to mitigate nutrient pollution in the United States (Haque, 2021; Kleinman et al., 2011). Kleinman et al. (2011) notes that a comprehensive nutrient management plan must address both acute and chronic sources of P. Acute P sources are those that are applied and at immediate risk of being transported to downstream waterbodies via precipitation events. Acute P losses can be applied and are lost in the span of days and weeks. Alternatively, chronic P sources include the dissolution and desorption of both legacy and recently applied P from the soil profile, which can persist over weeks, months, and years.

Other reviews have aimed to synthesize the effectiveness of specific nutrient management techniques to reduce P losses in North America (Christianson et al., 2016; King et al., 2018). Christianson et al. (2016) synthesized annual drainage TP and DRP data from sites in North America over a 50-year period and found that conclusions around the influence of the 4Rs (i.e., right rate, right source, right place, and right time) on P losses could not be verified due to a scarcity of field-scale studies quantifying P loss, nutrient application, and cropping management. Meanwhile, King et al. (2018) summarized annual edge-of-field network monitoring data from 38 agricultural fields ranging from 1 to 20 ha in Ohio. King et al. (2018) concluded that several portions of the 4R nutrient management framework can reduce P losses, including (1) the use of organic fertilizers applied at recommended P-based application rates, (2) frequent soil testing to ensure fertilization rates can follow the soil P based recommendations, (3) avoiding fertilizer application when the soil is or may quickly become saturated (e.g., during winter and early spring or prior precipitation events), and (4) placing fertilizer below the surface. However, this study was limited in spatial scope to tile drained fields in northwestern Ohio. Thus, there is a need to expand and improve upon these previous reviews using an analysis of current studies that span different spatial and temporal scales to develop a comprehensive and quantifiable understanding of the effectiveness of nutrient management to reduce P losses from agricultural areas.

The study objective was to conduct a comprehensive review to quantify the effectiveness of P nutrient management to influence P export. To meet our objective, we conducted a systematic review and analysis using data from plot-scale and field-scale studies to determine the performance effectiveness of 4R management on both acute and chronic DRP export, along with a cost-benefit analysis to determine the economic effectiveness of nutrient management.

Performance Effectiveness

Literature Search and Screening

The literature search aimed to collect peer reviewed research articles with quantitative scientific evidence. Article titles and abstracts were screened based on the following inclusion criteria: (1) the article title or abstract mentioned phosphorus; (2) the article focused on research conducted on P fertilizer application for row crop (e.g., cotton, corn, or soybean) agriculture in the USA; (3) the article focused or contained water quality effects of fertilizer management; (4) article focused on data obtained in the field (i.e., titles with reference to modeling or laboratory-scale with soil columns were removed). Once the initial screening was complete, the literature pool had been trimmed to 92 peer-reviewed publications. The 92 articles were obtained, and full papers were screened to ensure they contained extractable quantitative data on fertilizer management and DRP losses. Of the 92 potential articles, 24 articles contained extractable data. These articles were then further analyzed to ensure all the necessary data was available. The final collection consisted of 15 peer-reviewed articles, with 12 articles focused on plot-scale studies and 3 articles focused on field-scale studies.

The 12 plot-scale studies were conducted using runoff boxes or within field plots with a drainage area generally less than 0.05 ha and used rainfall simulators to artificially generate runoff. In these studies, precipitation was typically initiated soon after fertilizer placement, often less than 72 hours after application, and water quality samples were collected directly from the surface runoff for each simulated precipitation event. Thus, the plot-scale studies measured acute DRP export and represented worst-case scenarios where precipitation events occur shortly after fertilizer application. For these studies, DRP export was reported as an event concentration or load. Alternatively, the three field-scale studies were conducted in fields with drainage areas ranging from 0.05 to 20 ha. Field-scale studies collected water quality samples from naturally occurring precipitation events as part of monitoring projects. Thus, the field-scale studies measured annual mean flow-weighted DRP concentrations, or annual DRP loads, and represented a combination of acute and chronic DRP export. Because of these differences, the analysis was split into two categories: (1) plot-scale data that represented acute DRP losses from precipitation events and (2) field-scale data that represented both acute and chronic DRP losses from actual agricultural fields. To further emphasize this difference, plot-scale data were described as observations, and field-scale data were described as site-years. Additional details describing the methods used to conduct the literature review and data extraction were included in Supplemental Materials, along with summaries of the studies in the final collection.

DRP as Response Variables

We simplified the data analysis by categorizing all dissolved P species as DRP, because a majority of the studies reported DRP and dissolved P has been observed to be dominated by DRP in highly agricultural systems (Baker et al., 2014). DRP concentrations in the database included dissolved P species reported as dissolved reactive phosphorus (DRP) obtained via the molybdate method or reported as soluble phosphorus (WSP/SP) obtained via both ascorbic acid and colorimetric methods.

Ideally, the mass release of a pollutant is measured using the mass load. However, water quality samples are analyzed for pollutant concentration, and often only concentration is reported. Where DRP concentration or loads were not available, efforts were made to estimate missing DRP concentrations and loads as follows:

$$C_{weighted} = \frac{Load_i}{Discharge_i} \text{ or } Load_i = C_{weighted} * Discharge_i$$

where $C_{weighted}$ = flow-weighted concentration for the period of study (g m^{-3})

Discharge = flow over the period of study (m^3 d^{-1})

Load = pollutant load for the period of study (g d^{-1}).

After these efforts were made, DRP loads were still not available for all plot-scale studies in the collection. Due to the limited DRP load data, only DRP concentrations were used in the data analysis.

Categorization of 4R Nutrient Management

To conduct statistical analyses, publications were assigned a class for each nutrient management category that was considered: application rate, fertilizer source, and application method (table 1). Application rates were grouped into four classes based on the data distribution: Unfertilized, Low, Moderate, and High (table 1). These classes roughly followed the range of P application rates recommended for a corn crop at an expected yield of 200 bushels per acre in the midwestern USA (table S2). Along with expected yield, appropriate P application rates are determined by the soil test P. The Low and Moderate groups approximately matched the P fertilizer rates recommended when a field has high or low soil P, respectively. Meanwhile, the High group corresponded to P fertilizer rates greater than the maximum recommended rates (i.e., overfertilization). As an additional step in determining the influence of fertilizer rate, we attempted to gather soil P data. However, these data were limited and often only reported as a single average value for a site or set of plots.

Fertilizer sources were grouped into two classes: inorganic and organic. Application methods were grouped into surface and subsurface placements. The subsurface class included incorporated, injected, and banded fertilizer (Christianson and Harmel, 2015). The injected category included both knife injected and low disturbance injection (Jahanzad et al., 2019). Timings were not directly investigated due to the limited number of field-scale studies and the broad differences in application timings in plot-scale studies. Instead, timing was controlled in the plot-scale analysis by focusing on acute DRP losses. To maintain the focus on acute DRP losses, we only used observations from the first rainfall simulation on a plot after fertilizer application, and this simulation had to occur within 1 month (i.e., 30 days) of P application.

Data Analysis

The mean flow-weighted DRP concentration was used as the main response variable. Due to the substantial differences in monitoring periods between the two spatial scales, the statistical analyses were split into two parts, one for the plot-scale data and another for the field-scale data. The plot-scale analysis focused on the influence of nutrient management on acute DRP export in surface runoff. The field-scale analysis was then conducted on annual DRP export to investigate if the trends in the influence of nutrient management on DRP export observed at the plot-scale were matched in real-world scenarios.

At the plot scale, the data were first tested for normality (the Shapiro-Wilk test) and equality of variances (Levene's test). The results indicated that the data were non-normal, and variances were heterogeneous. Therefore, individual Kruskal-Wallis tests (Kruskal and Wallis, 1952) rather than ANOVAs were used to compare the DRP export for application rates, application methods, and application sources. If the null hypothesis of the Kruskal-Wallis test was rejected, then a Dunn's test (Dunn, 1964) was conducted to identify statistically significant differences in group medians. Detailed results for the Kruskal-Wallis and Dunn's tests were included in Supplemental Materials. In addition to median values, the geometric means were also reported for each category (hereafter, mean represents the geometric mean). Due to limited data, simple summary statistics were used to determine the combined influence of rate group, application method, and fertilizer source on DRP export.

Unlike the plot-scale studies, which only included surface runoff, field-scale studies included DRP export from both surface runoff and subsurface tile drainage. Therefore, site years were split into surface runoff and subsurface tile drainage under each 4R nutrient management category. Kruskal-Wallis tests and further statistical analyses were not conducted for field-scale studies due to limited data for select application methods and fertilizer sources. Instead, only medians and means were compared between nutrient management categories. Additionally, data ranges were visualized using boxplots. Data analyses were completed in R (R Core Team, 2022) using third-party packages *dplyr* (Wickham et al., 2022) and *ggplot2* (Wickham, 2016).

Performance Effectiveness

Within each aspect of nutrient management, performance effectiveness was evaluated using percent reductions in mean DRP concentrations. To calculate the percent reduction, the technique with the greatest mean DRP concentration was used as the baseline. To evaluate the performance effectiveness of nutrient management combinations on DRP losses, the high application rate (greater than 160 kg-P2O5 ha^{-1} or greater than 70 kg-P ha^{-1}) with surface application of fertilizer was used as the baseline. Data from plot-scale studies were used for performance effectiveness analysis because plot-scale studies provided a larger dataset and controlled precipitation events, which minimized the potential for site specific biases.

Cost-Benefit Analysis

The cost-benefit analysis was adapted from Koropeckyj-Cox et al. (2021) and Liu et al. (2021) and based on calculations of net revenue (i.e., subtracting the total costs of production from the gross revenues from crop sales for each management scenario). Details on the assumptions of the cost-benefit analysis were included in Supplemental Materials. Briefly, statistics on crop prices, yields, and production costs were gathered primarily from the USDA National Agricultural Statistics Service (NASS), the Iowa State University Cooperative Extension Service. Fertilizer costs were obtained from Bi-weekly Illinois Production Cost Reports provided by the USDA from January 2020 through February 2023 (fig. S1). In these reports, MAP was assumed to contain 46% P by mass, and DAP was assumed to have 52% P by mass. Both MAP and DAP had similar costs during this period, and both costs have increased rapidly in recent years. The recent volatility in fertilizer costs made it unclear if prices will be maintained at the current rate. Here, we used a moderate cost estimate ($700 per ton) to conduct our analysis. All costs were converted to $ per kg P using the assumed % P by mass for both MAP and DAP. Cost estimates were obtained for years ranging from 2016 to 2023, but the cost analysis was not normalized to a specific year. Annual revenues were then estimated for both continuous corn (CC) and corn-soybean (CS) rotations across all fertilizer rates.

Results & Discussion

Influence of Nutrient Management on P Loss in Plot-Scale Studies

Statistical Summary—In plot-scale studies, 113 observations were compiled. Across fertilizer rates, observations in the High group were nearly double those in either the Moderate or Low groups (table 2). For fertilizer sources, organic fertilizers were the dominant source. For fertilizer methods, surface broadcasting (i.e., Surface) had approximately two times more observations than subsurface placement (i.e., Subsurface).

DRP concentration data exhibited right or positive-skewed data with non-normal distributions (fig. 1). Environmental data are often right skewed due to a small number of extreme events. DRP concentrations ranged from 0.03 to 32.5 mg L^{-1} with a mean of 1.59 mg L^{-1}, and a median of 1.50 mg L^{-1}. These DRP losses were greater than the expected range for long-term edge-of-field losses but within the same order of magnitude. For example, in Pease et al. (2018), agricultural fields in the eastern corn belt with drainage areas from 1 to 20 ha had annual flow-weighted mean DRP concentrations of 0.46 ± 0.5 mg L^{-1} in surface runoff.

Influence of Fertilizer Rate—DRP losses generally increased as the application rate increased (table 3 & fig. 2). The mean DRP concentrations were nearly two times greater in the High group (3.47 mg L^{-1}) than in either the Low or Moderate group (1.25 and 1.54 mg L^{-1}, respectively) (table 3). The mean DRP concentration in the Unfertilized plots was 0.19 mg L^{-1}. The percent reductions in mean DRP concentrations from the High to Moderate and High to Low rates were 57 and 64%, respectively.

Differences in DRP concentrations were statistically significant between at least two rate groups (χ^2 = 38.8, df = 3, p < 0.001). Post-hoc Dunn's test found significant differences in median DRP concentrations between each fertilized group (i.e., Low, Moderate, and High groups) and the Unfertilized group (fig. S2), with the median DRP concentrations being significantly greater in each of the fertilized groups relative to the Unfertilized group. For pairwise comparisons between the fertilized groups, median DRP concentrations were not significantly different, even though the median DRP concentrations were substantially greater in the High group.

Overall, our analysis indicated that increases in application rate had a noticeable, though not statistically significant, increase in acute DRP export, especially if the application rate exceeded the maximum application rate recommended by state and regional guidelines (i.e., the High group). However, even if fertilizer is placed at an application rate consistent with fertilizer recommendations (i.e., the Low or Moderate group), there was still greater DRP export from fertilized plots than there would be if no fertilizer was used (fig. 2). Along with the statistical tests, we also observed that the greatest 10% of DRP concentrations (top 12 observations) occurred when fertilizer rates were applied above the maximum levels prescribed in state and regional application recommendations (i.e., the High group) (fig. 2). These results suggested that the negative consequences of the P application rate on downstream water quality may become much greater as the rate increases and that overapplication of fertilizer creates a greater potential for extreme DRP export events.

Influence of Application Method—Implementing subsurface placement of fertilizers resulted in substantially lower DRP concentrations in the surface runoff relative to surface broadcasting (fig. 3). The median DRP concentration for subsurface placement was 0.52 mg L^{-1}, while surface broadcasting produced a median DRP concentration of 4.75 mg L^{-1}. The mean DRP concentration for subsurface placement was 0.52 mg L^{-1}, while surface broadcasting produced a mean DRP concentration of 4.30 mg L^{-1}. The percent reduction in mean DRP concentrations from surface broadcasting to subsurface application was 88%. The mean P application rate for subsurface placement was slightly greater than the rate for surface broadcasting (141 to 123 kg-P2O5 ha^{-1}). Differences in DRP concentrations were statistically significant between at least two application methods ($\chi^2 = 70.8$, $df = 2$, $p < 0.001$). The subsequent Dunn's test found significant differences for the surface vs. subsurface ($p < 0.001$) and surface vs. unfertilized ($p < 0.001$) comparisons. Interestingly, there was not a significant difference in DRP concentration from subsurface application and unfertilized plots ($p = 0.18$).

A highlight of these results was the fact that there was no statistically significant difference in DRP export between subsurface placement and unfertilized plots. This striking result means that subsurface placement could provide an effective method to reduce the influence of fertilization on acute DRP export to downstream waterbodies. As for the mechanisms that drive these differences, Williams et al. (2018) hypothesized that the banding, incorporation, or injection of fertilizer can reduce dissolved P losses from agricultural fields because these methods (1) increase soil-fertilizer contact and (2) decrease contact between ponded water and soluble P. However, it should also be noted that these results were focused on surface runoff, not subsurface drainage, and subsurface placement may have a different effect on P export from subsurface drainage.

Influence of Fertilizer Source—Median DRP concentrations were 1.52 and 2.10 mg L^{-1} for inorganic and organic fertilizers, respectively (fig. 4). The mean values followed a similar pattern, with values of 1.55 mg L^{-1} and 2.49 mg L^{-1} for inorganic and organic fertilizers, respectively. These values correspond to 38% reduction in mean DRP concentrations when using inorganic fertilizers vs. organic fertilizers. Both groups had a mean DRP concentration substantially greater than the unfertilized plots (0.19 mg L^{-1}). Statistical analysis showed differences in DRP concentrations were statistically significant between at least two source groups ($\chi^2 = 32.2$, $df = 2$, $p < 0.001$). Dunn's test found that both the inorganic and organic groups were significantly different than the unfertilized plots ($p < 0.001$ for each comparison). Despite the 38% reduction in mean DRP concentration, there was no significant difference in DRP concentrations between inorganic and organic fertilizers ($p = 0.61$). However, organic fertilizers did increase the potential for extreme DRP export events.

One potential explanation for the slightly greater DRP concentrations from organic fertilizers was that organic fertilizers were often applied at greater rates. When organic fertilizers were used, the mean P application rate was 147 kg-P2O5 ha^{-1}; meanwhile, the mean P application rate of inorganic fertilizers was 88 kg-P2O5 ha^{-1}. The greater application rate for organic fertilizers was likely caused by the application of organic fertilizers at the recommended nitrogen rate, which results in overfertilization with respect to the recommended P rate (King et al., 2018). However, organic fertilizers were typically applied as liquids (e.g., manure slurry), while most inorganic fertilizers were applied as solids. Liquid P fertilizers have a greater opportunity to infiltrate the soil profile and bind to soil particles, thereby immobilizing the applied P and reducing the potential for acute P loss (Smith et al., 2016). Taken together, the fact that organic fertilizers were overapplied may explain why there were more extreme DRP export events for organic fertilizers, and the fact that organic fertilizers were often liquid may explain why there wasn’t a significant difference between the medians of the two groups even though organic fertilizers were applied at greater rates.

Combined Influences of Fertilizer Rate, Application Method, and Source— There were clear combinations of rate, method, and source that resulted in greater DRP export (table 4). The most notable of these combinations was the surface application of organic fertilizers at high rates. This combination of nutrient management factors produced a mean DRP concentration of 8.54 mg L^{-1}, which was higher than any other combination and nearly double the combination with the second median DRP concentration (table 4). The combination of surface application with inorganic fertilizers at high rates produced the second highest mean DRP concentration (4.77 mg L^{-1}). These results highlight the potential reduction of DRP export when using subsurface fertilizer placement. In all source and rate combinations, median DRP concentrations were lower when the fertilizer was applied to the subsurface instead of the surface (table 4).

To evaluate the performance effectiveness of nutrient management on DRP losses, the high application rate (> 160 kg-P2O5 ha^{-1}) with surface application of fertilizer was used as the baseline within each fertilizer source. The change from surface to subsurface application reduced mean DRP concentrations between 48 and 94% for inorganic fertilizers and 66 to 95% for organic fertilizers across all fertilizer rates (table 4). Overall, these results do not guide us to the exact right combination of rate, method, and source for reduce DRP export, but they do make it clear which combinations should be avoided if we want to reduce DRP export. Namely, broadcasting fertilizer on the soil surface at a rate greater than the recommended rate has the potential to result in substantial acute DRP export. If the application rate must be high, then fertilizer should at least be applied to the subsurface to reduce DRP losses.

Influence of Nutrient Management on P Loss at the Field Scale

Statistical Summary—Of the five field-scale studies, a total of 90 site years were compiled (table 5). There was nearly the same amount of surface runoff site-years (n = 51) as tile drainage site-years (n = 39). Site-years were recorded in studies from three states: Wisconsin, Illinois, and Kansas. When spilt by drainage location, there was a low number of site years within each fertilizer rate (table 5).

Fertilizer rates in the field studies ranged from 0 to 515 kg-P2O5 ha^{-1}, with mean values of 92 kg-P2O5 ha^{-1} and 104 kg-P2O5 ha^{-1} for surface runoff and tile drainage, respectively. Surface runoff typically carried slightly greater DRP concentrations than tile drainage (table 6). Overall, field-scale studies had similar mean DRP concentrations to the plot-scale studies. However, plot-scale studies had greater maximum DRP concentrations, which can likely be attributed to plot-scale studies measuring acute DRP export versus field-scale studies measuring more of the chronic annual DRP export.

Influence of Fertilizer Rate—The mean DRP concentrations for surface runoff were 0.53, 0.44, and 0.54 mg L^{-1} for the Low, Moderate, and High groups, respectively. For tile drainage, mean DRP concentrations were 0.21, 0.11, and 0.07 mg L^{-1} for the Low, Moderate, and High groups, respectively. Unlike the plot-scale results, there were no distinct differences in median DRP concentrations between rate groups in surface runoff, while median DRP concentrations tended to decrease in subsurface tile drainage as average applied P increased (fig. 5). This may have been the result of the small dataset, or it may signal that fertilizer rate doesn't directly influence chronic DRP export. Several factors may explain these results, including the initial soil test P, the amount of available data, or the other 4R management techniques. For soil test P, field scale studies often monitor fields under typical fertilization patterns; therefore, soils with high initial soil P would be expected to have low P applications (Culman et al., 2020). But high soil P has been linked to high P losses, especially in subsurface tile drainage (Duncan et al., 2017). Taken together, these factors would lead to greater DRP losses at low application rates. Next, the low number of site years within each fertilization rate group suggested that the results may not be very representative of real-world conditions and highlighted the need for more research into the influence of fertilizer rate at the field scale and the potential for additional factors like soil P to influence loss. Finally, the influence of other nutrient management categories will be discussed in the next sections.

Influence of Application Method—In surface runoff, mean DRP concentrations were similar across both application methods (table 7). The similarity in mean DRP concentrations for field-scale surface runoff indicated that the substantial reduction in DRP export due to subsurface placement observed in the plot-scale studies may be limited to acute DRP export (fig. 3 and table 4). However, surface application did produce a greater potential for extreme DRP export - like the plot-scale observations (fig. 6). This highlights the influence of acute DRP losses on long-term DRP export. Next, mean DRP concentrations in tile drainage were greater for subsurface placement of fertilizer than surface broadcasting (table 7). This matches results from Feyereisen et al. (2010), who observed that subsurface placement of P fertilizer may create a greater potential for chronic

P leaching to subsurface drainage because more of the initial application is held within the soil profile. While intriguing, this result may also simply be the product of very site-specific conditions in a limited dataset, as King et al. (2018) observed a different result with subsurface fertilizer placement corresponding to slightly lower subsurface P losses across 20 field-scale sites in Ohio. Overall, our plot-scale results showed that subsurface application can reduce acute DRP losses in surface runoff, while our field-scale results indicated this application method had limited influence on chronic DRP export in surface runoff and the potential to increase chronic DRP export in tile drainage. However, the small dataset used here, paired with conflicting results from other studies, highlights the need for further research before a general conclusion can be made.

Influence of Fertilizer Source—Median DRP concentrations were greater in both surface runoff and subsurface tile drainage when organic fertilizer was used (table 8 and fig. 7). Organic fertilizers also resulted in much greater DRP export when applied at a high rate (table 8). These results match those from King et al. (2018), which also found that sites using organic fertilizers had greater DRP export, but not significant differences. In their study, King et al. (2018) noted that the increase in P export when using organic fertilizer was likely caused by manure ative to inorganic fertilizers, but again, these organic fertilizers were often overapplied. In this review, the plot-scale studies had very high DRP concentrations when organic fertilizers were applied at high rates (i.e., overapplied relative to recommended rates). The field-scale results for surface runoff matched the plot-scale results, which suggests that the overapplication of organic fertilizer may be a major pathway for excessive DRP export in surface runoff.

The combination of organic fertilizers used at a low rate also produced the highest median DRP concentration in tile drainage. When combined with the surface runoff results, the higher DRP export in tile drainage at low rates suggests that there may be an inherent increased risk of DRP export when organic fertilizers are used. Again, this result was produced by a relatively low amount of data, and further research is needed to draw general conclusions about the influence of fertilizer source on field-scale DRP export.

Cost-Benefit Analysis

The net annual revenue for both MAP and DAP was similar within each system; therefore, MAP and DAP were averaged to obtain one cost estimate for each rate and system combination (fig. S2). In continuous corn systems, net revenues were estimated at 205, 162, and 126 \$ ha^{-1} yr^{-1} for Low, Moderate, and High fertilizer rates, respectively. In corn-soybean systems, net revenues were estimated at 164, 143, and 125 \$ ha^{-1} yr^{-1} for Low, Moderate, and High fertilizer rates, respectively. Across both systems, fertilizer rate reductions would produce estimated revenue increases ranging from 18 to 80 \$ ha^{-1} yr^{-1}. Additionally, if the cost of inorganic fertilizer remains high or even increases, reducing the application rate of P fertilizers will be even more economical. Furthermore, reducing the application rate of fertilizers was shown to decrease DRP export (table 3); thus, decreasing application rates has the potential to not only increase the revenue generated but also improve water quality.

Recommendations and Research Needs

4R nutrient management for P has the potential to reduce DRP export from agricultural fields. The analysis for plot-scale studies provided us with insights into DRP export during rainfall events and highlighted four key components of an effective P management strategy. First, fertilization rate must be managed to avoid overfertilization of P. No matter the application method or source, if the application rate is greater than the maximum recommended rate, DRP export from the field has the potential to be high. Second, subsurface placement of fertilizer, either by incorporation, injection, or banding, has the potential to reduce acute DRP export. Third, when using organic fertilizers, steps should be taken to limit the rate of P applied, as both the plot-scale and field-scale studies indicated that organic fertilizers applied at high rates had the potential for very high DRP losses (tables 4 and 8). While some insights can be drawn from this review, the limited number of studies made it difficult to develop a comprehensive and solid strategy of 4R nutrient management to reduce DRP losses.

There are several areas of research that should be pursued. First, further research is needed to create a more conservative approach to fertilization rate recommendations. Currently, in the Midwestern USA, the recommended fertilization rate is determined using decision matrices guided by soil test P and projected crop yields (Culman et al., 2020). This current system has the potential to lead to overfertilization if crop yields are overestimated or soil testing is limited in scope. Notably, King et al. (2018) found that 82% of the organically fertilized and 24% of the inorganically fertilized sites received an overapplication of fertilizer. To curb overapplication of fertilizer, a new fertilizer rate recommendation system should be developed. Second, there is a lack of knowledge regarding the impact of 4R nutrient management on chronic P export. For example, most plot-scale studies indicated that subsurface placement creates the lowest amount of DRP in surface runoff; however, subsurface placement may lead to a P buildup within the soil profile and a greater potential for chronic P losses. The third area of necessary research is application timing. Though not directly reviewed here, nutrient management focused on application timing may be very influential in controlling P losses (Christianson et al., 2016; Marie et al., 2016). Notably, application timing has already been addressed in some regional P fertilizer application regulations. For example, the state of Ohio recently created fertilizer application timing regulations for the Western Lake Erie Basin. A previous study in the region indicated that similar regulations reduced P losses in a 4,000 ha watershed (Jacquemin et al., 2018), but future research is needed to show whether these rules can be effective in reducing P loss at a broader scale. Finally, we need to better understand the economic influence of 4R nutrient management using farm scale research focused on the influence of nutrient management on crop yields and ultimately farm profit. For example, this research effort found limited data on the influence of P fertilization rates on crop yields.

Conclusion

The results from plot-scale studies made it clear that 4R nutrient management can have a substantial effect on P export. For acute DRP export, application method and fertilizer rate appeared to be the most influential factors. Notably, plot-scale results strongly indicated that subsurface application, instead of surface broadcasting, could provide a highly effective way to reduce acute DRP export. Furthermore, the combined plot-scale and field-scale results made it clear that overapplying fertilizers (e.g., applying at greater than the maximum recommended rate), especially organic fertilizers, will increase the risk of DRP losses to downstream waterbodies. Additionally, the reduction of fertilizer rate has the potential to increase farm revenue, assuming crop yield is not substantially influenced by fertilizer rate. Overall, we found that applying fertilizers at rates below 160 kg-P2O5 ha^{-1}, especially when using organic fertilizers, and placing fertilizer below the surface are likely to decrease P export. While limited by the number of publications focusing on P nutrient management to reduce DRP export to downstream waterbodies, our results still provide insights into the categories of nutrient management that have the potential to effectively reduce P losses at broader scales and direct the focus of future studies and innovations. This study also exposed the limited literature on field-scale studies focused on P-based nutrient management and highlighted the need for more field-scale research to be conducted before we can provide thorough guidelines for effective 4R P management.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

Adeli A, Tewolde H, Shankle MW, Way TR, Brooks JP, & McLaughlin MR (2013). Runoff quality from no-till cotton fertilized with broiler litter in subsurface bands. J. Environ. Qual, 42(1), 284–91. 10.2134/jeq2012.0358 [PubMed: 23673763]

Alexander RB, Smith RA, Schwarz GE, Boyer EW, Nolan JV, & Brakebill JW (2008). Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River Basin. Environ. Sci. Technol, 42(3), 822–30. 10.1021/es0716103 [PubMed: 18323108]

Algoazany AS, Kalita PK, Czapar GF, & Mitchell JK (2007). Phosphorus transport through subsurface drainage and surface runoff from a flat watershed in east central Illinois, USA. J. Environ. Qual, 36(3), 681–93. 10.2134/jeq2006.0161 [PubMed: 17412904]

Annex 4. (2015). Recommended phosphorus loading targets for Lake Erie. Annex 4 objectives and targets task team final report to the nutrients annex subcommittee.

Baker DB, Confesor R, Ewing DE, Johnson LT, Kramer JW, & Merryfield BJ (2014). Phosphorus loading to Lake Erie from the Maumee, Sandusky and Cuyahoga rivers: The importance of bioavailability. J. Great Lakes Res, 40(3), 502–517. 10.1016/j.jglr.2014.05.001

Carver RE, Nelson NO, Roozeboom KL, Kluitenberg GJ, Tomlinson PJ, Kang Q, & Abel DS (2022). Cover crop and phosphorus fertilizer management impacts on surface water quality from a no-till corn-soybean rotation. J. Environ. Manag, 301, 113818. 10.1016/j.jenvman.2021.113818

Christianson LE, & Harmel RD (2015). The MANAGE Drain Load database: Review and compilation of more than fifty years of North American drainage nutrient studies. Agric. Water Manag, 159, 277–289. 10.1016/j.agwat.2015.06.021

Christianson LE, Harmel RD, Smith D, Williams MR, & King K (2016). Assessment and synthesis of 50 years of published drainage phosphorus losses. J. Environ. Qual, 45(5), 1467–1477. 10.2134/jeq2015.12.0593 [PubMed: 27695749]

Conley DJ, Paerl HW, Howarth RW, Boesch DF, Seitzinger SP, Havens KE,... Likens GE. (2009). Controlling eutrophication: Nitrogen and phosphorus. Science, 323(5917), 1014–1015. 10.1126/science.1167755 [PubMed: 19229022]

Crain AS (2006). Concentrations, and estimated loads and yields of nutrients and suspended sediment in the Little River basin, Kentucky, 2003–04. Scientific Investigations Report 2006–5204. 31. 10.3133/sir20065204

Culman SW, Fulford AM, Camberato J, & Steinke K (2020). Tri-state fertilizer recommendations. Columbus, OH: The Ohio State University, College of Food, Agricultural, and Environmental Sciences.

Daverede IC, Kravchenko AN, Hoeft RG, Nafziger ED, Bullock DG, Warren JJ, & Gonzini LC (2004). Phosphorus runoff from incorporated and surface-applied liquid swine manure and phosphorus fertilizer. J. Environ. Qual, 33(4), 1535–1544. 10.2134/jeq2004.1535 [PubMed: 15254136]

Dodd JR, & Mallarino AP (2005). Soil-test phosphorus and crop grain yield responses to long-term phosphorus fertilization for corn-soybean rotations. Soil Sci. Soc. Am. J, 69(4), 1118–1128. 10.2136/sssaj2004.0279

Dougherty BW, Pederson CH, Mallarino AP, Andersen DS, Soupir ML, Kanwar RS, & Helmers MJ (2020). Midwestern cropping system effects on drainage water quality and crop yields. J. Environ. Qual, 49(1), 38–49. 10.1002/jeq2.20007 [PubMed: 33016359]

Duncan EW, King KW, Williams MR, LaBarge G, Pease LA, Smith DR, & Fausey NR (2017). Linking soil phosphorus to dissolved phosphorus losses in the midwest. Agric. Environ. Lett, 2(1). 10.2134/ael2017.02.0004

Dunn OJ (1964). Multiple comparisons using rank sums. Technometrics, 6(3), 241–252. 10.1080/00401706.1964.10490181

Feyereisen GW, Kleinman PJ, Folmar GJ, Saporito LS, Way TR, Church CD, & Allen AL (2010). Effect of direct incorporation of poultry litter on phosphorus leaching from coastal plain soils. J. Soil Water Conserv, 65(4), 243–251. 10.2489/jswc.65.4.243

Fulford AM, & Culman SW (2018). Over-fertilization does not build soil test phosphorus and potassium in Ohio. Agron. J, 110(1), 56–65. 10.2134/agronj2016.12.0701

Gildow M, Aloysius N, Gebremariam S, & Martin J (2016). Fertilizer placement and application timing as strategies to reduce phosphorus loading to Lake Erie. J. Great Lakes Res, 1281–1288. 10.1016/j.jglr.2016.07.002

Gilley JE, Eghball B, & Marx DB (2007). Nutrient concentrations of runoff during the year following manure application. Trans. ASABE, 50(6), 1987–1999. 10.13031/2013.24102

Grande JD, Karthikeyan KG, Miller PS, & Powell JM (2005). Corn residue level and manure application timing effects on phosphorus losses in runoff. J. Environ. Qual, 34(5), 1620–1631. 10.2134/jeq2004.0462 [PubMed: 16091615]

Hanrahan BR, King KW, Williams MR, Duncan EW, Pease LA, & LaBarge GA (2019). Nutrient balances influence hydrologic losses of nitrogen and phosphorus across agricultural fields in northwestern Ohio. Nutr. Cycling Agroecosyst, 113(3), 231–245. 10.1007/s10705-019-09981-4

Haque SE (2021). How effective are existing phosphorus management strategies in mitigating surface water quality problems in the U.S.? Sustainability, 13(12), 6565. 10.3390/su13126565

Howarth R, & Paerl HW (2008). Coastal marine eutrophication: Control of both nitrogen and phosphorus is necessary. Proc. Natl. Acad. Sci, 105(49). 10.1073/pnas.0807266106

Jacquemin SJ, Johnson LT, Dirksen TA, & McGlinch G (2018). Changes in water quality of Grand Lake St. Marys watershed following implementation of a distressed watershed rules package. J. Environ. Qual, 47(1), 113–120. 10.2134/jeq2017.08.0338 [PubMed: 29415096]

Jahanzad E, Saporito LS, Karsten HD, & Kleinman PJ (2019). Varying influence of dairy manure injection on phosphorus loss in runoff over four years. J. Environ. Qual, 48(2), 450–458. 10.2134/jeq2018.05.0206 [PubMed: 30951117]

Jarvie HP, Johnson LT, Sharpley AN, Smith DR, Baker DB, Bruulsema TW, & Confesor R (2017). Increased soluble phosphorus loads to Lake Erie: Unintended consequences of conservation practices? J. Environ. Qual, 46(1), 123–132. 10.2134/jeq2016.07.0248 [PubMed: 28177409]

Johnson KN, Kleinman PJ, Beegle DB, Elliott HA, & Saporito LS (2011). Effect of dairy manure slurry application in a no-till system on phosphorus runoff. 201–212. 10.1007/s10705-011-9422-8

Kane DD, Conroy JD, Richards PR, Baker DB, & Culver DA (2014). Re-eutrophication of Lake Erie: Correlations between tributary nutrient loads and phytoplankton biomass. J. Great Lakes Res, 40(3), 496–501. 10.1016/j.jglr.2014.04.004

Kast JB, Apostel AM, Kalcic MM, Muenich RL, Dagnew A, Long CM,... Martin JF. (2021). Source contribution to phosphorus loads from the Maumee River watershed to Lake Erie. J. Environ. Manage, 279, 111803. 10.1016/j.jenvman.2020.111803 [PubMed: 33341725]

King KW, Williams MR, LaBarge GA, Smith DR, Reutter JM, Duncan EW, & Pease LA (2018). Addressing agricultural phosphorus loss in artificially drained landscapes with 4R nutrient management practices. J. Soil Water Conserv, 73(1), 35–47. 10.2489/jswc.73.1.35

Kleinman PJ, & Sharpley AN (2003). Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events. J. Environ. Qual, 32(3), 1072–81. 10.2134/jeq2003.1072 [PubMed: 12809308]

Kleinman PJ, Sharpley AN, McDowell RW, Flaten DN, Buda AR, Tao L,... Zhu Q. (2011). Managing agricultural phosphorus for water quality protection: Principles for progress. Plant Soil, 349(1), 169–182. 10.1007/s11104-011-0832-9

Kleinman PJ, Sharpley AN, Moyer BG, & Elwinger GF (2002). Effect of mineral and manure phosphorus sources on runoff phosphorus. J. Environ. Qual, 31(6), 2026–33. 10.2134/jeq2002.2026 [PubMed: 12469853]

Koropeckyj-Cox L, Christianson RD, & Yuan Y (2021). Effectiveness of conservation crop rotation for water pollutant reduction from agricultural areas. Trans. ASABE, 64(2), 691–704. 10.13031/trans.14017 [PubMed: 35950102]

Kovar JL, Moorman TB, Singer JW, Cambardella CA, & Tomer MD (2011). Swine manure injection with low-disturbance applicator and cover crops reduce phosphorus losses. J. Environ. Qual, 40(2), 329–336. 10.2134/jeq2010.0184 [PubMed: 21520739]

Kruskal WH, & Wallis WA (1952). Use of ranks in one-criterion variance analysis. J. Am. Stat. Assoc, 47(260), 583–621. 10.2307/2280779

Liu W, Yuan Y, & Koropeckyj-Cox L (2021). Effectiveness of nutrient management on water quality improvement: A synthesis on nitrate-nitrogen loss from subsurface drainage. Trans. ASABE, 64(2), 675–689. 10.13031/trans.14078 [PubMed: 34336367]

Madison AM, Ruark MD, Stuntebeck TD, Komiskey MJ, Good LW, Drummy N, & Cooley ET (2014). Characterizing phosphorus dynamics in tile-drained agricultural fields of eastern Wisconsin. J. Hydrol, 519, 892–901. 10.1016/j.jhydrol.2014.08.016

Michalak AM, Anderson EJ, Beletsky D, Boland S, Bosch NS, Bridgeman TB,... Zagorski MA. (2013). Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. Proc. Natl. Acad. Sci, 110(16), 6448–6452. 10.1073/pnas.1216006110 [PubMed: 23576718]

Ni XJ, Yuan YP, & Liu WL (2020). Impact factors and mechanisms of dissolved reactive phosphorus (DRP) losses from agricultural fields: A review and synthesis study in the Lake Erie basin. Sci. Total Environ, 714, 13. 10.1016/j.scitotenv.2020.136624

NRCS. (2019). Nutrient management, Code 590. In National handbook of conservation practices. Washington, DC: USDA Natural Resources Conservation Service. Retrieved from https://www.nrcs.usda.gov/sites/default/files/2022-09/Nutrient_Management_590_NHCP_CPS_2017.pdf

Pease LA, King KW, Williams MR, LaBarge GA, Duncan EW, & Fausey NR (2018). Phosphorus export from artificially drained fields across the Eastern Corn Belt. J. Great Lakes Res, 44(1), 43–53. 10.1016/j.jglr.2017.11.009

R Core Team. (2022). R: A Language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from https://www.R-project.org/

Scavia D, Allan JD, Arend KK, Bartell S, Beletsky D, Bosch NS,... Zhou Y. (2014). Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia. J. Great Lakes Res, 40(2), 226–246. 10.1016/j.jglr.2014.02.004

Schilling KE, Streeter MT, Seeman A, Jones CS, & Wolter CF (2020). Total phosphorus export from Iowa agricultural watersheds: Quantifying the scope and scale of a regional condition. J. Hydrol, 581. 10.1016/j.jhydrol.2019.124397

Sharpley A (1995). Identifying sites vulnerable to phosphorus loss in agricultural runoff. J. Environ. Qual, 24(5), 947–951. 10.2134/jeq1995.00472425002400050024x

Smith DR, Francesconi W, Livingston SJ, & Huang CH (2015). Phosphorus losses from monitored fields with conservation practices in the Lake Erie Basin, USA. Ambio, 44(Suppl 2), S319–S331. 10.1007/s13280-014-0624-6 [PubMed: 25681988]

Smith DR, Harmel RD, Williams M, Haney R, & King KW (2016). Managing acute phosphorus loss with fertilizer source and placement: Proof of concept. Agric. Environ. Lett, 1(1), 150015. 10.2134/ael2015.12.0015

Smith DR, Huang C, & Haney RL (2017). Phosphorus fertilization, soil stratification, and potential water quality impacts. J. Soil Water Conserv, 72(5), 417–424. 10.2489/jswc.72.5.417

Smith DR, Owens PR, Leytem AB, & Warnemuende EA (2007). Nutrient losses from manure and fertilizer applications as impacted by time to first runoff event. Environ. Pollut, 147(1), 131–137. 10.1016/j.envpol.2006.08.021 [PubMed: 17029684]

Smith VH, & Schindler DW (2009). Eutrophication science: Where do we go from here? Trends. Ecol. Evol, 24(4), 201–207. 10.1016/j.tree.2008.11.009 [PubMed: 19246117]

Tabbara H (2003). Phosphorus loss to runoff water twenty-four hours after application of liquid swine manure or fertilizer. J. Environ. Qual, 32(3), 1044–1052. 10.2134/jeq2003.1044 [PubMed: 12809305]

USEPA. (2016). Governments of Canada and the United States announce phosphorus reduction targets of 40 percent to improve Lake Erie water quality and reduce public health risk. USEPA. Retrieved from https://19january2017snapshot.epa.gov/newsreleases/governments-canada-and-united-states-announce-phosphorus-reduction-targets-40-percent_.html

USEPA. (2017). National water quality inventory: Report to congress. EPA 841-R-16–011. Washington, DC: USEPA. Retrieved from https://www.epa.gov/sites/default/files/2017-12/documents/305brtc_finalowow_08302017.pdf

USEPA. (2022). Hypoxia task force new goal framework. USEPA. Retrieved from https://www.epa.gov/ms-htf/hypoxia-task-force-new-goal-framework

Wickham H (2016). ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York. Retrieved from https://ggplot2.tidyverse.org

Wickham H, Francois R, Henry L, & Muller K (2022). dplyr: A Grammar of Data Manipulation. Retrieved from https://github.com/tidyverse/dplyr

Williams MR, King KW, Duncan EW, Pease LA, & Penn CJ (2018). Fertilizer placement and tillage effects on phosphorus concentration in leachate from fine-textured soils. Soil Tillage Res, 178, 130–138. 10.1016/j.still.2017.12.010

Yuan M, Fernandez FG, Pittelkow CM, Greer KD, & Schaefer D (2018). Tillage and fertilizer management effects on phosphorus runoff from minimal slope fields. J. Environ. Qual, 47(3), 462–470. 10.2134/jeq2017.07.0271 [PubMed: 29864186]

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HIGHLIGHTS

- Dissolved reactive P concentration increased with an increased fertilization rate.
- Subsurface placement of P fertilizer can reduce acute DRP export regardless of fertilization rates.
- More research connecting P fertilizer use and P export at the field-scale is needed.

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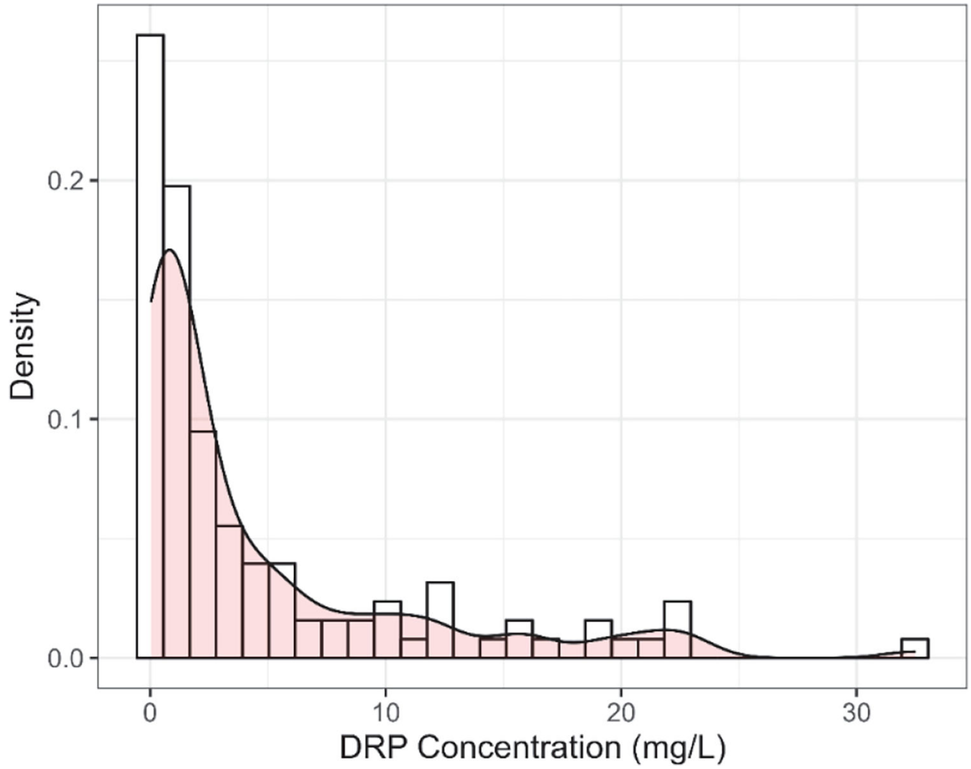

Figure 1.
Distribution of plot-scale DRP concentration observations.

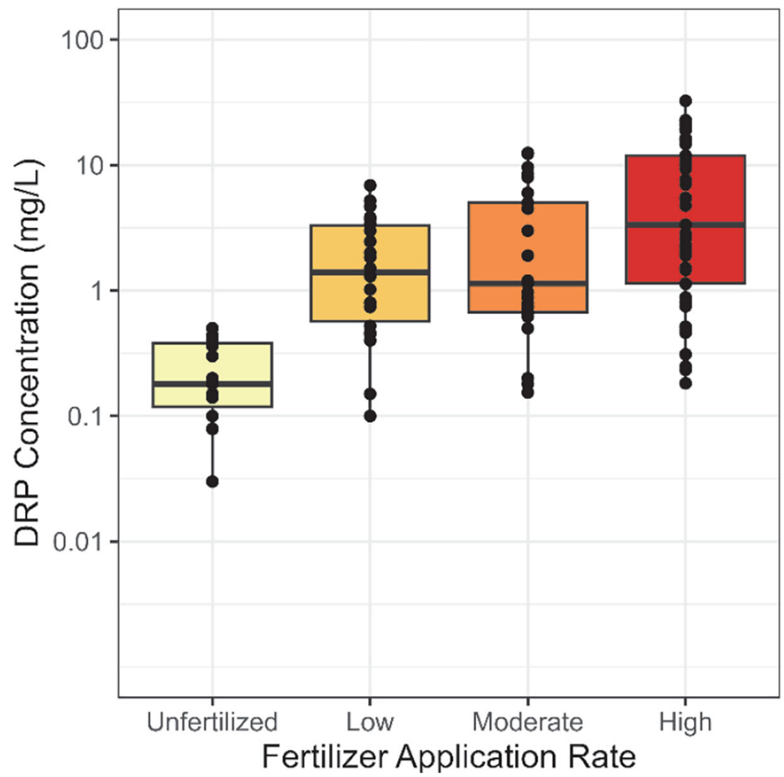

Figure 2.
Dissolved reactive phosphorus (DRP) concentrations for the different fertilizer application rate groups in plot-scale studies. Boxplots span the interquartile range (IQR), with a solid line representing the median value. The y-axis has been set to log10 scale.

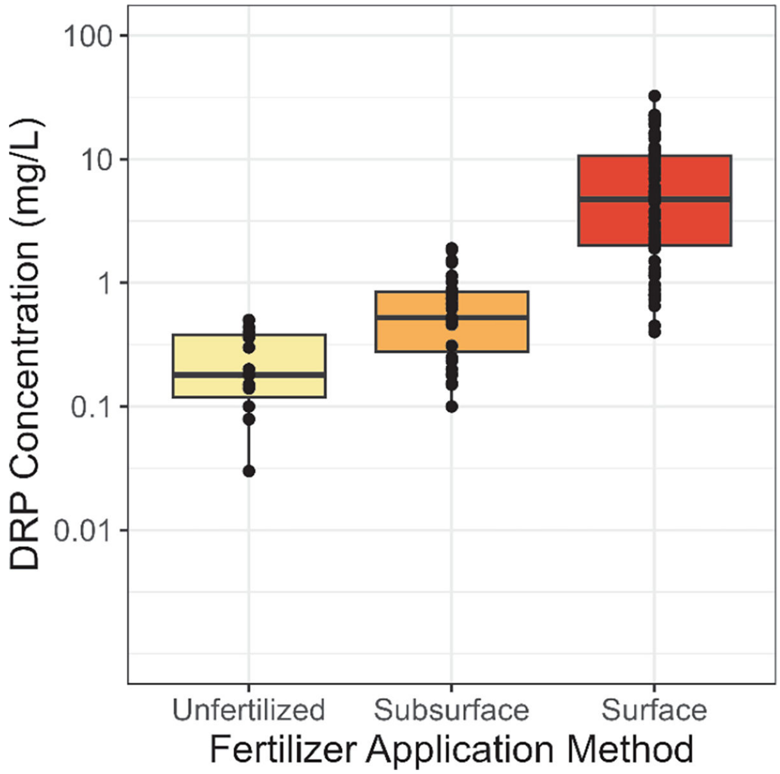

Figure 3.
DRP concentrations for the different fertilizer application methods in plot-scale studies. Boxplots span the interquartile range (IQR), with a solid line representing the median value. The y-axis has been set to log10 scale.

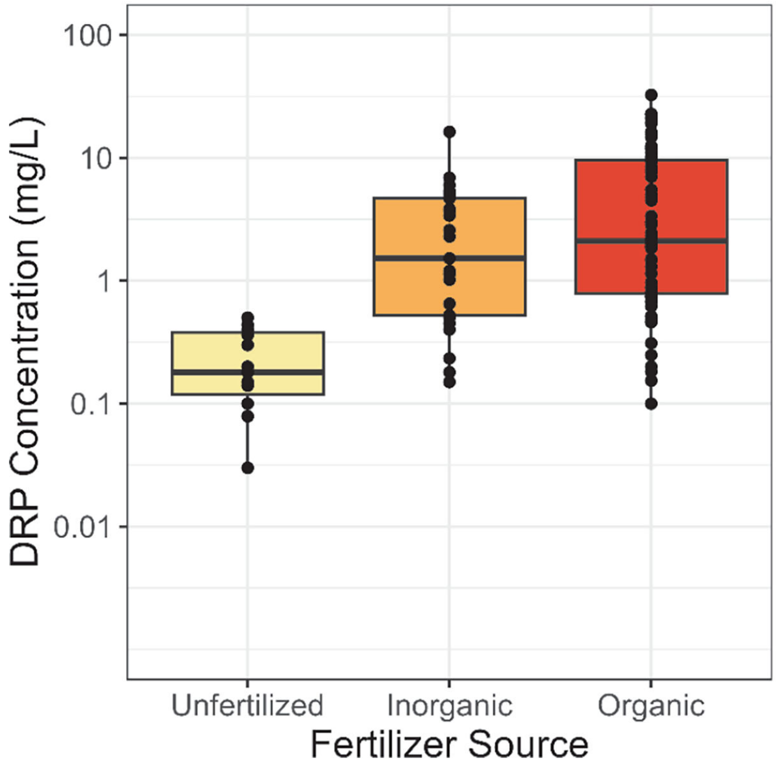

Figure 4.

DRP concentrations for the different classes of fertilizer sources in plot-scale studies. Boxplots span the interquartile range (IQR), with a solid line representing the median value. The y-axis has been set to log10 scale.

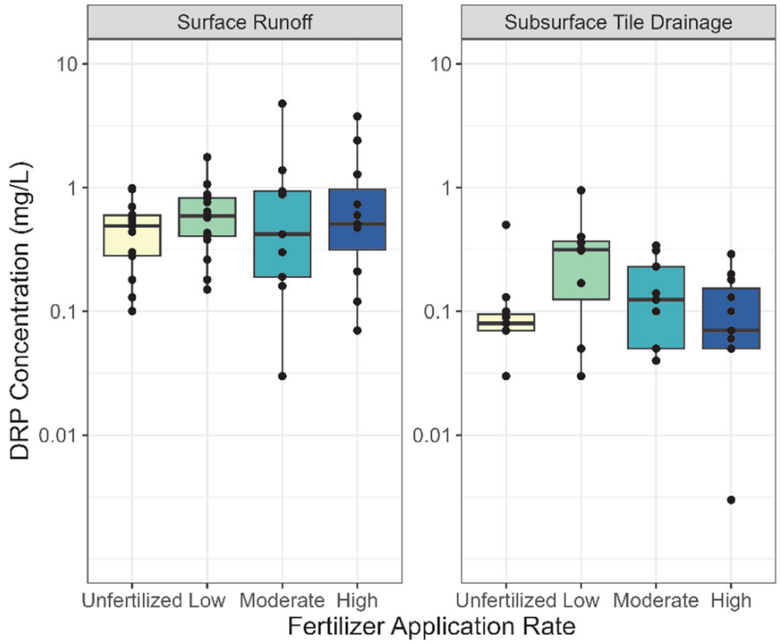

Figure 5.

Influence of P fertilizer rate on field-scale DRP concentrations in surface runoff (Left) and subsurface tile drainage (Right). The y-axis has been set to log10 scale.

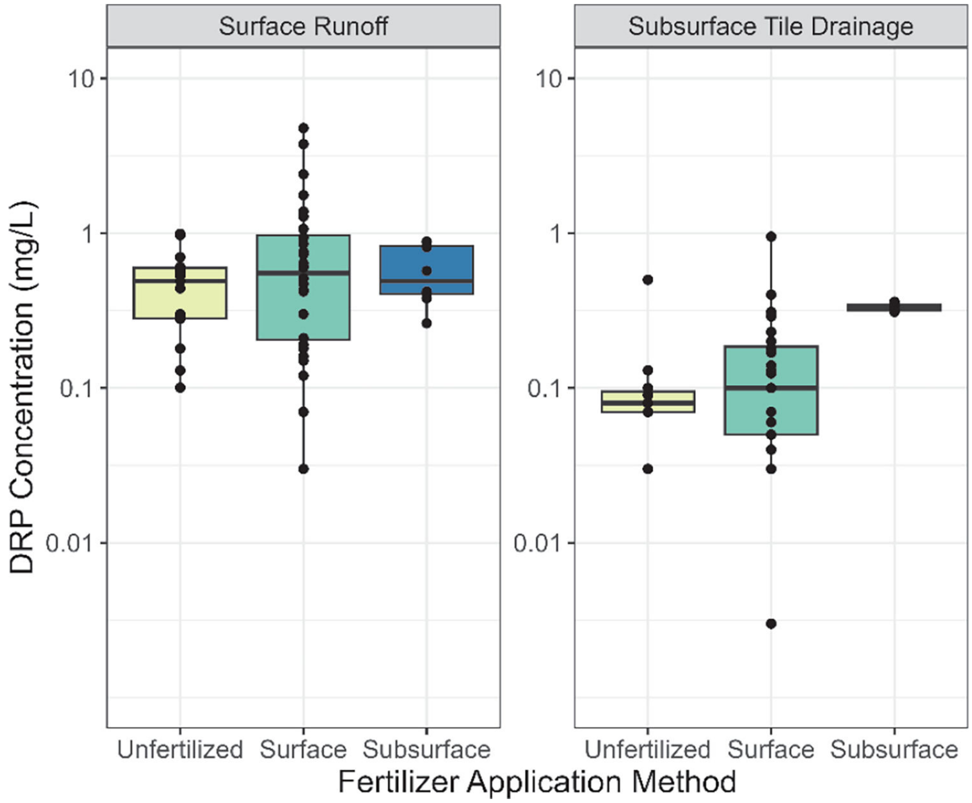

Figure 6.

Influence of P application method on field-scale DRP concentrations in surface runoff (Left) and subsurface tile drainage (Right). The y-axis has been set to log10 scale.

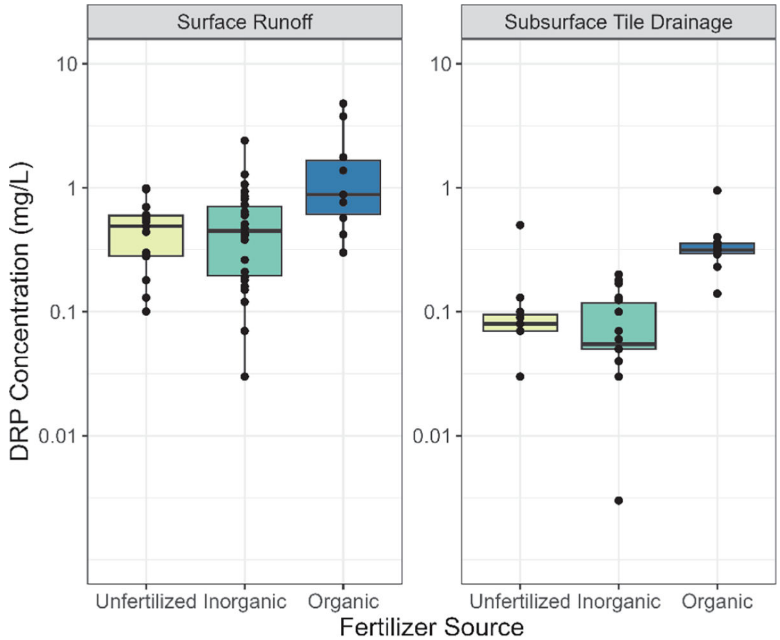

Figure 7.
Influence of P fertilizer source on field-scale DRP concentrations in surface runoff (Left) and subsurface tile drainage (Right). The y-axis has been set to log10 scale.

Table 1.

Categories of P fertilizer rates, sources, and application methods.

Categories	Descriptions
Fertilizer rates	
Unfertilized	0 kg-P2O5 ha^{-1}
Low	< 80 kg-P2O5 ha^{-1} (< 35 kg-P ha^{-1})
Moderate	80 to 160 kg-P2O5 ha^{-1} (35 to 70 kg-P ha^{-1})
High	> 160 kg-P2O5 ha^{-1} (> 70 kg-P ha^{-1})
Fertilizer sources	
Inorganic	MAP, DAP, Poly, and other synthetic fertilizers
Organic	Liquid or solid manure derived from swine, dairy, poultry, etc.
Application methods	
Surface	Surface broadcast fertilizers
Subsurface	Incorporated, injected, and banded fertilizer

Table 2.

Number of plot-scale observations for each class within each nutrient management category.

Fertilizer Application Category		Observations
Unfertilized		15
Fertilizer Rate	Low	22
	Moderate	27
	High	49
Fertilizer Source	Organic	73
	Inorganic	25
Fertilizer Method	Surface	67
	Subsurface	31

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Table 3.

Overview of central tendencies for fertilizer rate and DRP concentration for each fertilization rate group.

	Fertilizer Rate Group			
	Unfertilized	Low	Moderate	High
Mean Fertilizer Rate (kg-P2O5 ha^{-1})	0	38	107	247
Median DRP concentration (mg L^{-1})	0.18	1.40	1.14	3.36
Mean DRP concentration (mg L^{-1})	0.19	1.25	1.54	3.47

Table 4.

Mean DRP concentration within each rate, method, and source combination. Color was used to highlight differences, with darker values representing higher values. Percent (%) reduction was calculated relative to the surface application of fertilizer at a high rate for each fertilizer source. The unfertilized plots were not included.

			Fertilizer source					
			Inorganic			Organic		
	Fertilizer Rate	**Application Method**	***n***	**Mean**	***% Reduction***	***n***	**Mean**	**% Reduction**
DRP Concentration (mg L^{-1})	Low	Subsurface	3	0.43	91%	4	0.50	94
		Surface	8	2.48	48%	7	1.52	82
	Moderate	Subsurface	2	0.30	94%	6	0.43	95
		Surface	4	2.2	54%	15	2.89	66
	High	Subsurface	4	0.82	83%	12	0.57	93
		Surface	4	4.77		29	8.54	

Table 5.

Number of site years from field data for each class within each nutrient management category.

Fertilizer Application Category		Surface Runoff	Tile Drainage
Unfertilized		15	11
Fertilizer Rate	Low	16	8
	Moderate	9	9
	High	11	11
Fertilizer Source	Organic	10	10
	Inorganic	26	18
Fertilizer Method	Surface	28	24
	Subsurface	8	4

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Table 6.

Summary statistics for DRP concentrations in surface runoff and tile drainage from field-scale studies.

Statistic	Concentration (mg L^{-1})	
Type of Flow	Surface Runoff	Tile Drainage
Minimum	0.00	0.003
Median	0.54	0.13
Mean	0.83	0.18
Maximum	4.77	0.95

Table 7.

Central tendencies of DRP export across each class of application method in the field-scale studies. Unfertilized studies were omitted due to the low number of site years for tile drainage.

		Runoff Location					
		Surface Runoff			Tile Drainage		
	Application Method	***n***	**Mean**	**Median**	***n***	**Mean**	**Median**
DRP Concentration (mg L^{-1})	Subsurface	8	0.53	0.49	4	0.33	0.33
	Surface	28	0.50	0.55	24	0.09	0.10

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Table 8.

Median DRP concentration for each combination of fertilizer source and fertilizer rate in the field-scale studies. Color was used to highlight differences, with darker values representing higher values.

		Fertilizer Source							
		Inorganic				Organic			
		Surface Runoff		Tile Drainage		Surface Runoff		Tile Drainage	
	Fertilizer Rate	***n***	**Median**	***n***	**Median**	***n***	**Median**	***n***	**Median**
DRP Concentration (mg L^{-1})	Low	11	0.43	3	0.08	5	0.76	5	0.36
	Moderate	5	0.19	5	0.07	4	1.13	4	0.27
	High	10	0.51	10	0.09	1	3.76	1	0.29