

Linking Soil Phosphorus to Dissolved
Phosphorus Losses in the MidwestEmily W. Duncan,* Kevin W. King, Mark R. Williams, Greg LaBarge,
Lindsay A. Pease, Douglas R. Smith, Norman R. Fausey

Core Ideas

- Soil test phosphorus remains an important factor in studying dissolved reactive P loss.
- Identifying higher risk fields with STP could inform future management practices to reduce DRP loss.
- STP was linearly related to DRP concentration loads in tile-drained fields.
- Monitoring STP in addition to implementing other BMPs should be considered to decrease DRP loss.

Abstract: Harmful and nuisance algal blooms resulting from excess phosphorus (P) have placed agriculture in the spotlight of the water quality debate. Sixty-eight site years of P loading data (combined surface runoff and tile flow) from 36 fields in Ohio were used to see if a soil test P (STP) concentration could be identified that allowed P application while still meeting recommended loss thresholds. Regression analysis revealed that P application to soils with STP concentration in the “critical level” range would result in P losses above the recommended Annex 4 thresholds. In addition, fertilizer application increased the risk of dissolved reactive P (DRP) loss as compared to years in which fertilizer was not applied. We determined that STP was a good screening method to identify fields that are at risk for greater P loss, but STP alone was not a good predictor of DRP loss, suggesting that a more holistic approach that includes upland management, edge-of-field practices, and in-stream approaches will be required to decrease DRP loading.

E.W. Duncan, K.W. King, L.A. Pease, N.R. Fausey (retired), USDA-ARS Soil Drainage Research Unit, 590 Woody Hayes Dr., Columbus, OH 43210; M.R. Williams, USDFA-ARS National Soil Erosion Research Lab., 275 South Russell St., West Lafayette, IN 47907; G. LaBarge, Ohio State Univ., 222 W. Center St., Marion, OH 43302; D.R. Smith, USDA-ARS Grassland, Soil and Water Research Lab., 808 East Blackland Rd., Temple, TX 76502.

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*Corresponding author (emily.duncan@ars.usda.gov).

HARMFUL and nuisance algal blooms (HNABs) in Lake Erie have been linked to excess phosphorus (P) loss, much of which stems from agricultural sources throughout its drainage basin (Ohio P Task Force, 2013). Microcystin from these algal blooms presents a public health risk to 11 million people around Lake Erie who depend on the lake for their drinking water supply. For instance, in August 2014, Toledo, OH, issued a “Do Not Use” warning to 400,000 plus residents due to microcystin concentrations in finished drinking water greater than 1 ppb, a toxic threshold set by the World Health Organization (2003). The HNABs have also negatively affected an annual \$12.5 billion tourism and sport fishing industry (Ohio P Task Force, 2013).

The Nutrients Annex of the Great Lakes Water Quality Agreement recommends a 40% reduction in both spring (March–July) and water year (October–September) loadings of dissolved reactive P (DRP) from 2008 levels to meet water quality goals for the Western Lake Erie Basin (WLEB) (Ohio P Task Force, 2013; Annex 4, 2015). The 2008 loadings were measured at the USGS gauging station (USGS gauge 04193500) located on the Maumee River near Waterville, OH. A reduction of this magnitude equates to an acceptable spring target loading of 186 metric tons of DRP and a water year target loading equivalent to 501 metric tons of DRP.

Historic P application across the WLEB to agricultural fields has led to an accumulation of P in the watershed (Powers et al., 2016; Williams et al., 2016b), which may make achieving DRP load reductions difficult. The accumulation of P or “legacy” P can result in substantial P losses from fields and watersheds (Kleinman et al., 2011; Hamilton 2012; Sharpley et al., 2013; King et al., 2017). Previous work has shown a strong correlation between soil test P (STP) levels and P loss in surface runoff (e.g., Pote et al., 1999), with STP often used as an indicator for the risk of P loss (Lemunyon and Gilbert, 1993; Williams et

Abbreviations: DRP, dissolved reactive phosphorus; STP, soil test phosphorus; WLEB, Western Lake Erie Basin.

al., 2016b). Throughout much of the WLEB, however, the majority of P is exported via tile drainage (King et al., 2015; Smith et al., 2015; Williams et al., 2015a; Williams et al., 2016b). Few studies have explored the potential link between STP and P loss in tile-drained landscapes (Heckrath et al., 1995; Beauchemin et al., 1998; Smith et al., 1998; Hesketh and Brooks 2000; McDowell and Sharpley 2001). Thus, the objectives of this manuscript were to determine the relationship between STP and edge-of-field DRP losses and to compare edge-of-field DRP losses (and the respective STP levels) to recommended water quality thresholds for the WLEB (Ohio P Task Force, 2013; Annex 4, 2015). Understanding these relationships is critical for identifying fields with the greatest potential for P loss and identifying agricultural management practices that can address water quality concerns in the Lake Erie region.

Methods

Experimental Sites

Sixty-eight site years of data from the USDA-ARS paired edge-of-field research sites in Ohio (Williams et al., 2016a) were used in the current study. At each location, two adjacent fields (one pair) are monitored, which allows for side-by-side treatment comparisons. The research sites are located in the northwest quadrant of Ohio and represent the soils, crop rotation, tillage, and fertility approaches used for crop production in the WLEB (King et al., unpublished data). Edge-of-field sites ranged in size from 1.5 to 18.3 ha, and all fields were underlain by subsurface (tile) drainage. Soils were characterized from loams to clays. The primary crop rotation across sites was corn (*Zea Mays* L.)–soybean [*Glycine max* (L.) Merr.]–wheat (*Triticum aestivum* L.). The second most common rotation was corn–soybean; corn–wheat and continuous corn were also represented. Tillage classification across sites ranged from no-till (soil disturbance only during planting) to rotational till (tillage prior to corn planting) to conventional tillage (disk/chisel plow every year, with disturbance ≤ 15 cm). Inorganic fertilizer, organic, and a combination of both of these sources were used to meet fertility demands. Mean annual organic application for all fields was 33 kg ha^{-1} (range 0–110) and 19 kg ha^{-1} (range 0–50) for inorganic fertilizer sources. Soil test P concentrations (0–20 cm) across study fields ranged from 12 to 412 mg kg^{-1} (King et al., unpublished data).

Instrumentation, Data Collection, and Laboratory Analysis

All of the edge-of-field locations were instrumented as described in Williams et al. (2016a), and sampling began at the first locations in summer 2011. Each field had a sampling point for surface and subsurface monitoring that was instrumented to collect discharge and water quality. The surface discharge control volume consisted of a 0.6-m H-flume (Tracom, Inc.). The control volume for measuring tile discharge was a compound weir (Thel-Mar, LLC). All sites were instrumented with automated water quality samplers (Isco 6712, Teledyne Isco). Surface and subsurface discharge was measured year-round on a 10-min time interval. Surface

samples were collected using a flow proportional approach. During each event, a 200-mL aliquot was collected every 1 mm of volumetric depth. Ten samples were placed in a 2-L bottle. Subsurface samples were collected using a time proportional approach. Four 200-mL aliquots were collected every 6 h and composited into a single 1-L bottle for one daily sample. Water samples (both surface and tile) were retrieved from the field at least once per week. All water samples were handled according to USEPA method 365.1 for P analysis (USEPA, 1983). Following collection, samples were vacuum filtered ($0.45 \mu\text{m}$), stored below 4°C (39°F), and analyzed within 28 d. Dissolved nutrients were determined on the filtered samples. Dissolved reactive P concentrations were determined colorimetrically by flow injection analysis using a Lachat Instruments QuikChem 8000 FIA Automated Ion Analyzer. The DRP concentration was determined by the ascorbic acid reduction method (Parsons et al., 1984).

Soil Test Phosphorus

Soil samples from six to eight locations, dependent on contributing area and soil classification, were collected from each field in fall 2015. At each location, eight cores (0–20 cm) radially distributed around a point were collected, air dried, and shipped to the USDA-ARS Grassland Soil and Water Research Laboratory (Temple, TX) for analysis. Soils were extracted using Mehlich III (M3P) followed by subsequent colorimetric P determination (Sans++ segmented flow analyzer, Skalar Inc.). Field-level STP concentrations were determined as the average across all soil sampling locations within the respective field and ranged from 12–400 mg kg^{-1} M3P.

Dissolved Reactive Phosphorus Loading and Concentration Targets

The Annex 4 agreements recommend loading reductions based on USGS gauging station measurements from 2008. The 40% reductions equate to spring loading of 186 metric tons DRP and a water year loading allowance of 501 metric tons of DRP. The unit area load, or “measuring stick,” used to gauge the risk of different crop production fields was calculated by dividing permissible loading values by the entire drainage area of the Maumee River basin (1,711,881 ha). Calculated unit area target loads were 0.29 and $0.11 \text{ kg DRP ha}^{-1}$ for the water year and spring season, respectively. A target flow-weighted mean concentration of 0.05 mg L^{-1} dissolved P was also recommended to address the extent and frequency of HNABs in Lake Erie (Ohio P Task Force, 2013; Annex 4, 2015). If all lands were contributing equally and were below loading and concentration thresholds, water quality goals should theoretically be met.

Statistical Analysis

Linear interpolation was used to create a 10-min concentration file. The resulting 10-min concentration file was merged with the 10-min discharge file to create a 10-min loading file. This method has been shown to reduce the uncertainty associated with collecting both surface and subsurface samples for water quality loading in tile-drained landscapes (Williams et al., 2015b). Loads were calculated as

the product of the 10-min concentrations and 10-min discharges summed over the entire water year and the spring loading period. Field DRP loads were then determined by adding loads in surface runoff and tile discharge. Soil test P was subsequently regressed against water year and spring P loads and mean concentrations. The resulting linear relationship was used to identify the STP level corresponding to recommended target concentrations and unit area loadings. Years with and without P fertilizer application were separated for linear regression analysis. Regression models (least squares method) were developed and tested within SigmaStat 3.4 statistical software (Systat Software, 2006) using a significance level of 0.05.

Results

Mean spring DRP load across sites was 0.41 kg ha^{-1} ($0.01\text{--}1.13 \text{ kg ha}^{-1}$), and mean water year DRP load was 0.71 kg ha^{-1} ($0.047\text{--}3.72 \text{ kg ha}^{-1}$). There were fewer fields in the spring season with fertilizer application (25%) than without application (75%, primarily due to soybeans in rotation). On a water year basis, 63% of fields had fertilizer applied compared with 37% without. When a P application occurred, mean spring DRP load was 0.40 kg ha^{-1} ($0.03\text{--}0.96 \text{ kg ha}^{-1}$), whereas the water year load was 0.71 kg ha^{-1} . Of the fields that received P applications (43 of 68), only 30% (13 of 43) of the fields produced loadings less than the 0.29 kg ha^{-1} water year recommendation (Fig. 1). For spring loads with P application, only 24% (4 of 17) of the loads were below the 0.11 kg ha^{-1} threshold (Fig. 1). A slight improvement was observed when no P application occurred. For water years when no application was made, 52% (13 of 25) of the sites had DRP loadings less than the threshold, whereas for spring loads with no application, 28% (7 of 25) of the sites fell below the threshold (Fig. 1).

Relationships between STP and both spring and water year DRP concentrations were all significant (Fig. 1, Supplemental Table S1). For both spring and water year periods, only 25% (17 of 68) of the locations had flow-weighted mean DRP concentrations that met the 0.05 mg L^{-1} recommendation. During application years, only 21% of the water year concentrations fell below the 0.05 mg L^{-1} recommendation and 28% (4 of 17) of the spring flow-weighted mean concentrations were below 0.05 mg L^{-1} .

For the spring period, back-calculated M3P STP levels required to meet the 0.05 mg L^{-1} DRP recommendation were below zero. A similar negative value was calculated for the water year when an application was made (Fig. 1, Supplemental Table S1). In years without application, however, a 31 mg kg^{-1} STP level was identified for meeting the

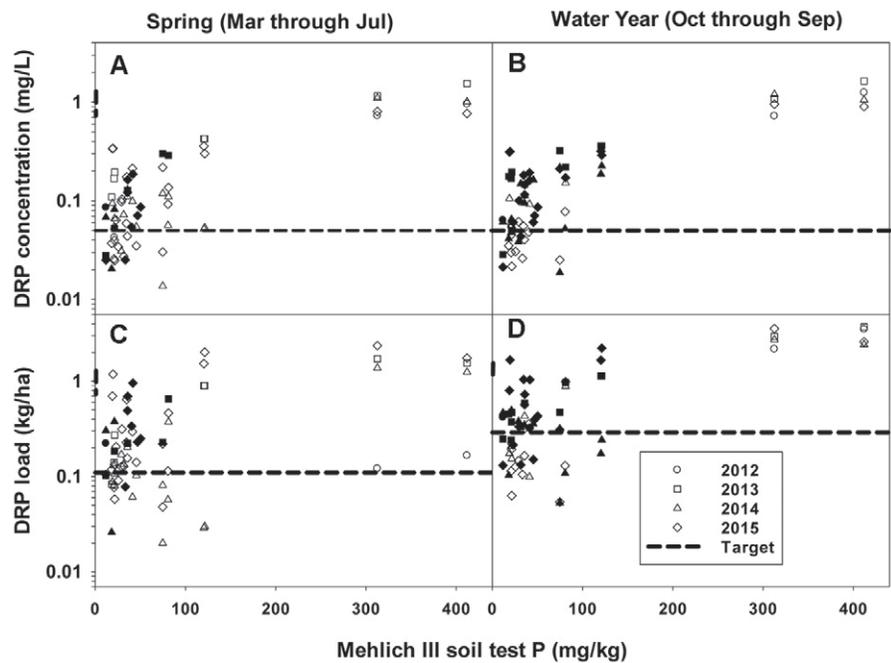


Fig. 1. Relationship between soil test P (STP) (0–20 cm) and mean dissolved reactive phosphorus (DRP) concentrations and loads for spring (March–July) and water year (October–September) time periods for 68 site years of data. Horizontal line represents target thresholds (Annex 4, 2015). Open symbols indicate no P fertilizer application during the time period; closed symbols indicate P application during time period. (A) Spring mean DRP concentration vs. STP no application, R^2 : 0.4; and with application, R^2 : 0.16. (B) Water year DRP concentration vs. STP no application, R^2 : 0.92; and with application, R^2 : 0.17. (C) Spring DRP load vs. STP no application, R^2 : 0.87; and with application, R^2 : 0.18. (D) Water year DRP load vs. STP no application, R^2 : 0.92; and with application, R^2 : 0.34.

desired threshold based on DRP concentrations (Fig. 1, Supplemental Table S1). Similarly, a STP value of 28 mg kg^{-1} was determined for the water year without fertilizer application based on load data. Spring and water year DRP load analysis indicated that fertilized fields would not meet load thresholds because the STP values were below zero, -10 and -2 , respectively (Fig. 1, Supplemental Table S1). Similarly, spring DRP loads from fields that did not receive fertilizer had a M3P STP value of -12 (Fig. 1, Supplemental Table S1).

Discussion

Findings suggest that a fairly strong relationship exists between soil test P and resulting edge-of-field P loads and concentrations. The relationships tend to be stronger during periods with no application compared with those with P application. Relationships between STP and surface P losses have been previously documented (Sharpley and Smith, 1994; Pote et al., 1999; Pierson et al., 2001). Pote et al. (1999) found greater DRP concentrations in surface runoff losses in August as compared to May, with STP ranging from approximately 50 to 240 mg kg^{-1} . Pierson et al. (2001) found an increase in DRP concentration with an increase in M3P, and the reverse was true when M3P concentrations decreased; however, they found that it was also dependent on the timing of the last broiler litter application, which supports the fertilizer timing analysis in this study.

Spring and water year DRP loading with no application was significantly correlated with STP. Using linear regression, 28 mg kg⁻¹ (M3P) was identified as the STP threshold risk level for the water year. That is, fields with STP greater than 28 mg kg⁻¹ were more prone to produce DRP loads above the Annex 4 recommended water year unit load of 0.29 kg ha⁻¹. However, with respect to the spring load with no application, an STP level of -12 mg kg⁻¹ was identified. Given the rainfall during this study period, many fields were already at levels that would not meet the Annex 4 recommendations unless further conservation management practices were implemented.

The edge-of-field findings indicate that fields with STP as low as 28 mg kg⁻¹ cannot meet the loading or concentrations goals set forth by the Great Lakes Water Quality Agreement (Annex 4, 2015) without additional conservation management practice adoption. For fields hovering around threshold values, management practices such as 4R nutrient stewardship could potentially help these fields meet Annex 4 loading recommendations. However, for fields with elevated STP (>75 to 80 ppm M3P), attainment of water quality goals may only be addressed through other measures or a combination of practices including drawdown (Withers et al., 2014; Rowe et al., 2016) or a one-time inversion tillage if severely stratified to increase the buffering capacity of the upper layers of the soil (Sharpley, 2003; Baker et al., 2017). In addition to drawing down STP or implementing inversion tillage, gypsum (Chardon et al., 2012; King et al., 2016) and controlled drainage (Williams et al., 2015a; Ross et al., 2016) offer alternative practices to potentially remove or mitigate P loss.

Given the variability of both spring and water year loading with respect to STPs below 100 mg kg⁻¹, using only STP levels to assess the risk of P loss from tile-drained fields is not recommended. For sites with STP less than 100 M3P and loads over the Annex 4 water quality targets, the mean overage for the water year was 0.57 kg ha⁻¹ (0.31–1.67 kg ha⁻¹) compared with 0.32 kg ha⁻¹ (0.12–1.18 kg ha⁻¹) for the spring period. The findings suggest that for those sites with STP below 100, the mean reduction in DRP loading needed to meet Annex 4 recommendations would range from 0.29 to 0.31 kg ha⁻¹ in spring with and without fertilizer application. Water year DRP loads require similar reductions to meet the recommendations, with the exception of DRP loads from fields without fertilizer application. Fields that did not apply fertilizer, and had STP ≤115 M3P during the water year were all below the Annex 4 DRP loading target of 0.29 kg ha⁻¹.

Meeting the P load and concentration standards for Lake Erie may be very difficult because the data presented represents prevailing agricultural practices found throughout the WLEB. Practices range from fertilizer incorporation to strip till to no-till with cover crops. Greater than 60% of the fields have wheat in the rotation (King et al. unpublished data). However, the data is representative of periods with greater than normal precipitation and a full crop rotation is not captured at some field locations. Across all sites and years, the average annual precipitation was 960 mm, which is 90 mm greater than the long-term average annual precipitation at Bowling Green, OH (centrally located within the WLEB). Strong relationships between STP and loads/concentrations

exceeding recommendations during years without application suggest that legacy P could be a major factor in losses. Indeed, Williams et al. (2016b) suggested a ubiquitous source of P driven by changes in hydrology is responsible for algal blooms in Lake Erie. Sharpley et al. (2013) showed legacy P can create a delay between implementation of best management practices and water quality improvements; therefore, newly implemented practices and strategies should consider this time frame, as well as the scale of monitoring (e.g., field versus watershed).

Results of the current study point to the need to revisit soil test levels and application recommendations within the tri-state region (Ohio, Michigan, and Indiana) (Vitosh et al., 1995). Based on the currently available data, spring DRP load thresholds could not be met using current tri-state critical level criteria. In all cases, the STP concentration that would place fields above the recommended DRP threshold was near 8 mg kg⁻¹ or below zero. This indicates that any application would further exacerbate losses, leading to larger and potentially more toxic blooms. With respect to water year loadings, DRP loads in years without fertilizer application were similar to the current critical levels outlined by the tri-state recommendations.

The buildup or maintenance approach to fertilizer application (applying P at a rate to continue building up STP concentrations or maintain current STP levels) may actually be exacerbating the problem, while annual applications at crop removal rates should minimize losses. This provides evidence to move to a “feed the crop” rather than “feed the soil” approach, keeping in mind specific weather dependent management issues whereby fertilizer might not be applied due to wet soils in the spring. Reduced fertilizer application that incorporates lower rates and timely application to mitigate any potential crop stress could still provide a drawdown in higher STP fields and reduction of P loss from farm fields (Rowe et al., 2016).

Conclusions

Soil test P should be a starting point for identifying critical source areas for offsite P transport in the poorly drained humid regions of the world. Tile drainage provides for hydrologic connectivity, and as shown by the initial data set in this study, even relatively low STP can produce P loss concentrations and loads well above the recommended thresholds. When even judicious application of P can lead to appreciable losses, adherence to the application rates within the maintenance range should be followed. It may also be important to revisit tri-state guidelines to make sure that only what is needed is being recommended to account for legacy P. Established goals may not always be realistic considering the legacy effects; therefore, the challenge remains in finding a balance between economic and environmental needs. While STP should provide a starting point for P management, other targeted upland practices such as 4Rs, surface amendments, cover crops, and edge-of-field (e.g., bioreactors, steel slag filters, controlled drainage) practices may help most farm fields meet Great Lakes Water Quality Agreement concentration and loading goals.

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