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Vertical Stratification of Soil Phosphorus as a Concern for Dissolved Phosphorus Runoff in the Lake Erie Basin

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Abstract

During the re-eutrophication of Lake Erie, dissolved reactive phosphorus (DRP) loading and concentrations to the lake have nearly doubled, while particulate phosphorus (PP) has remained relatively constant. One potential cause of increased DRP concentrations is P stratification, or the buildup of soil-test P (STP) in the upper soil layer (<5 cm). Stratification often accompanies no-till and mulch-till practices that reduce erosion and PP loading, practices that have been widely implemented throughout the Lake Erie Basin. To evaluate the extent of P stratification in the Sandusky Watershed, certified crop advisors were enlisted to collect stratified soil samples (0–5 or 0–2.5 cm) alongside their normal agronomic samples (0–20 cm) (n = 1758 fields). The mean STP level in the upper 2.5 cm was 55% higher than the mean of agronomic samples used for fertilizer recommendations. The amounts of stratification were highly variable and did not correlate with agronomic STPs (Spearman's $r = 0.039$, $p = 0.178$). Agronomic STP in 70% of the fields was within the buildup or maintenance ranges for corn (*Zea mays* L.) and soybeans [*Glycine max* (L.) Merr.] (0–46 mg kg^{-1} Mehlich-3 P). The cumulative risks for DRP runoff from the large number of fields in the buildup and maintenance ranges exceeded the risks from fields above those ranges. Reducing stratification by a one-time soil inversion has the potential for larger and quicker reductions in DRP runoff risk than practices related to drawing down agronomic STP levels. Periodic soil inversion and mixing, targeted by stratified STP data, should be considered a viable practice to reduce DRP loading to Lake Erie.

Core Ideas

- P stratification increases surficial soil-test levels by 55% over agronomic cores.
- Agronomic soil-test levels are not good indicators of surficial soil-test levels.
- Soils in maintenance range account for the largest proportion of DRP runoff risks.
- Targeted stratification reduction could reduce DRP runoff more than drawdown.
- Stratification reduction could reduce DRP runoff more quickly than drawdown.

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There is a long history of phosphorus (P) control programs in the Lake Erie Basin aimed at reducing cultural eutrophication. The first programs began in the 1970s and focused on controlling point sources (IJC, 1978), while the second focused on agricultural nonpoint sources, primarily through erosion control programs (IJC, 1983). The first was eminently successful in reducing total P (TP) loading from ~28,000 Mg yr^{-1} in 1968 to ~11,000 Mg yr^{-1} in 1981 (DePinto et al., 1986), while the second has fallen well short of its additional 2000-Mg yr^{-1} reduction target (OEPA, 2010; Baker et al., 2014a). In response to these P control programs, Lake Erie was viewed as a "poster child" for successful eutrophication control in the late 1980s and early 1990s (Matisoff and Ciborowski, 2005). Unfortunately, beginning in the late 1990s, the lake has undergone re-eutrophication such that the algal blooms of 2011 and 2015 were the largest and most widespread ever noted (Scavia et al., 2014; Stumpf et al., 2016).

The re-eutrophication of Lake Erie corresponded temporally with the implementation of agricultural nonpoint-source controls that focused on the use of no-till and mulch-till practices to reduce erosion and particulate P (PP) loading (Richards et al., 2002; NRCS, 2008). At the same time, tributary monitoring studies began to show large increases in the loading of highly bioavailable dissolved reactive P (DRP) (OEPA, 2010; Joosse and Baker, 2011; Baker et al., 2014a; IJC, 2014). Numerous agricultural studies have shown that erosion control programs, and related PP control programs, are often accompanied by increased DRP export (Logan and Adams, 1981; Sharpley and Smith, 1994; Kleinman et al., 2011a, 2015; Smith et al., 2015b). While DRP comprised only 23% of the TP export from the Sandusky and Maumee Rivers from 2003 to 2012, it comprised 53% of the chemically bioavailable P exported from these watersheds (Baker et al., 2014a). Furthermore, PP is subject to deposition to bottom sediments in lakes prior to release of its chemically bioavailable forms, further reducing its significance as a cause of eutrophication relative to DRP (Sonzogni et al., 1982; Baker et al., 2014b). Because increased DRP loading has been identified as an important cause of Lake Erie re-eutrophication (Matisoff and Ciborowski, 2005;

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Abbreviations: A-STP, agronomic soil-test phosphorus (0–20 cm core); BMP, best management practice; CCA, certified crop advisor; CEE, cumulative edaphic exposure (for dissolved reactive phosphorus runoff); DRP, dissolved reactive phosphorus; E-STP, environmental soil-test phosphorus (0–2.5 or 0–5.0 cm core portions); M3P, Mehlich-3 phosphorus, soil test phosphorus (inductively coupled plasma analysis); PP, particulate phosphorus; SS, suspended solids; STP, soil-test phosphorus; TP, total phosphorus; WLEB, Western Lake Erie Basin.

Michalak et al., 2013; Scavia et al., 2014; Kane et al., 2014), the governments of the United States and Canada are now calling for programs to specifically reduce DRP loading from major agricultural tributaries to the lake, in addition to the traditional calls for TP load reductions (Binational.net, 2016; Annex 4, 2015).

Many potential causes of increased DRP export from agricultural watersheds have been identified (Smith et al., 2015b). One of these is the stratification of P at the soil surface that often accompanies adoption of no-till and reduced-till management. This stratification is caused by P released from breakdown of surficial crop residues and by surficial applications of fertilizers and manure, coupled with a lack of inversion tillage. Stratification results in higher soil-test P (STP) levels in the upper 0 to 5 cm of soil than deeper in the soil column (e.g., 5–20 cm). This upper layer of soil represents the "zone of interaction" between runoff water and soil (Sharpley, 1985; Vadas et al., 2005b). The DRP concentrations in runoff water increase as STP levels in this zone increase (Davis et al., 2005; Vadas et al., 2005a; Allen et al., 2006; Wang et al., 2010). Thus, in agricultural landscapes, two types of STP measurements are needed—agronomic STP (A-STP) to support fertility management and environmental STP (E-STP) to reflect conditions in the zone of interaction that influence DRP concentrations in runoff water.

No-till management also enhances the development of macropores in the soil that, in this region, convey surface runoff from the zone of interaction through the soil column to tile drain lines, and hence directly to streams (Shipitalo et al., 2000; King et al., 2015; Smith et al., 2015a). Since this macropore flow bypasses the soil matrix, its DRP concentrations reflect E-STP levels. Yet another cause of high DRP concentration in runoff waters is linked to direct dissolution of surface-applied fertilizers and manures before that P interacts with surficial soils. Kleinman et al. (2011b) have referred to direct dissolution of surface-applied materials as acute or incidental losses, while referring to P released from soils in proportion to STP levels as edaphic or chronic losses.

In this study, we have examined P stratification at the watershed scale, its relationship to A-STP, its potential contribution to increased edaphic DRP export from this region, and its significance for targeting DRP load reduction programs. We have also examined stratification reduction as a potential best management practice (BMP) for reducing DRP loading to Lake Erie.

Materials and Methods

The Study Area

The stratified sampling area is located in the central portion of the Sandusky River Watershed (Fig. 1). The Sandusky and Maumee Watersheds make up most of Ohio's Western Lake Erie Basin (WLEB) agricultural subregion (Supplemental Fig. S1). This row-crop-dominated landscape is the major source of agricultural P loading to Lake Erie (OEPA, 2010) and is the major focus of Lake Erie DRP load reduction programs (OEPA, 2013; Annex 4, 2015). In a study of the 2008 TP loading to all five Great Lakes, USEPA found that, among the 80 major tributaries, the Maumee River had the largest load, and the Sandusky River ranked second (Kreis et al., 2014). These two rivers account for >50% of the monitored tributary TP loads entering Lake Erie from the United States and Canada (Dolan and Chapra, 2012; Baker et al., 2014a). From 2008 to 2013, municipal and industrial point sources upstream from the tributary monitoring stations for the Maumee and Sandusky Watersheds could account for only 5 and 3%, respectively, of their average annual TP export (Maccoux et al., 2016).

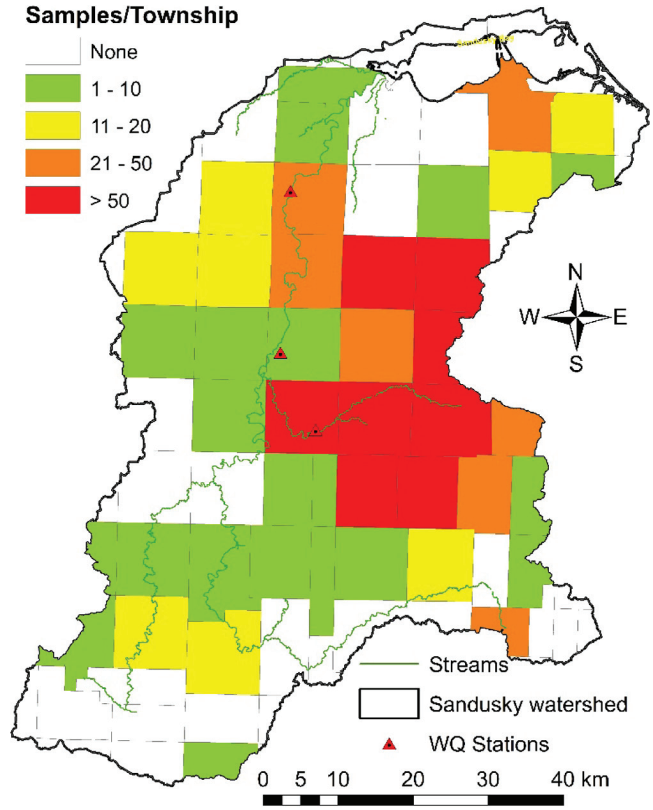

Fig. 1. Distribution of fields with stratified sampling among townships in the Sandusky River Watershed. WQ, water quality.

Cropland P-balance assessments for Ohio show that P applied to cropland as fertilizer and manure has been approximately in balance with crop removal since the late 1990s (Bruulsema et al., 2012). About 60% of the fertilizer is broadcast, with only one-half of that incorporated. About 33% of the fertilizer is banded and very little is injected. For the Sandusky Watershed, the NRCS observed that animals within the watershed produced only enough P to replace 8.2% of average annual crop removal (NRCS, 2008). For the Ohio portion of WLEB, Williams et al. (2015) calculated that manure provided 9.2% of P requirements. Thus, P export from these watersheds is dominated by agricultural nonpoint pollution, with commercial fertilizers as the dominant P source.

Major crops include soybeans [*Glycine max* (L.) Merr.], corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and hay, with these crops occupying ~50, 35, 13, and 2% of the cropland, respectively. No-till management is used on about 65% of the soybeans, 71% of the wheat, and 19% of the corn, while mulch tillage is used on 9, 19, and 12%, respectively (NRCS, 2011). Vertical tillage with <30% residue is used on 69% of the corn. Very little cropland is in continuous no-till production. The cropland is relatively flat, with an average slope of 1.8% (Williams et al., 2015). Most soils (~80%) fall into the somewhat poorly drained, poorly drained, and very poorly drained drainage classes. Tile drainage is used extensively throughout the area (Sugg, 2007). Additional land use and land management data are shown in Supplemental Table S1.

Phosphorus Stratification Studies

The stratified soil-testing program was organized to allow comparison between E-STP and A-STP levels. Local certified crop advisors (CCAs) collaborated in the study by collecting stratified soil samples alongside the routine soil-sampling program they conduct for their customers. At each location in a field where the CCAs collected a 0- to 20-cm (0–8 in.) soil core for an A-STP sample, the CCA also collected a second 0- to 20-cm core for the stratified samples. Stratified samples were divided into 0- to 5-cm (0–2 in.) and 5- to 20-cm (2–8 in.) sections for two-part studies, or into 0- to 2.5-cm (0–1 in.), 2.5- to 5-cm (1–2 in.), 5- to 12.5-cm (2–5 in.), and 12.5- to 20-cm (5–8 in.) sections for four-part studies. This procedure was repeated at multiple locations in each field, yielding separate composite samples for the A-STP and each portion of the stratified samples. Preprinted labels were provided to the CCAs to facilitate sample tracking. Each field had a unique identification number with separate labels for its A-STP sample, each layer of its stratified sample, and a supplemental information sheet. These sheets requested information regarding the sample collection date, the field location (county, township, and section), dominant soil type, the previous and planned crops, the tillage practices, and the fertilizer and/or manure management practices (see Supplemental Materials: Information Sheet). The stratified sampling program began in 2008 and concluded in 2012, with the bulk of the samples collected in 2009 to 2011.

To assure consistency with their ongoing records, the CCAs shipped their A-STP samples to the soil-testing laboratory they normally use. Stratified samples were all sent to the same soil-testing laboratory (Spectrum Analytic Inc., Washington Court House, OH). All STP analyses used the Mehlich-3 P (M3P) extraction procedure with inductively coupled plasma (ICP) analyses and are reported as mg kg^{-1} in the soil. In addition to P, the analytical results included: pH, buffer pH, organic matter (%), K mg kg^{-1}, Mg mg kg^{-1}, Ca mg kg^{-1}, cation exchange capacity, K % saturation, Mg % saturation, Ca % saturation, K/Mg ratio, Ca/Mg ratio, Fe mg kg^{-1}, and Al mg kg^{-1}.

Samples from 1526 fields were submitted to the soil testing laboratory for the two-part stratification study, and 232 fields for the four-part studies, during the 5-yr operation of the sampling program. Supplemental information sheets were returned for 1239 fields with two-part studies and 231 fields with four-part studies. Rather than use the A-STP results from the 0- to 20-cm cores that CCAs sent to various laboratories, A-STP levels for each field were calculated using the results of the stratified testing, with each stratum contributing to the A-STP in proportion to its fraction of the total 20-cm core (See Supplemental Materials: Excel Spreadsheet). Researchers from the Ohio State University and the USDA–ARS Soil Drainage Research Unit provided us with STP data they had collected from Ohio's major soil-testing laboratories. Those data allowed comparison of A-STP levels from the stratification study with those of the Sandusky Watershed and the WLEB as a whole.

Statistical Analyses

For the two-part stratification studies, we compared the top section (0–5 cm) with the bottom section (5–20 cm) of each core using a paired *t* test. For the four-part stratification studies, we compared each section (0–2.5, 2.5–5.0, 5.0–12.5, and 12.5–20.0 cm) using a one-way ANOVA blocked by field, followed by a Tukey test. All data were log transformed prior to analysis to meet the assumptions of normality and equal variance. The A-STP levels were correlated with E-STP and the stratification increments (i.e., E-STP − A-STP for each field) using the nonparametric Spearman rank correlation. Data were unable to be transformed to meet the parametric assumptions of normality (tested with Shapiro–Wilk) and equal variance (tested residuals vs. *x*-data with Spearman rank correlation). All tests were performed using SigmaPlot 13.0 (Systat Software, 2014) with statistical significance determined at the $\alpha = 0.05$ level.

Results and Discussion

Extent of Stratification

Higher STP levels in near-surface strata were evident in both the two- and four-part stratification studies (Fig. 2). For the two-part study, the mean M3P of the top section (0–5 cm, $\bar{x} = 59.4$ mg kg^{-1}) was 68% higher than the mean of the lower section

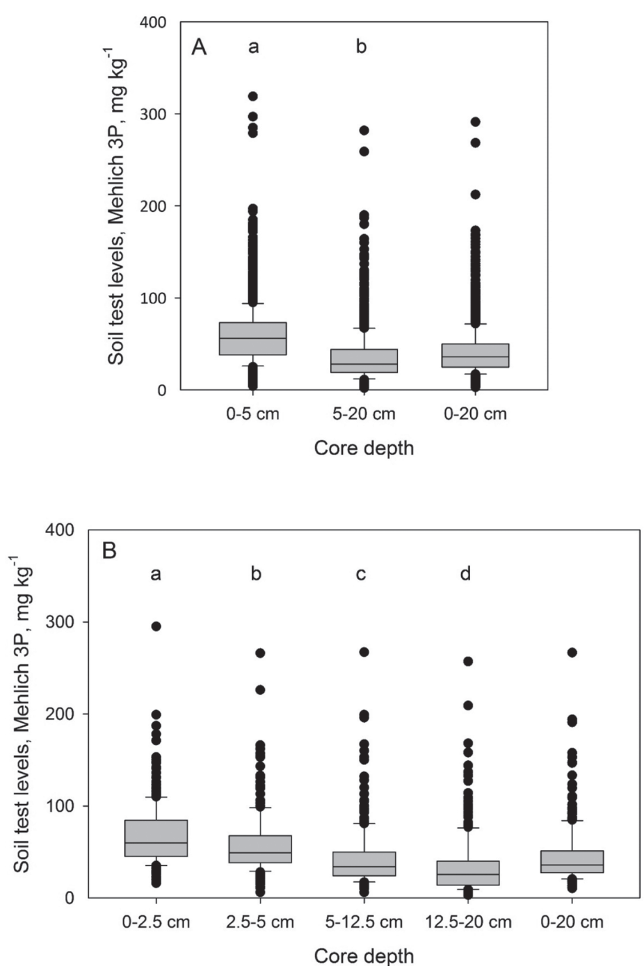

Fig. 2. Boxplots showing soil test phosphorus (STP) stratification in the (A) two-part and (B) four-part stratification studies. The 0- to 20-cm agronomic STP values were calculated from their component strata STP values. Boxes are drawn from the 25th to 75th percentiles, and the horizontal line within each box is the median. Vertical lines extending above and below the box represent data within the 10th and 90th percentiles, with data lying outside this range represented by circles. Letters denote significant differences determined using either (A) paired *t* test or (B) one way ANOVA blocked by field followed by a Tukey's test.

(5–20 cm, $\bar{x}$ = 35.4 mg kg^{-1}, paired t test $p < 0.001$, log normalized) and 43% higher than the mean of the entire 0- to 20-cm core (41.4 mg kg^{-1}) (Table 1). In the four-part studies, the mean M3P of the top section (0–2.5 cm) (68.8 mg kg^{-1}) was 95% higher than the mean of the lowest section (12.5–20 cm) (35.2 mg kg^{-1}), and each of the sections was significantly different from each other (one-way ANOVA blocked by field, followed by a Tukey test, $p < 0.001$, log normalized).

The mean A-STP values for the two- and four-part stratified datasets, the Sandusky Watershed and the WLEB were 41.4, 45.5, 41.2, and 48.1 mg kg^{-1}, respectively. Percentile distributions for each stratum of both the two- and four-part studies and for the A-STP levels for the stratified samples, the Sandusky River Watershed, and the WLEB are also shown in Table 1. Although the medians were similar in all four datasets, the 75th percentile values for the WLEB were higher than those of the stratification and Sandusky Watershed datasets.

To take into account stratification within the upper 5 cm of soil, as evident from the four-part studies, and to better represent E-STP levels in the zone of interaction, data from the four-part studies were used to estimate 0- to 2.5-cm STP values for the two-part studies. This estimation was done by calculating the average 0- to 5-cm STP value for the four-part studies, the ratio of the 0- to 2.5-cm average value to the 0- to 5-cm average value for the four-part studies (1.083), and multiplying the 0- to 5-cm value from the two-part studies by that ratio (see Supplemental Equations S1). This allowed the two- and four-part studies to be merged into a single dataset of 1758 fields for subsequent analyses of E-STP and A-STP values. In the merged dataset, the 0- to 2.5-cm mean E-STP (64.9 mg kg^{-1}) was 55% higher than the A-STP mean (42.0 mg kg^{-1}).

Relationships between Environmental and Agronomic Soil-Test Levels

Environmental STP levels varied widely at a given A-STP level (Fig. 3A). For example, fields with A-STPs between 24 and 26 mg kg^{-1} ($N = 95$) had E-STPs that varied between 23 and 105 mg kg^{-1}, with a mean of 48 and a median of 45 mg kg^{-1}. Although there was a significant correlation between E-STP and A-STP values (Fig. 3A, Spearman's $r = 0.818$, $p < 0.001$), the variation in E-STP also significantly increased with A-STP levels ($p < 0.001$), indicating that estimation of E-STPs from A-STPs would be accompanied by large errors. Similarly, the stratification increments, calculated by subtracting A-STP values from E-STP values for each field, increased in variation with A-STP levels, and though there was a significant

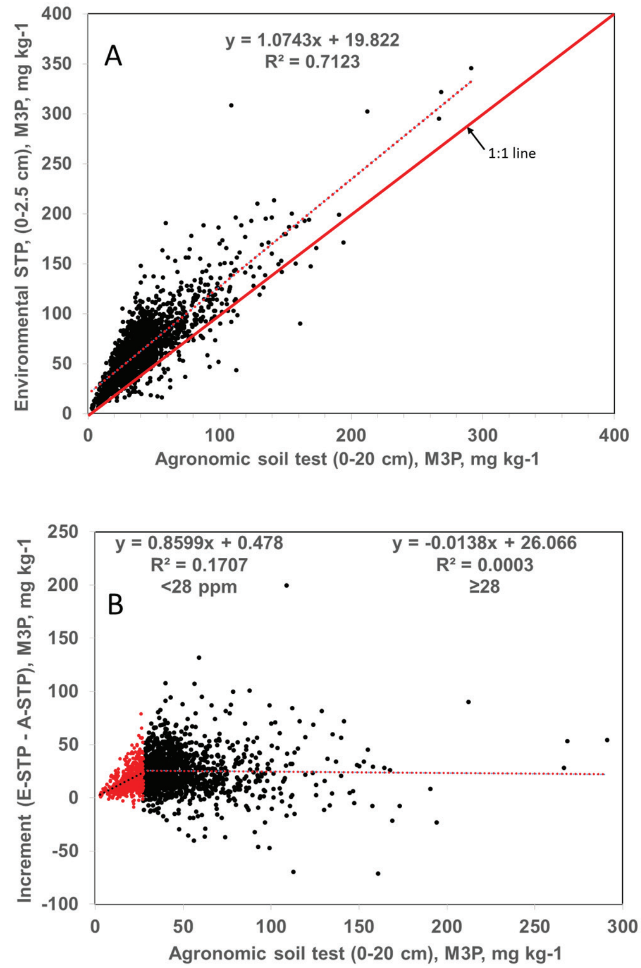

Fig. 3. (A) Correlations between environmental soil-test phosphorus levels (E-STP, 0–2.5 cm) and agronomic soil test phosphorus levels (A-STP, 0–20 cm) for 1763 fields and (B) between increments in soil-test values (E-STP minus A-STP) in relation to A-STP levels for A-STP <28 mg kg^{-1} and $\geq$28 mg kg^{-1}.

Table 1. Summary of soil test values in two- and four-part stratification studies as shown in Fig. 2 and for agronomic soil test results for the Sandusky River Watershed and the Western Lake Erie Basin (WLEB).

Sample source	Mean concentration	Minimum concentration	25th percentile	50th percentile	75th percentile	Maximum concentration
			mg kg^{-1}			
Two-part stratification, N = 1526						
0–5 cm	59.4	4	38	56	75	319
5–20 cm	35.4	2	19	28	44	282
0–20 cm	41.4	3	25	36	50	291
Four-part stratification, N = 232						
0–2.5 cm,	68.8	16	45	60	83	295
2.5–5 cm	58.2	6	38	49	67	266
5–12.5 cm	43.9	6	24	34	49	267
12.5–20 cm	35.2	3	14	25	40	257
0–20 cm	45.5	10	28	36	51	267
Sandusky River Watershed, 2009–2011, N = 33,844						
0–20 cm	41.2	2	22	32	48	1227
WLEB, Ohio portion, 2009–2011, N = 140,214 (includes Sandusky Watershed samples)						
0–20 cm	48.1	0	25	36	56	2301

correlation for A-STP < 28 mg kg^{-1} (Fig. 3B, Spearman's $r = 0.402$, $p < 0.001$), there was no correlation between the stratification increments and A-STP values >28 mg kg^{-1} (Fig. 3B, $r = -0.039$, $p = 0.178$). This further illustrates the difficulty in predicting E-STP values or levels of P stratification from A-STP values.

Agronomic Soil-Test Levels in Relation to Fertilizer Application Guidelines

In Ohio, the Tri-State fertility recommendations for corn, soybeans, wheat, and alfalfa (*Medicago sativa* L.) (Vitosh et al., 1995) are widely used to guide fertilizer management. These guidelines identify four management ranges for P fertilizer applications based on A-STP values: a buildup range, where values fall below the critical level that supports optimum economic growth and where fertilizer application should exceed crop removal; a maintenance range, where application rates should match crop removal rates; a drawdown range, where application rates are less than crop removal; and a no-further-application range, where further application is unwarranted. The STP levels associated with these agronomic ranges are shown in Table 2, where the BrayP1 STP units of the Tri-State recommendations were converted to M3P units using the equation of Watson and Mullen (2007). Note the higher A-STP levels required for wheat, which is included in some rotations, than for corn and soybeans.

To assess the distribution of A-STP values relative to these management ranges, the percentile distribution of A-STP values was calculated and plotted in relation to the A-STP values and associated management ranges (Fig. 4). Percentile distributions of A-STP values were also used to determine the percentage of fields in each of the management ranges for the stratified, Sandusky, and WLEB datasets (Table 2). For the stratified samples, A-STP levels for ~71% of the fields fell in the buildup or maintenance ranges for corn and soybeans and ~83% for wheat.

Agronomic STP levels for the stratified sampling program were similar to those of the Sandusky Watershed as a whole and were somewhat lower than the Ohio portion of the WLEB. The WLEB has lower STP levels than most other agricultural subregions of Ohio (see OEPA, 2013, subregion 9; Fig. 3). Furthermore the median of Ohio's A-STP values were lower than those of Indiana, Michigan, and Ontario (IPNI, 2010). In general, the A-STP values in the WLEB were not excessively high, yet the average annual DRP export rates from 2006 to 2015 for the Maumee River (0.35 kg ha^{-1} yr^{-1}) and Sandusky River (0.44 kg ha^{-1} yr^{-1}) were high relative to other Lake Erie tributaries (Maccoux et al., 2016) and are comparable with those of other agricultural watersheds with DRP export data (Richards et al., 2010).

The Significance of Stratification in Increasing Edaphic DRP Runoff

The significance of stratification and its relevance to site assessment depends on the role of E-STP values in relation to other factors that influence edaphic DRP runoff. These other factors, along with STP values, are incorporated into state-level P Risk Indices that are used for targeting P reduction programs (Nelson and Schober, 2012). These indices combine field-specific P-transport and P-source factors to estimate risk levels. For Ohio's P Index, transport factors include erosion rate, connectivity to flowing water, runoff class (as determined by soil hydrological group and field slope), and presence or absence of filter strips (NRCS, 2001). Transport factors affect how much runoff water from a particular field will reach flowing streams. The source factors, which affect DRP concentrations in runoff, include the STP values, as well as the forms, rates, timing, and methods of fertilizer or manure P application.

As a prelude to revisions of the Ohio P Index, Williams et al. (2015) conducted a sensitivity analysis of Ohio's P Risk Index for five Ohio watersheds, including the WLEB, to determine which factors had the greatest impact on variability in the combined risk score. They found that, across Ohio, three factors dominated variability in total risk. The largest was connectivity to flowing water, followed by runoff class, and then A-STP. For the WLEB, connectivity is likely less important as a source of variability in runoff risk than in other parts of Ohio because of the extensive use of tile drainage in this area. Tile drainage is not included in the Ohio P Index, even though the WLEB area is one of the most intensively drained landscapes in the United States (Sugg, 2007). Reid et al. (2012) have noted that, where preferential flow through macropores can convey P to tile systems, management to mitigate P losses could be required across the entire tile drained

Table 2. Percent of fields and percent of the cumulative edaphic exposure (CEE) falling within various Tri-State agronomic ranges for corn and soybeans and for wheat in the stratified testing program, the Sandusky Watershed, and the Western Lake Erie Basin (WLEB). For the stratified samples, CEEs are presented for both agronomic (A-STP) and environmental (E-STP) soil-test phosphorus values.

Soil-test range, Mehlich-3 P	Tri-State fertilizer recommendations	Stratified sampling program (*N* = 1758)			Sandusky Watershed		WLEB	
		Fields	CEE (A-STP)	CEE (E-STP)	Fields	CEE (A-STP)	Fields	CEE (A-STP)
mg kg^{-1}		%						
Corn and soybeans								
0–27	Build-up	29.5	13.6	16.6	39.4	18.4	31.7	12.8
28–46	Maintenance	41.0	35.3	39.3	33.5	29.1	33.2	24.7
47–58	Drawdown	12.4	15.3	14.8	10.1	12.7	11.9	12.9
≥59	No application	17.1	35.8	29.4	17.0	39.8	23.2	49.5
Wheat								
0–39	Build-up	57.8	36.2	42.1	63.6	37.7	55.5	29.1
40–58	Maintenance	25.0	28.1	28.5	19.4	22.4	21.4	21.3
59–70	Drawdown	6.4	9.8	8.7	5.9	9.1	7.7	10.3
≥71	No application	10.7	25.9	20.7	11.1	30.7	15.4	39.2
>181	Possible change point	0.3	1.7	1.3	0.9	6.5	1.8	10.6
CEE			73,785	114,116		1,395,186		6,748,390

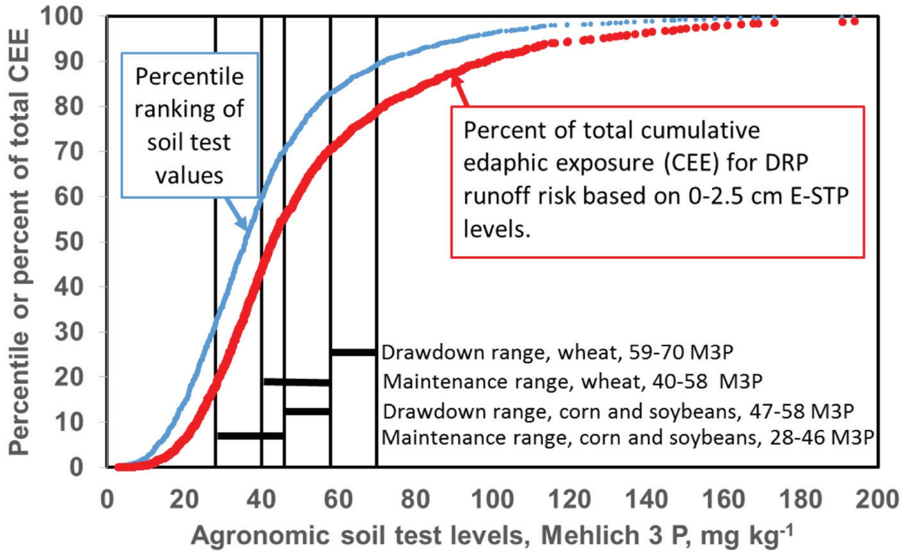

Fig. 4. Percentile distribution of agronomic soil-test phosphorus values (A-STP) in relation to agronomic soil-test levels and associated agronomic soil-test ranges (vertical lines) for the stratified sampling dataset (*n* = 1763 fields) and percent of total cumulative edaphic exposure for dissolved reactive phosphorus (DRP) runoff risk based on environmental soil-test phosphorus (E-STP, 0–2.5 cm), also in relation to A-STP values.

area. Because connectivity would be high for most WLEB fields, it would account for little variation in risk for P loss.

Most soils in the WLEB are in hydrological soil groups C and D (somewhat poorly drained or very poorly drained) and thus are in a relatively high runoff class. Williams et al. (2015) observed that, in contrast with other areas of Ohio, runoff class accounted for little variability in P runoff risk in the WLEB. These transport characteristics are reflected in the high flashiness of WLEB streams (Baker et al., 2004). High flashiness, or "event responsiveness," has historically been linked to high nutrient export rates for tributaries to the Great Lakes (Richards, 1990). Kleinman et al. (2011b) have noted the "overwhelming role of hydrology on P transfers." Within the WLEB, the dominance of soils in high-runoff classes, coupled with stratification of soils with otherwise modest STP levels, results in high DRP-loading rates. Because of the uniformity in transport factors in WLEB, STP levels account for much of the variability in risk for DRP losses and hence are very important for site assessment relative to DRP loss.

DRP Runoff Risks in Relation to Agronomic Soil-Test Ranges

For developing programs to reduce edaphic DRP loading to the WLEB, it is useful to know the relative importance of the many fields with maintenance-range A-STP levels to the fewer fields with high A-STP levels. That is, can DRP losses from fields be sufficiently reduced by targeting BMPs to fields with high A-STP levels? By assuming that the relationship between DRP concentrations in runoff water and E-STP is linear (Pote et al., 1996; Vadas et al., 2005a; Wang et al., 2010) and that each mg kg^{-1} unit of E-STP represents one unit of relative risk, the distribution of risks within a set of fields can be estimated using cumulative risk calculations. To examine this we (i) ranked the fields from lowest to highest A-STP values, as used to determine percentile rankings; (ii) calculated the cumulative sum of E-STP values through each field of the ranked A-STP values; and (iii) expressed these E-STP cumulative soil-test sums for each field as a percentage of the cumulative E-STP value for the field with the highest A-STP value (Fig. 4, Table 2). The cumulative value through the field with the highest A-STP value in that set of fields represents the cumulative edaphic exposure (CEE) for risk of DRP runoff from that set of fields. Although field size at a given STP value would also influence the distribution of relative risks, there was no relationship between field size and either A-STP or E-STP values in the stratified sampling program (Supplemental Fig. S2). Consequently, field size was not included in the cumulative risk calculations. Where E-STP data are not available, CEEs can be estimated from cumulative A-STP values.

For fields in the stratified testing programs, the CEE based on E-STP values (114,116) was 55% higher than the CEE calculated from A-STP values (73,785) (Table 2), as expected from the ratio of their average values. Note also that the distribution of risks shifts toward fields in lower A-STP ranges when the CEE is based on E-STP values rather than A-STP values. Thus, based on A-STP values for corn and soybeans, fields in the maintenance and no-further-application ranges accounted for almost equal portions of the CEE (35.3 and 35.8%, respectively). Based on E-STP values, 39.3% of the CEE was associated with maintenance-range fields, and 29.4% of the CEE was from fields in the no-application range. This shift occurred because the stratification increments were higher in maintenance- range fields than in no-further-application fields (Fig. 3B), leading to a greater runoff risk from maintenance-range fields. Comparison of the distribution of DRP runoff risks for the stratified testing program, the Sandusky Watershed, and the WLEB, as calculated from cumulative A-STP data, indicates that fields with A-STP < 71 mg kg^{-1}—the no further application level for wheat—accounted for 74, 69, and 61% of their CEEs, respectively (Table 2), while fields with A-STP values $\geq$ 71 mg kg^{-1} accounted for 26, 31, and 39% of their respective CEEs. If E-STP data were available for the Sandusky Watershed and WLEB, the proportions of CEEs associated with fields with A-STP $\geq$ 71 mg kg^{-1} would likely decrease, while those in the maintenance range would increase, as illustrated in the stratification study.

As noted above, these calculations assume a constant linear relationship between STP values and DRP runoff concentrations over the full range of STP concentrations. Some studies have found a change point in this relationship wherein STP concentrations increase more rapidly with increasing STP values above a breakpoint than below. For example, McDowell and Sharpley (2001) and Dayton et al. (2014) have suggested breakpoints at M3P STP values of 185 and 181 mg kg^{-1}, respectively. In the stratified testing program, 0.3% of the fields had A-STP values > 181 mg kg^{-1}, compared with 0.9% the Sandusky and

1.8% in the WLEB. Although fields with unusually high A-STP values do make proportionally larger contributions to the total CEE for a set of fields, their small numbers restrict their importance in contributing to the total CEE risk for DRP runoff.

This analysis indicates that the cumulative risks for edaphic DRP losses from the many fields in the buildup, maintenance, and drawdown agronomic ranges exceed the cumulative risks from the fields in the no-further-application range. The 40% reduction target for DRP (Annex 4, 2015) will require load reductions from fields across a broad spectrum of A-STP ranges, including those in the maintenance range.

Evaluating Edaphic DRP Reduction Scenarios Using CEEs

For a given set of fields, edaphic losses of DRP are proportional to the CEE for their E-STP values. The effectiveness of various BMP reduction scenarios for a set of fields can be evaluated by calculating their impact on CEEs, as illustrated in Table 3. Drawdown or zero-application rates can gradually lower the A-STP levels; however, their impact on lowering stratification increments is uncertain. There was no significant relationship between stratification increments and A-STP values above 28 mg kg^{-1} (Fig. 3B). Assuming that stratification increments are unchanged by drawdown or zero-application rate, then the decrease in CEE can be calculated using the targeted A-STP levels. For example, if drawdown efforts were targeted to reduce fields with A-STP levels $\geq$ 71 mg kg^{-1} down to A-STP levels of 71 mg kg^{-1}, the CEE drops from a current value of 114,116 to 108,332, or by 5.1%. Even if approaches were applied to draw down all fields with A-STP levels > 40 mg kg^{-1} to A-STP levels of 40 mg kg^{-1}, the critical level for wheat production, the reduction relative to current CEE would be only 15.3% (Table 3).

A second potential way to reduce risks for DRP runoff by lowering CEE would be to reduce P stratification. As noted by Sharpley (2003) and by Kleinman et al. (2015), that could be accomplished by a one-time inversion tillage to thoroughly mix the soil in the plow layer. Upon mixing, the E-STP levels would be reduced to the existing A-STP level, so stratification increments would be reduced to zero. If the 28.7% of fields with stratification increments > 30 mg kg^{-1} were treated, the resulting CEE would be 91,467 and the runoff risk relative to current conditions (CEE = 114,116) would be lowered by 19.8% (Table 3). Treating the 28.7% of fields with the highest A-STP levels, rather than highest stratification increments, would lower the CEE to 101,846 or by only 10.8%. If all fields with increments > 20 mg kg^{-1} were treated (51.3% of the fields), the CEE level would be reduced by 28.5%, while treating the 51.3% of the fields with the highest A-STP levels would reduce CEE by 20.4%. If stratification increments were reduced to zero for all fields, CEE would equal the current CEE for A-STP, amounting to a reduction of 35.3%. In general, reducing stratification has the potential for much larger reductions in CEE than applying drawdown approaches. Furthermore, reducing CEE by mixing the soil is much more efficient when based on E-STP measurements and stratification increments than arbitrarily using A-STP as a surrogate for E-STP.

Since the reservoir of P in the soil is large relative to annual crop removal, drawdown approaches to lower CEE will be gradual and take many years to reach targets (Kleinman et al., 2011a; Muenich et al., 2016). In contrast, stratification reduction by periodic inversion tillage would have immediate effects where applied. Advocates of using periodic moldboard plowing to reduce stratification generally suggest that such procedures be followed by BMPs to reduce erosion, such as no-till and winter cover crops, as well as by fertilizer injection or deep banding to minimize subsequent stratification. In the WLEB, inversion tillage would likely occur prior to corn planting and, as such, would replace a year of relatively aggressive vertical tillage. Consequently, any increases in watershed-scale erosion and related PP transport should be modest. Because of the low chemical bioavailability of PP and its tendency to settle out of the water column prior to release of orthophosphate, the benefits in DRP reduction would greatly exceed adverse eutrophication impacts from small increases in PP loading. Where fertilizers are being applied at either maintenance or drawdown rates, subsurface applications have a double benefit of reducing stratification and immediately preventing conditions for acute DRP runoff events. Research programs should be mounted to compare drawdown approaches and stratification reduction approaches in terms of their practicality and effectiveness in reducing edaphic losses of DRP.

Table 3. Comparison in the reductions in risks of edaphic dissolved reactive phosphorus (DRP) runoff for fields in the stratified sampling program, based on lowering cumulative edaphic exposures (CEEs) by either drawdown best management practices (BMPs) or by selective stratification removal by inversion tillage and soil mixing.

BMP scenario†	Total CEE	Reduction in CEE relative to current E-STP	Fields with BMP applied
		%	
Current conditions			
Current E-STP conditions (0–2.5 cm)	114,116	–	–
Current A-STP conditions (0—20 cm)	73,785	–	–
Drawdown approaches with no change in stratification increments			
Reduce all A-STP > 71 to 71 mg kg^{-1}	108,322	5.1	10.4
Reduce all A-STP > 58 to 58 mg kg^{-1}	105,854	7.8	17.1
Reduce all A-STP > 46 to 46 mg kg^{-1}	100,333	12.1	29.9
Reduce all A-STP > 40 to 40 mg kg^{-1}	96,651	15.3	40.5
Remove stratification such that E-STP = A-STP with no change in A-STP			
Treat all fields with stratification increments $\geq$ 30 mg kg^{-1}	91,467	19.8	28.7
Treat 28.7% of fields with highest A-STP	101,846	10.8	28.7
Treat all fields with stratification increments $\geq$ 20 mg kg^{-1}	81,608	28.5	51.3
Treat 51.3% of fields with highest A-STP	90,874	20.4	51.3

† E-STP, environmental soil-test phosphorus; A-STP, agronomic soil-test phosphorus.

The A-STP datasets do contain a small number of samples with extremely high STP values (>1000 mg kg^{-1}). These samples need to be evaluated on a case-by-case basis to determine whether they represent a composite sample from a whole field or a single sample from a gridded field. Where whole fields have exceptionally high A-STP values, edge-of-field treatment systems, such as wetlands or nutrient removal systems at tile outlets, may be necessary to reduce DRP export (Smith et al., 2015b).

Conclusions

- Stratification in the study area significantly increased the risk of edaphic DRP runoff. The STP values in the upper 2.5 cm of soil averaged 55% higher than in 0- to 20-cm cores.
- Stratification increments were highly variable and had a low correlation with agronomic soil-test levels. Consequently, site assessment for managing edaphic DRP losses will benefit greatly from systematic stratified sampling.
- The cumulative risk for DRP runoff was greater from the large number of fields in the maintenance agronomic range than from the fewer fields in the no-further-application range.
- Drawdown fertilizer application rates where agronomic STP levels exceed maintenance ranges have limited potential to reduce risks for edaphic DRP losses, and reductions will be slow to develop.
- For fields with large amounts of stratification, a one-time soil inversion and mixing has the potential for larger reductions in risk for edaphic DRP losses, and reductions will occur immediately on implementation.
- Shifting from broadcast to subsurface placement of P fertilizer will minimize stratification and immediately reduce risks for acute DRP runoff.
- Achieving a 40% reduction in DRP loading will require adoption of BMPs in fields across the full range of agronomic soil-test levels, as well as addressing both edaphic and acute risks for DRP runoff.

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