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EVALUATION OF PHOSPHORUS INDICES: TWENTY YEARS OF SCIENCE AND DEVELOPMENT

Phosphorus Indices: Why We Need to Take Stock of How We Are Doing

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Many states have invested significant resources to identify components of their Phosphorus (P) Index that reliably estimate the relative risk of P loss and incentivize conservation management. However, differences in management recommendations and manure application guidelines for similar field conditions among state P Indices, coupled with minimal reductions in the extent of P-impaired surface waters and soil test P (STP) levels, led the U.S. Natural Resources Conservation Service (NRCS) to revise the 590 Nutrient Management Standard. In preparation for this revision, NRCS requested that a review of the scientific underpinnings and accuracy of current P Indices be undertaken. They also sought to standardize the interpretation and management implications of P Indices, including establishment of ratings above which P applications should be curtailed. Although some states have initiated STP thresholds above which no application of P is allowed, STP alone cannot define a site's risk of P loss. Phosphorus Indices are intended to account for all of the major factors leading to P loss. A rigorous evaluation of P Indices is needed to determine if they are directionally and magnitudinally correct. Although use of observed P loss data under various management scenarios is ideal, such data are spatially and temporally limited. Alternatively, the use of a locally validated water quality model that has been shown to provide accurate estimates of P loss may be the most expedient option to conduct Index assessments in the short time required by the newly revised 590 Standard.

A Phosphorus (P) Index is an applied assessment tool used to identify agricultural fields most vulnerable to P loss by accounting for the major source and transport factors controlling P movement (Lemunyon and Gilbert, 1993; Sharpley et al., 2003). Lemunyon and Gilbert (1993) proposed the P Index as a voluntary educational tool to help farmers identify fields with a high probability of P loss in runoff. In the two decades since its introduction, the P Indexing concept has evolved and expanded, and there are now P Indices that serve as best management practice selection and targeting tools, manure application scheduling tools, manure application rate calculators, and regulatory tools in some states (DeLaune et al., 2007; Sharpley et al., 2009).

The P Index has been integrated into the Natural Resources Conservation Service (NRCS) 590 Nutrient Management Standard since 1999 (U.S. Department of Agriculture-Natural Resources Conservation Service, 2011a). Also, the 2003 revision of EPA regulations for concentrated animal feeding operations (U.S. Environmental Protection Agency, 2003) recommends the P Index as a field-specific P loss assessment tool on permitted concentrated animal feeding operations. Currently, 48 U.S. states have adopted a P Index as a site assessment tool to identify critical source areas and to target practices to reduce P loss. In most of these states, the P Index is required by the NRCS 590 Nutrient Management Standard and other state and federal programs (Sharpley et al., 2003). In addition, versions of a P Index have been proposed for several Canadian provinces (Salvano et al., 2009; van Bochove et al., 2006) and European countries (Bechmann et al., 2005; Buczko and Kuchenbuch, 2007; Heckrath et al., 2008).

Despite the apparent success of the P Index concept, there remain concerns about the effectiveness of the Indexing approach for attaining water quality goals. Different versions of the P

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Abbreviations: DPS, degree of phosphorus saturation; NRCS, Natural Resources Conservation Service; RUSLE2, Revised Universal Soil Loss Equation Version 2; SERA-17, Southern Extension-Research Activity Group 17; STP, soil test phosphorus.

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Index have emerged to account for regional differences in soil types, land management, climate, physiographic and hydrologic controls, manure management strategies, and policy conditions. Differences in P Index manure management recommendations under relatively similar site conditions have also emerged. For instance, a survey of P Indices from 12 southern U.S. states by Osmond et al. (2006) revealed a large diversity in P Index ratings and P application guidelines for similar conditions. Under the conditions tested, some P Indices did not reach a risk level restricting manure application, whereas others did (Osmond et al., 2006). Thus, one of the goals of revising the P-risk assessment component of the 590 Standard was to develop a strategy to define the conditions where the risk of P loss is so great that no P should be applied in any form (U.S. Department of Agriculture-Natural Resources Conservation Service, 2011a).

There is growing concern that existing P management guidelines are not bringing about as great a reduction in soil P levels and P loss from agricultural lands as expected or desired. For instance, recent reports related to mitigation effectiveness in the Chesapeake Bay fueled concern that site risk assessment using the P-Indexing approach was inadequate (Kovzelove et al., 2010; U.S. Environmental Protection Agency, 2010b). The lack of soil and water quality response may, in part, reflect legacy effects of past management and a slow ecosystem response to changes in state-, watershed-, and farm-level nutrient imbalances. Nevertheless, there is a need to reassess approaches to determine and guide P management as a component of the 590 Nutrient Management Standard and to address problems related to nutrient imbalance.

In 2009, as part of their effort to revise the 590 Nutrient Management Standard, NRCS requested that a Working Group of scientists within the Southern Extension-Research Activity Group 17 (SERA-17) review the current 590 Standard and make recommendations on how to address the concerns outlined above (Sharpley et al., 2011). Specifically, the group (i) assessed the evolving role of P Indices in risk assessment, (ii) established the role of soil test P (STP) in P-based nutrient management and P loss risk assessment, (iii) defined a process to evaluate P Indices, and (iv) recommended long-term goals for the development of the next generation of P Indices. This paper documents the major findings and recommendations of the SERA-17 working group in response to the NRCS request.

The Current Role of Phosphorus Indices in Risk Assessment and Resource Conservation

Three Approaches to Phosphorus Loss Assessment

The P Index is one of three P loss assessment strategies recommended by the NRCS 590 Nutrient Management Standard (U.S. Department of Agriculture-Natural Resources Conservation Service, 2011a). The two alternatives to the P Index were the "agronomic" approach, which limits P applications to rates recommended by soil test–based fertilizer recommendations, and the "P threshold" approach, which identifies a STP level where risk of P loss to water resources increases beyond desired levels.

Historically, soil testing has been the primary tool for managing P application to agricultural fields. Like the P Index, agronomic soil testing and interpretation for P developed primarily at the state level led to a diversity of approaches and interpretations guiding fertilizer recommendations for P. For example, a survey of P recommendations in 24 states identified six different extracts used to measure STP and recommended depths of soil sampling ranging from 7.5 to 20 cm (Table 1). Most states recommend no application of additional P for agronomic purposes if STP is above a certain level (Table 1). The exceptions to this among the 24 states surveyed were P recommendations for potatoes in Colorado and Wisconsin. Differences among states for the STP level where no P is recommended are apparent despite the difficulty of comparing STP obtained by different extracts. These thresholds serve as P application limits when the agronomic approach is used for P loss assessment. Consequently, agronomic limits on P application "zero out" manure applications when used as a P loss management strategy and facilitate maintaining field P at or below the state-identified STP level for which no additional P is recommended.

Phosphorus thresholds have been implemented in a number of ways. Some states use STP as a stand-alone tool and establish an upper limit to P application, irrespective of other P loss factors. Examples of STP thresholds include 100 mg kg^{-1} Olsen STP or 150 mg kg^{-1} Bray-1 STP in South Dakota (U.S. Department of Agriculture–Natural Resources Conservation Service–South Dakota, 2007); 150 mg kg^{-1} Mehlich-3 STP in nutrient impaired watersheds in Oklahoma (Zhang et al., 2005); 150 mg kg^{-1} Bray-1 STP in Michigan (U.S. Department of Agriculture–Natural Resources Conservation Service–Michigan, 2005); 200 mg kg^{-1} Bray-1 or Mehlich-3 STP in Indiana (U.S. Department of Agriculture–Natural Resources Conservation Service–Indiana, 2001); a court-mandated Mehlich-3 STP threshold of 300 mg kg^{-1} used in the Eucha-Spavinaw Watershed, Northwest Arkansas (DeLaune et al., 2007); and 533 mg kg^{-1} Mehlich-3 STP in Kentucky (U.S. Department of Agriculture–Natural Resources Conservation Service–Kentucky, 2001).

Phosphorus thresholds can also be used as a screening tool to identify fields where the more time- and data-intensive P Index approach must be used. Examples include a limit of 200 mg kg^{-1} Mehlich-3 P in Pennsylvania above which the P Index must be used (Weld et al., 2007) and limits of 200 mg kg^{-1} Mehlich-3 P in East Texas and 350 mg kg^{-1} Mehlich-3 P in West Texas above which the P Index must be used (U.S. Department of Agriculture–Natural Resources Conservation Service–Texas, 2007). Virginia has two STP thresholds: a lower limit above which the P Index must be used and an upper limit above which no P applications are permitted (Wolfe et al., 2005). Generally, STP thresholds are well above recommended levels reported for agronomic purposes (Table 1). States that use STP thresholds as upper limits for manure application that supersede any P Index–assigned risk have a clearly defined point where manure applications zero out, which is compliant with the newly revised 590 Standard (U.S. Department of Agriculture-Natural Resources Conservation Service, 2011a).

Current P Indices are generally less restrictive than agronomic limits on P application. Reviewing current P loss assessment strategies from 24 states shows that P Indices in seven of these states may in fact restrict P application to fields when STP values are below the agronomic threshold where P is recommended for optimum agronomic production (Table 1). In six of these seven

states, it is possible for P Indices to recommend no application of P in any form on some fields with a STP below agronomic optimum where transport factors combine to increase the risk of P loss in runoff. In most cases, this would occur under specific and limited conditions (e.g., organic soils, high transport potential, proximity to a stream, and specialty crops [such as potatoes in New York]) and when P application rate is high.

Phosphorus Indices and Resource Conservation

The SERA-17 Working Group believes that P applications in excess of agronomic recommendations should be evaluated by a P Index. However, states vary on the need to run the P Index to assess applications recommended by agronomic soil tests (Table 1). Most of these states do not require a P Index assessment when P applications are based on land-grant university agronomic nutrient recommendations. A justification for this approach is that the risk of P loss may frequently be too low to justify the expense and logistics of having to conduct a P Index assessment. In some states, a fairness issue is cited, stating that agronomic applications of manure should not be limited by requirements stricter than equivalent commercial fertilizer applications. On the other hand, limiting manure P applications to recommended agronomic rates does not guarantee a low risk of P loss from a field (see discussion in the next section).

Even in situations where a P application is recommended, it may be valuable to perform a P Index assessment as an

Table 1. Soil test phosphorus level at which land-grant universities recommend no additional phosphorus be applied.

State	Method	Soil sampling depth	Agronomic soil test P threshold	Can P Index limit applied P below recommendations for soils with an agronomic need for P?	Reference
		cm	mg kg^{-1}		
AK	Mehlich-3	plow depth to a maximum of 15 cm	15–66; starter P typically recommended	yes	U.S. Department of Agriculture–Natural Resources Conservation Service–Alaska, 2008
AR	Mehlich-3	10 (pastures) or 15 (row crops)	36–50	no	Espinosa et al., 2006; Moore et al., 2010; Sharpley et al., 2010
CO	Olsen	plow depth or 10 inches	15–22; P always recommended for potatoes	no	Davis et al., 2009
DE	Mehlich-3	10 pastures; 20 row crops	100†	no	Sims and Leytem, 2002; Sims et al., 2002
GA	Mehlich-1	10 (pastures); 15 row crops (vegetables)	14–70	yes	Cabrera et al., 2002; Kissel and Sonon, 2008
IN	Bray 1	20	40–50	no	Vitosh et al., 1996
KS	Bray 1	15	20–30	no	Leikam et al., 2003
KY	Mehlich 3	7.5–10 (cons till);‡ 15–17.5 (conv till)	30–40	no	Murdock and Schwab, 2010
MI	Bray 1	20	40–50	no	Vitosh et al., 1996
MD	Mehlich-3	20	50	yes	Coale, 2005; McGrath, 2010
ME	Morgan	15	20	no	Hoskins, 1997
MO	Bray 1	15	35	no	Lory et al., 2007
MS	Lancaster	10–15 pastures; 15 crops	36	no	Oldham and Crouse, 2008
NC	Mehlich 3	10 (cons till) or 20 (conv till)	60	yes	Hardy et al., 2009; Johnson et al., 2005
NY	Morgan	15– 20	20	yes	Czymmek et al., 2003; Ketterings et al., 2003
OH	Bray 1	20	40–50	no	Vitosh et al., 1996
OK	Mehlich 3	15	41¶	no	Zhang and Raun, 2006
PA	Mehlich 3	20	50	yes	Agricultural Analytical Services Laboratory, 2010; Weld et al., 2007
SC	Mehlich 1	15 (crops); 7.5 (pasture)	27.5–40	no	U.S. Department of Agriculture–Natural Resources Conservation Service–South Carolina, 2004
TN	Mehlich 1	15	>15	no	Savoy and Joines, 2009
TX	Mehlich 3	15	50	no	Provin, 2010
UT	Olsen P	30	15§	no	Cardon et al., 2008
VA	Mehlich 1	10 no-till; 15–20 conv till	55	no	Maguire and Heckendorn, 2011
WI	Bray 1	15–20	17–80;†† P always recommended for potatoes	yes‡‡	Laboski et al., 2006

† Optimum range for M3-P in Delaware is 50–100 mg kg^{-1} by Mehlich 3 P. In almost all cases, only starter P is recommended when Mehlich-3 soil P values are >50 mg kg^{-1}.

‡ Cons till, conservation tillage; conv till, conventional tillage.

¶ Recommendation is that the sample be confined to the upper 30 cm. Most will focus on extracting from 15 to 25 cm deep.

§ Value is 32.5 mg kg^{-1} if P is measured colorimetrically.

†† Value within range depends on crop and soil type.

‡‡ For manure only.

educational tool so farmers can better understand the impact of their management on P loss potential. This may result in improved management even if P applications are not limited at these agronomically responsive STP levels. We recommend that such issues are best decided at a state level where the environmental protection goals and available P Index resources are best understood.

Systemic regional P imbalances exist in portions of the United States where concentrated animal production has led to inputs of P in feed, bedding, and fertilizer in excess of outputs in crops and animals (Kellogg et al., 2000; Maguire et al., 2009; Sharpley et al., 2007). Because P is a finite natural resource that needs to be conserved (Cordell et al., 2010; Steen, 1998; Syers et al., 2011), such imbalances are not consistent with long-term resource sustainability. Thus, consideration needs to be given to achieving on-farm and regional P balance, with the long-term goal of applying P to meet agronomic requirements. However, the P Index, as a field-based loss assessment tool, cannot address P balance issues at these larger scales. A P Index should limit P applications on individual fields at some point, although this point varies greatly among states because the current P Index cutoff values (i.e., the P Index value where no additional P is recommended) are not consistent across states.

Are Soil Test Phosphorus Thresholds a Suitable Alternative to a Phosphorus Index for Protecting Water Quality?

Environmental soil P thresholds are similar to agronomic limits in that they evaluate the potential for P loss in runoff based on a single parameter, STP. The assumption of this method is that there is a STP break point, different from the agronomic limit for crop response, where higher STP leads to a greater potential for P loss in runoff (Feagley and Lory, 2008; Wang et al., 2012). One of the main justifications for using a STP threshold approach is its simplicity, using soil test information farmers frequently have for many fields. This combined ease of implementation and interpretation make it attractive to policymakers seeking to limit manure applications due to water quality concerns.

Another approach to determining environmental soil P thresholds was recently proposed in the Chesapeake Bay Watershed (Kovzelove et al., 2010; U.S. Environmental Protection Agency, 2010a) based on the degree of P sorption saturation of the soil (DPS). This DPS approach is based on the premise that the saturation of P sorbing sites for a soil determine P release (intensity factor) as well as the level of soil P (capacity factor) (Breeuwsma and Silva, 1992; Kleinman and Sharpley, 2002). For example, soils of similar STP but different texture may differ in P release to runoff because P may be bound more tightly to clay than to sandy soils (Sharpley and Tunney, 2000). Phosphorus sorption saturation also represents the capacity of a soil to sequester added P and thereby reduce its potential to enrich runoff P (Lookman et al., 1996; Schoumans et al., 1987). The addition of P to a soil with a high DPS enriches runoff P more than if P was added to a soil with a low P sorption saturation, independent of STP (Leinweber et al., 1997; Sharpley, 1995). The estimate of DPS is commonly derived from Mehlich or oxalate-extractable Al, Fe, and P. These extraction methods are only appropriate on noncalcareous soils where soil P reactions are dominated by Al and Fe compounds. Thus, the potential applicability of a DPS approach across the United States would exclude calcareous or Ca-reaction–dominated soils.

The highly significant, positive correlation between STP or DPS and runoff dissolved P concentration is well established (Vadas et al., 2005) and is frequently used to justify the use of thresholds to limit P application. However, a wealth of scientific evidence is available documenting that, in addition to STP and DPS, P application rate, timing, and method; erosion; runoff; and drainage influence field P loss. The use of STP or DPS alone does not accurately portray a site's risk for P loss because it does not capture the P transport potential of a field. If STP is the only assessment used, P runoff and/or leaching losses might be allowed to continue on sites with high P transport potentials, and conversely P application may be restricted, although the risk of P loss is low (Fig. 1). The data in Fig. 1 are from the FD-36

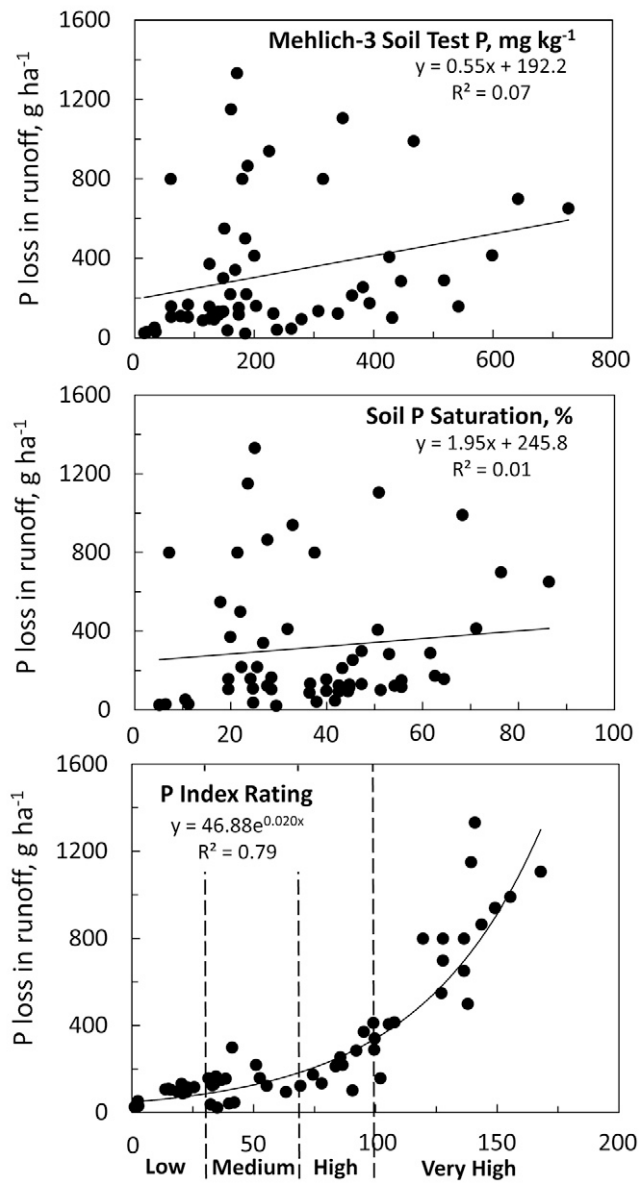

Fig. 1. Relationship between the loss of total P in runoff and Mehlich-3 soil test P, soil P saturation, and the Pennsylvania P Index ratings for the plots in the FD-36 watershed, Pennsylvania (adapted from Sharpley et al., 2001).

watershed in south-central Pennsylvania (adapted from that presented in Sharpley et al. [2001]). Runoff was collected from 2-m^2 plots subject to 70 mm h^{-1} of rainfall (to create 30 min of runoff) across the watershed and related to plot Mehlich-3 STP and soil P saturation of 0- to 5-cm samples collected after rainfall as well as P Index ratings determined by the Pennsylvania P Index (Sharpley et al., 2001). Of the three methods, the P Index rating best represented the actual loss of P in runoff over the various soil, management, hydrologic, and topographic conditions across the watershed (Fig. 1).

An important lesson from the above analysis is that there were sites with "low" STP and soil P saturation that had high losses of P due to a combination of factors that include high runoff volumes and/or application of fertilizer or manure. These "low" P sites are above the agronomic response range (i.e., >50 mg P kg^{-1} as Mehlich-3 soil P). On the other hand, there were sites with low P loss but with high STP or soil P saturation values (Fig. 1). A similar lack of a strong relationship between STP (as Mehlich-1 soil P) and runoff P loss was demonstrated by Butler et al. (2010) for runoff from nine fields in Georgia that had received varying amounts and forms of P.

Consideration of site hydrology is critical for determining P loss (Gburek and Sharpley, 1998). For instance, Buda et al. (2009) monitored contour-cropped fields on a Pennsylvania hillslope where the bottom field possessed the lowest relative STP (roughly twofold lower than the other fields). Although this bottom field was the only one that did not receive P amendments during the study period, it yielded runoff volumes roughly 50-fold greater than the other fields included in the study. Annual loads of P from this hydrologically active field were >8 kg ha^{-1}, in comparison to 1 kg ha^{-1} or less from the other fields. This study highlights the ability of site hydrology to overwhelm source factors in determining P loss. More importantly, it points to the ability of hydrology to convert a modest source of P into a major P load. Research supports the view that STP thresholds are poorly correlated with P loads from agricultural fields, and strategies based on such limits typically will perform poorly compared with P Indices. Consequently, the use of a STP threshold rather than an effectively designed P Index cannot be justified to manage fields on a P loss and water quality perspective.

Evaluation of Phosphorus Indices

The previous sections established that P Indices are a superior tool, when compared with agronomic or threshold STP values when used alone, for identifying fields with a high potential for P loss. This recommendation is predicated on the assumption that state P indices effectively identify fields that have a high potential for P loss and have the associated rating system calibrated to limit P applications under conditions that will likely lead to degradation of water resources.

Although a P Index is used in the majority of states to assess risk of P loss from agricultural fields for manure P management planning, most state P Indices have not been rigorously evaluated to determine whether they are directionally and magnitudinally correct. This lack of P Index evaluation in many states is a result of a lack of resources, ability, or motivation to evaluate them. Ideally, a P Index should be evaluated against observed P loss data under various scenarios and measured at the point where runoff from a field reaches a field edge, stream, tile inlet, or other water source. Although some edge-of-field P loss data are available, only a handful of studies exist that have compared observed edge-of-field P loss data with P Index values or rankings over a sufficient range in time and management practices to reliably assess Indexed risk (DeLaune et al., 2004a, 2004b; Eghball and Gilley, 2001; Harmel et al., 2005; Sharpley et al., 2001; Sonmez et al., 2009; Good et al., 2012).

When observed P loss data are not available to calibrate and evaluate P indices, simulated P loss data generated from process-based models may be a suitable alternative, provided the models have been shown to provide accurate estimates of P loss for the region of interest (Sharpley et al., 2011). Although a P Index need not quantify P loss, its output should be directionally consistent with output from an appropriate process-based model that does quantify P loss. Veith et al. (2005) used this approach to evaluate the Pennsylvania P Index by comparing index values with average annual P loss values calculated with the SWAT model. They found good correlations between the P Index and output from SWAT and concluded that the Pennsylvania P Index provided a reliable assessment of P loss risk (Veith et al., 2005). Bolster (2011) compared output from the Kentucky P Index with simulated P loss data generated with the Annual P Loss Estimation model (Vadas et al., 2009) for several hypothetical fields. Bolster (2011) found that, although index values were generally correlated with simulated data, important limitations exist with the index, including how erosion is accounted for and how the different factors are weighted. If a P Index is deemed to perform inadequately, the same model output can be used to guide Index revisions, such as modifying how the Index is calculated, what factors are included, and how each factor is weighted (Bolster et al., 2012).

Each factor included in a P Index is weighted in such a way as to define that factor's relative contribution to P loss. Ideally, P Index weights should be obtained from measured P loss data combined with best management practices that can reduce P loss in a particular region. For many P indices, however, weights have been based on the professional judgment of the Index developers. Also, few studies have evaluated whether the relative magnitudes of the weights adequately describe the importance of each factor contributing to P loss and/or incentivize corrective management practices. Several studies that have specifically addressed index weightings have shown improved P Index performance when weights are based on scientific data. For instance, Eghball and Gilley (2001) improved the performance of the original P Index of Lemunyon and Gilbert (1993) by modifying several index weights.

Sonmez et al. (2009) slightly improved the correlation between the Kansas P Index and measured P loss data by modifying weights for erosion and STP, whereas DeLaune et al. (2004b) used regression analysis with runoff data to update weights on STP and water-extractable manure P for the Arkansas P Index. Bolster et al. (2012) found an improved correlation between the Pennsylvania P Index and the P loss data set of Vadas et al. (2009) after modifying the weights of the Pennsylvania P Index by fitting P loss data generated with the Annual P Loss Estimation model. These studies demonstrate that placing greater emphasis on science-based P Index weights will likely lead to meaningful improvements in index performance as a P loss estimator.

There is clearly an urgent need to assess state P Indices to document that each state P Index is magnitudinally and directionally correct, to bring more uniformity to recommendations among states, and to provide basic support for tool development. Such assessments are a critical first step to ensure that state P Indices are protecting water quality. Given the paucity of appropriate water quality data and the expense associated with obtaining sufficient data across the United States, it is inevitable that appropriately calibrated models will play a role in assessing and updating state P Indices.

Defining Long-Term Goals for the Next Generation of Phosphorus Indices

Physiographic Regionalization

Phosphorus Indices have become state specific due to the requirements of state regulations and state 590 standards. Differences in soils, climate, cropping systems, water body sensitivities, and dominant P loss pathways preclude the development and use of a single national P Index that addresses all of these differences. A more logical approach to overcoming interstate discrepancies would be the development of P Indices along physiographic regions rather than state boundaries.

In the Chesapeake Bay Watershed, for example, there are five distinctly different physiographic regions: Coastal Plain, Piedmont, Great Valley, Appalachian Mountains, and Appalachian Plateau (Fig. 2). Most of the states in this watershed contain three or more of these physiographic regions. It is difficult to develop a practical P loss assessment tool that will work equally well for all of these physiographic regions when P transport is dominated by different processes across the regions. Consequently, compromises are commonly made to address state-imposed regulatory approaches, which often results in less-than-ideal results for any specific physiographic region.

Thus, in the Chesapeake Bay Watershed, a better approach would be to have a P Index for each of the physiographic regions rather than one for each state (i.e., Delaware, Maryland, New York, Pennsylvania, Virginia, and West Virginia). These region-based P Indices would be specifically tailored to the soils, climate, animal industries, and management systems in these regions and provide more accurate results and more meaningful management interventions. The challenge will be to get acceptance among government programs and agencies of P Indices that cross state lines.

Need for More Efficient Site Data Acquisition

The NRCS 590 standard requires use of the Revised Universal Soil Loss Equation, Version 2 (RUSLE2) (Foster et al., 2003) to determine soil erosion when developing nutrient management plans. The standard approach to estimating edge-of-field soil loss with RUSLE2 involves selecting a single soil type in the field. If the field has more than one soil type, the field's "dominant critical area" is supposed to be used as a "surrogate" to determine soil loss for the entire field. The "dominant critical area" is usually the most erodible soil that constitutes at least 10% of the field's area and represents the soil type, slope, and length of slope on which conservation treatments are based for the entire field. The goal of conservation treatments is to reduce soil loss to the representative soil's "T" factor. However, the "dominant critical area" soil may not be the predominant soil in the field, and it may not be the soil that should be used in making nutrient recommendations or in assessing the risk of P loss from the field.

A "spatial" approach to estimating soil loss for a field with RUSLE2 involves estimating soil loss for all digitized soil survey polygons whose boundaries overlap with a field boundary. This would eliminate the need to select a single soil for a field to run RUSLE2 while allowing traditional nutrient management planning to be done on the basis of an individual soil polygon or the entire field. Also, instead of using a single distance to water for the field, a distance for each soil polygon could be estimated automatically. Geographical Information Systems could then be used to calculate the distance between any point on a soil polygon's application area boundary and any point on a surface water boundary.

Need to Recognize Uncertainty in Risk Assessment

The objective of any P Index is to guide field management to prevent P losses that would lead to water quality degradation. To achieve that objective, a P Index must reliably estimate the risk of P loss by accounting for the main drivers controlling P movement to surface water (or direct hydrological connection to surface water) at any given landscape position. It must be recognized, however, that a significant amount of uncertainty will be associated with the output from any P Index. Several sources contribute to this uncertainty, including errors in the P Index input variables such as STP, manure P application rates, erosion, and runoff, along with model error reflecting the fact that a P Index is an incomplete representation of the complex processes controlling P loss at the field scale.

These sources of error can produce a significant amount of scatter between P Index predictions and actual risk of P loss. For instance, Bolster et al. (2012) observed a mean absolute percent error exceeding 60% between output from a modified version of the Pennsylvania P Index and observed edge-of-field P loss using measured runoff and erosion as inputs into the P Index. When runoff and erosion are estimated from field-scale tools such as the NRCS curve number method and RUSLE2, respectively, the uncertainty associated with P loss risk assessment is even greater (Eghball and Gilley, 2001; Harmel et al., 2005). The inherent uncertainty associated with P Index values should be understood when making land management decisions based on P Index values. Recognition of this uncertainty is even more critical where Indices are used as management planning tools to meet predetermined P loss thresholds (U.S. Department of Agriculture–Natural Resources Conservation Service, 2011b). As an example, NRCS is proposing allowable P runoff losses to be <2.2 kg ha^{-1} (low), 2.2 to 5.6 kg ha^{-1} (moderate), and >5.5 kg ha^{-1} (high) (U.S. Department of Agriculture–Natural Resources Conservation Service, 2011b).

Conclusions

Many states have developed adequate tools to guide field-level P loss management by accounting for the main factors and conditions controlling P loss in their state. However, inconsistencies in the interpretation of P loss risk (ranking categories and associated management interventions) are evident among states. In fact, many of the currently publicized failings of the P Indexing approach derive from risk interpretation and associated management guidelines assigned by a P Index,

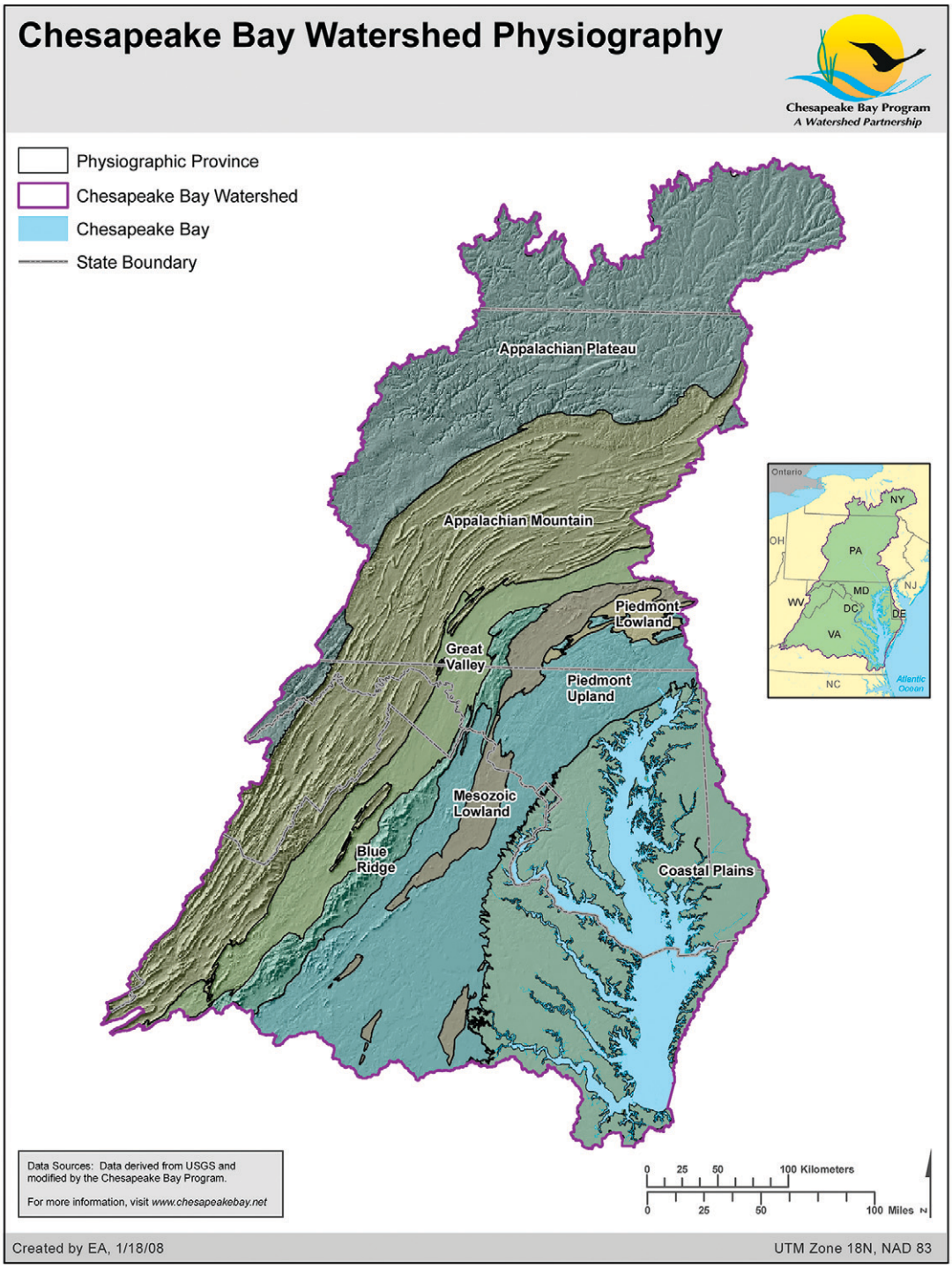

Fig. 2. Physiographic regions of the Chesapeake Bay Watershed (courtesy of the Chesapeake Bay Program Resource Library, http://www.chesapeakebay.net/maps.aspx?menuitem=16825).

which have typically been modified with local and regional political and stakeholder involvement. As a result, there needs to be a rigorous assessment of P Indices to document that the appropriate risk is being assigned using local water quality data or a locally calibrated water quality model that has been shown to provide accurate estimates of P loss.

There needs to be a concerted training effort on how to use P Indices in the context of nutrient management planning and how to address concerns identified by the P Index during the planning process. This training must include not only the direct users of the P Index (i.e., planners and farmers) but also the policymakers that use P Index–based nutrient plans to document proper resource management at the local, state, and national levels. Finally, P Indices and their role in P management will and should continue to evolve as we improve our ability to estimate the impact of P management at the field scale on water quality.

References

Agricultural Analytical Services Laboratory. 2010. Penn State soil fertility handbook. http://aasl.psu.edu/ (accessed 16 Sept. 2012).

Bechmann, M.E., T. Krogstad, and A.N. Sharpley. 2005. A phosphorus index for Norway. Acta Agriculturae Scandinavica, Section B: Plant. Soil Sci. 55(3):205–213.

Bolster, C.H. 2011. A critical evaluation of the Kentucky phosphorus index. J. Kentucky Acad. Sci. 72:46–58. doi:10.3101/1098-7096-72.1.46

Bolster, C.H., P.A. Vadas, A.N. Sharpley, and J.A. Lory. 2012. Using a P loss model to evaluate and improve P Indexes. J. Environ. Qual. (in press). doi:10.2135/jeq2011.0457

Breeuwsma, A., and S. Silva. 1992. Phosphorus fertilisation and environmental effects in the Netherlands and the Po region (Italy). Report 57. DLO The Winand Staring Centre, Wageningen, The Netherlands.

Buczko, U., and R.O. Kuchenbuch. 2007. Phosphorus indices as risk-assessment tools in the U.S.A. and Europe: A review. J. Plant Nutr. Soil Sci. 170:445–460. doi:10.1002/jpln.200725134

Buda, A.R., P.J.A. Kleinman, M.S. Srinivasan, R.B. Bryant, and G.W. Feyereisen. 2009. Effects of hydrology and field management on phosphorus transport in surface runoff. J. Environ. Qual. 38:2273–2284. doi:10.2134/jeq2008.0501

Butler, D.M., D.H. Franklin, M.L. Cabrera, L.M. Risse, D.E. Radcliffe, L.T. West, and J.W. Gaskin. 2010. Assessment of the Georgia Phosphorus Index on farm at the field scale for grassland management. J. Soil Water Conserv. 65:200–210. doi:10.2489/jswc.65.3.200

Cabrera, M.L., D.H. Franklin, G.H. Harris, V.H. Jones, H.A. Kuykendall, D.E. Radcliffe, L.M. Rise, and C.C. Truman. 2002. The Georgia phosphorus index. Cooperative Extension Service, Publications Distribution Center, University of Georgia, Athens, GA.

Cardon, G.E., J. Kotuby-Amacher, P. Hole, and R. Koenig. 2008. Understanding your soil test report. Utah State Cooperative Extension Service AG/Soils/2008–01pr. http://extension.usu.edu/files/publications/publication/AG_Soils_2008-01pr.pdf (accessed 16 Sept. 2012).

Coale, F.J. 2005. The Maryland phosphorus site index technical users guide. Soil Fertility Management Series, SFM-7. Maryland Cooperative Extension. http://www.anmp.umd.edu/files/SFM-7.pdf (accessed 16 Sept. 2012).

Cordell, D., J.O. Drangert, and S. White. 2010. The story of phosphorus: Global food security and food for thought. Glob. Environ. Change 19:292–305. doi:10.1016/j.gloenvcha.2008.10.009

Czymmek, K.J., Q.M. Ketterings, L.D. Geohring, and G.L. Albrecht. 2003. The New York Phosphorus Runoff Index. User's manual and documentation. CSS Extension Publ. E03–13. The Pennsylvania phosphorus index: Version 2. Pennsylvania State Univ., University Park.

Davis, J.G., R.D. Davidson, and S.Y.C. Essah. 2009. Fertilizing potatoes. Pub. 0.541. Colorado State Univ. Extension, Fort Collins, CO.

DeLaune, P.B., P.A. Moore, Jr., D.K. Carmen, A.N. Sharpley, B.E. Haggard, and T.C. Daniel. 2004a. Development of a phosphorus index for pastures fertilized with poultry litter- factors affecting phosphorus runoff. J. Environ. Qual. 33:2183–2191. doi:10.2134/jeq2004.2183

DeLaune, P.B., P.A. Moore, Jr., D.K. Carmen, A.N. Sharpley, B.E. Haggard, and T.C. Daniel. 2004b. Evaluation of the phosphorus source component in the phosphorus index for pastures. J. Environ. Qual. 33:2192–2200. doi:10.2134/jeq2004.2192

DeLaune, P.B., B.E. Haggard, T.C. Daniel, I. Chaubey, and M.J. Cochran. 2007. The Eucha/Spavinaw Phosphorus Index: A court mandated index for litter management. J. Soil Water Conserv. 61:96–105.

Eghball, B., and J.E. Gilley. 2001. Phosphorus risk assessment index evaluation using runoff measurements. J. Soil Water Conserv. 56:202–206.

Espinosa, L., N. Slaton, and M. Mozaffari. 2006. The soil test report. University of Arkansas Division of Agriculture, Cooperative Extension Service fact sheet FSA2153. http://www.uark.edu/depts/soiltest/NewSoilTest/pdf_files/FSA-2153.pdf (accessed 16 Sept. 2012).

Feagley, S.E., and J.A. Lory. 2008. Soil test phosphorus threshold levels. Southern Extension-Research Activity Group 17 Policy Workgroup Publication. http://www.sera17.ext.vt.edu/Documents/P_Soil_Threshold_Levels_2009.pdf (accessed 16 Sept. 2012).

Foster, G.R., D.G. Yoder, G.A. Weesies, D.K. McCool, K.C. McGregor, and R.L. Bingner. 2003. User's guide: Revised Universal Soil Loss Equation. Version 2. RUSLE2. U.S. Department of Agriculture-Agricultural Research Service, Washington, DC. http://fargo.nserl.purdue.edu/rusle2_dataweb/userguide/RUSLE2-2-3-03.pdf (accessed 16 Sept. 2012).

Gburek, W.J., and A.N. Sharpley. 1998. Hydrologic controls on phosphorus loss from upland agricultural watersheds. J. Environ. Qual. 27:267–277. doi:10.2134/jeq1998.00472425002700020005x

Good, L.W., P. Vadas. J.C. Panuska, C.A. Bonilla, and W.E. Jokela. 2012. Testing the Wisconsin P Index with year-round, field-scale runoff monitoring. J. Environ. Qual. (in press). doi:10.2135/jeq2012.0001

Hardy, D.H., M.R. Tucker, and C.E. Stokes. 2009. Crop fertilization based on soil test report. http://www.ncagr.gov/agronomi/pdffiles/obook.pdf (accessed 16 Sept. 2012).

Harmel, R.D., H.A. Torbert, P.B. DeLaune, B.E. Haggard, and R. Haney. 2005. Field evaluation of three phosphorus indices on new application sites in Texas. J. Soil Water Conserv. 60:29–42.

Heckrath, G., M. Bechmann, P. Ekholm, B. Ulén, F. Djodjic, and H.E. Andersen. 2008. Review of indexing tools for identifying high risk areas of phosphorus loss in Nordic countries. J. Hydrol. 349:68–87. doi:10.1016/j.jhydrol.2007.10.039

Hoskins, B.R. 1997. Soil testing handbook. Revised 2001. http://anlab.umesci.maine.edu/soillab_files/faq/handbook.pdf (accessed 16 Sept. 2012).

Johnson, A.M., D.L. Osmond, and S.H. Hodges. 2005. Predicted impacts of North Carolina's Phosphorus Loss Assessment Tool. J. Environ. Qual. 34:1801–1810. doi:10.2134/jeq2005.0020

Kellogg, R.L., C.H. Lander, D.C. Moffitt, and N. Gollehon. 2000. Manure nutrients relative to the capacity of cropland and pastureland to assimilate nutrients: Spatial and temporal trends for the United States. Resource Assessment and Strategic Planning Working Paper nps00–0579, USDA, Natural Resources Conservation Service and Economic Research Service, General Services Administration, National Forms and Publication Center, Fort Worth, TX. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_012133.pdf (accessed 16 Sept. 2012).

Ketterings, Q.M., K.J. Czymmek, and S.D. Klausner. 2003. Phosphorus guidelines for field Crops in New York. Second release. Department of Crop and Soil Sciences Extension Series E03–15, Cornell Univ., Ithaca, NY.

Kissel, D.E., and L.S. Sonon. 2008. Soil test handbook for Georgia. http://aesl.ces.uga.edu/publications/soil/STHandbook.pdf (accessed 16 Sept. 2012).

Kleinman, P.J.A., and A.N. Sharpley. 2002. Estimating soil phosphorus sorption saturation from Mehlich-3 data. Commun. Soil Sci. Plant Anal. 33:1825–1839. doi:10.1081/CSS-120004825

Kovzelove, C., T. Simpson, and R. Korcak. 2010. Quantification and implications of surplus phosphorus and manure in major animal production regions of Maryland, Pennsylvania, and Virginia. Water Stewardship, Annapolis, MD. http://waterstewardshipinc.org/downloads/P_PAPER_FINAL_2-9-10.pdf (accessed 16 Sept. 2012).

Laboski, C.A., J.B. Peters, and L.G. Bundy. 2006. Nutrient application guidelines for field, vegetable, and fruit crops in Wisconsin. UW-Extension paper A2809. Univ. of Wisconsin Extension, Madison.

Leikam, D.F., R.E. Lamond, and D.B. Mengel. 2003. Soil test interpretations and fertilizer recommendations. Pub. MF-2586. Kansas State Univ. Agricultural Experiment Station and Cooperative Extension Service, Manhattan.

Leinweber, P., F. Lunsmann, and K.U. Eckhardt. 1997. Phosphorus sorption capacities and saturation of soils in two regions with different livestock densities in northwest Germany. Soil Use Manage. 13:82–89. doi:10.1111/j.1475-2743.1997.tb00562.x

Lemunyon, J.L., and R.G. Gilbert. 1993. Concept and need for a phosphorus assessment tool. J. Prod. Agric. 6(4):483–486.

Lookman, R., K. Jansen, R. Merckx, and K. Vlassak. 1996. Relationship between soil properties and phosphate saturation parameters: A transect study in northern Belgium. Geoderma 69:265–274. doi:10.1016/0016-7061(95)00068-2

Lory, J.A., R. Miller, G. Davis, D. Steen, and B. Li. 2007. The Missouri Phosphorus Index. University of Missouri Extension Pub. G9184. Univ. of Missouri, Columbia, MO.

McGrath, J. 2010. Agronomic crop nutrient recommendations based on soil tests and yield goals. Soil Fertility Management Series, SFM-1.Maryland Cooperative Extension. http://www.anmp.umd.edu/files/SFM-1.pdf (accessed 16 Sept. 2012).

Maguire, R.O., and S.E. Heckendorn. 2011. Soil test recommendations for Virginia. Virginia Cooperative Extension, Blacksburg, VA. http://www.soiltest.vt.edu/PDF/recommendation-guidebook.pdf (accessed 16 Sept. 2012).

Maguire, R.O., G.H. Rubaek, B.E. Haggard, and B.H. Foy. 2009. Critical evaluation of the implementation of mitigation options for phosphorus from field to catchment scales. J. Environ. Qual. 38:1989–1997. doi:10.2134/jeq2007.0659

Moore, P.A., Jr., A.N. Sharpley, W. Delp, B. Haggard, T. Daniel, K. VanDevender, A. Baber, and M. Daniel. 2010. The Revised Arkansas Phosphorus Index. Arkansas Natural Resources Commission Title 20. http://www.anrc.arkansas.gov/Rules%20and%20Regulations/title_22.pd (accessed 16 Sept. 2012).

Murdock, L., and G. Schwab. 2010. 2010–2011 Line and nutrient recommendations. AGR-1.Cooperative Extension Service, College of Agriculture, University of Kentucky, Lexington, KY. http://www.ca.uky.edu/agc/pubs/agr/agr1/agr1.pdf (accessed 16 Sept. 2012).

Oldham, J.L., and K.K. Crouse. 2008. Soil test-based inorganic fertilizer nutrient recommendations for Mississippi agronomic crops. MSU Extension Service Soil Testing Laboratory. Mississippi State Univ., Starkville, MS.

Osmond, D., M. Cabrera, S. Feagley, G. Hardee, C. Mitchell, P. Moore, R. Mylavarapu, J. Oldham, J. Stevens, W. Thom, F. Walker, and H. Zhang. 2006. Comparing southern P indices. J. Soil Water Conserv. 61:325–337.

Provin, T. 2010. Soil, water and forage testing laboratory methods and recommendations. http://soiltesting.tamu.edu (accessed 16 Sept. 2012).

Salvano, E., D.N. Flaton, A.N. Rousseau, and R. Quilbe. 2009. Are current phosphorus risk indicators useful to predict the quality of surface waters in Southern Manitoba, Canada? J. Environ. Qual. 38:2096–2105. doi:10.2134/jeq2008.0159

Savoy, H.J., and D. Joines. 2009. Lime and fertilizer recommendations for the various crops of Tennessee. http://soilplantandpest.utk.edu/pdffiles/soiltestandfertrecom/chap2-agronomic_mar2009.pdf (accessed 16 Sept. 2012).

Schoumans, O.F., A. Breeuwsma, and W. de Vries. 1987. Use of soil survey information for assessing the phosphate sorption capacity of heavily manured soils. In: W. van Duijvenbooden and H.G. van Waegeningh, editors, Proceedings of the International Conference on the Vulnerability of Soil and Groundwater to Pollutants (VSGP), 30 Mar.–3 Apr. 1987, Noordwijkaan Zee, The Netherlands. p. 1079–1088.

Sharpley, A.N. 1995. Dependence of runoff phosphorus on extractable soil phosphorus. J. Environ. Qual. 24:920–926. doi:10.2134/jeq1995.00472425002400050020x

Sharpley, A.N., and H. Tunney. 2000. Phosphorus research strategies to meet agricultural and environmental challenges of the 21st century. J. Environ. Qual. 29:176–181. doi:10.2134/jeq2000.00472425002900010022x

Sharpley, A.N., S. Herron, and T.C. Daniel. 2007. Overcoming the challenges of phosphorus-based management in poultry farming. J. Soil Water Conserv. 62:375–389.

Sharpley, A.N., S. Herron, C. West, and T.C. Daniel. 2009. Outcomes of phosphorus-based nutrient management in the Eucha-Spavinaw watershed. In: A. Franzluebbers, editor, Farming with grass: Achieving sustainable mixed agricultural landscapes. Soil and Water Conservation Society, Ankeny, IA. p. 192–204.

Sharpley, A.N., R.W. McDowell, J.L. Weld, and P.J.A. Kleinman. 2001. Assessing site vulnerability to phosphorus loss in an agricultural watershed. J. Environ. Qual. 30:2026–2036. doi:10.2134/jeq2001.2026

Sharpley, A.N., J.L. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A. Moore, Jr., and G. Mullins. 2003. Development of phosphorus indices for nutrient management planning strategies in the United States. J. Soil Water Conserv. 58:137–151.

Sharpley, A.N., P.A. Moore, Jr., K. VanDevender, M. Daniels, W. Delp, B. Haggard, T. Daniel, and A. Baber. 2010. Arkansas Phosphorus Index. Fact Sheet FSA 9531. Cooperative Extension Service, Division of Agriculture, Univ. of Arkansas, Little Rock, AR. http://www.uaex.edu/Other_Areas/publications/PDF/FSA-9531.pdf (accessed 16 Sept. 2012).

Sharpley, A.N., D. Beegle, C. Bolster, L. Good, B. Joern, Q. Ketterings, J. Lory, R. Mikkelsen, D. Osmond, and P. Vadas. 2011. Revision of the 590 Nutrient Management Standard: SERA-17 Recommendations. Southern Cooperative Series Bulletin No. 412. SERA-IEG-17, Virginia Tech. University, Blacksburg, VA. http://www.sera17.ext.vt.edu/Documents/590Recommends2011.pdf (accessed 16 Sept. 2012).

Sims, J.T., and A.B. Leytem. 2002. The Phosphorus Site Index: A phosphorus management strategy for Delaware's agricultural soils. Nutrient Management Fact Sheet No. 5. Univ. of Delaware College of Agriculture and Natural Resources, Newark.

Sims, J.T., A.B. Leytem, and K.L. Gartley. 2002. Interpreting soil phosphorus tests. Nutrient Management Fact Sheet No. 4. Univ. of Delaware College of Agriculture and Natural Resources, Newark.

Sonmez, O., G.M. Pierzynski, L. Frees, B. Davis, D. Leikam, D.W. Sweeney, and K.A. Janssen. 2009. A field-based assessment tool for phosphorus losses in runoff in Kansas. J. Soil Water Conserv. 64:212–222. doi:10.2489/jswc.64.3.212

Steen, I. 1998. Phosphorus availability in the 21st Century: Management of a nonrenewable resource. Phosphorus Potassium 217:25–31.

Syers, K., M. Bekunda, D. Cordell, J. Corman, J. Johnston, A. Rosemarin, and I. Salcedo. 2011. Phosphorus and food production. In: UNEP Year Book 2011: Emerging Issues in Our Global Environment. United Nations Environment Programme, Nairobi, Kenya. http://www.unep.org/yearbook/2011 (accessed 16 Sept. 2012). p. 35–45.

U.S. Department of Agriculture–Natural Resources Conservation Service. 2011a. Conservation Practice Standard, Nutrient Management 590. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1046177.pdf (accessed 16 Sept. 2012).

U.S. Department of Agriculture–Natural Resources Conservation Service. 2011b. Title 190–National instruction (Title 190-NI, Amend., December 2011) 302-X.1, Part 302– Nutrient management policy implementation. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1046177.pdf (accessed 16 Sept. 2012).

U.S. Department of Agriculture–Natural Resources Conservation Service–Alaska. 2008. Technical note 16: Making fertilizer recommendations from soil test reports. USDA-NRCS, Washington, DC.

U.S. Department of Agriculture–Natural Resources Conservation Service–Indiana. 2001. The Conservation Practice Standard: Nutrient management–590. Indiana NRCS Field Office technical guide, July 2001. USDA-NRCS, Washington, DC.

U.S. Department of Agriculture–Natural Resources Conservation Service–Kentucky. 2001. Kentucky phosphorus (P) matrix. Conservation Practice Standard: Nutrient Management Code 590. USDA-NRCS, Washington, DC.

U.S. Department of Agriculture–Natural Resources Conservation Service–Michigan. 2005. The Conservation Practice Standard: Nutrient management–590. Technical guide section IV: State-wide nutrient management 590–9. USDA–NRCS, Washington, DC.

U.S. Department of Agriculture–Natural Resources Conservation Service–South Carolina. 2004. The Phosphorus Index: South Carolina. 210-AWMFH, SC Supplement, July, 2004. USDA-NRCS, Washington, DC.

U.S. Department of Agriculture–Natural Resources Conservation Service–South Dakota. 2007. The Conservation Practice Standard: Nutrient management– 590. SDTG Notice 264, Section IV, NRCS-December 2007. USDA-NRCS, Washington, DC.

U.S. Department of Agriculture–Natural Resources Conservation Service–Texas. 2007. The Conservation Practice Standard: Nutrient management–590. July 2007. USDA–NRCS, Washington, DC. http://www.tx.nrcs.usda.gov/programs/EQIP/docs/590_nutrient_management.pdf (accessed 16 Sept. 2012).

U.S. Environmental Protection Agency. 2003. Technical support document for the revisions to the National Pollutant Discharge Elimination System regulations for concentrated animal feeding operations. EPA-821-R-03–002. USEPA, Water Permits Division, Office of Wastewater Management, Washington, DC. http://www.epa.gov/npdes/pubs/cafo_tech_support.pdf (accessed 16 Sept. 2012).

U.S. Environmental Protection Agency. 2010a. Guidance for Federal land management in the Chesapeake Bay Watershed. Chapter 2: Agriculture. EPA841-R-10–002. USEPA, Nonpoint Source Pollution, Office of Wetlands, Oceans, and Watersheds, Washington, DC. http://www.epa.gov/nps/chesbay502/pdf/chesbay_chap02.pdf (accessed 16 Sept. 2012).

U.S. Environmental Protection Agency. 2010b. Review of empirical approaches for nutrient criteria development. USEPA Scientific Advisory Board, Washington, DC. http://yosemite.epa.gov/sab/sabproduct.nsf/95eac6037dbee075852573a00075f732/E09317EC14CB3F2B85257713004BED5F/$File/EPA-SAB-10-006-unsigned.pdf (accessed 16 Sept. 2012).

Vadas, P.A., P.J.A. Kleinman, and A.N. Sharpley. 2005. Relating soil phosphorus to dissolved phosphorus in runoff: A single extraction coefficient for water quality modeling. J. Environ. Qual. 34:572–580. doi:10.2134/jeq2005.0572

Vadas, P.A., L.W. Good, P.A. Moore, Jr., and N. Widman. 2009. Estimating phosphorus loss in runoff from manure and fertilizer for a phosphorus loss quantification tool. J. Environ. Qual. 38:1645–1653. doi:10.2134/jeq2008.0337

vanBochove, E., G. Thériault, F. Dechmi, A.N. Rousseau, R. Quilbé, M.-L. Leclerc, and N. Goussard. 2006. Indicator of risk of water contamination by phosphorus from Canadian agricultural land. Water Sci. Technol. 53:303–310.

Veith, T.L., A.N. Sharpley, J.L. Weld, and W.J. Gburek. 2005. Comparison of measured and simulated phosphorus losses with indexed site vulnerability. Trans. ASAE 48:557–565.

Vitosh, M.L., J.W. Johnson, and D.B. Mengel. 1996. Tri-state fertilizer recommendations for corn, soybeans, wheat and alfalfa. Bull. E-2567. Ohio State Univ., Columbus.

Wang, Y.T., T.Q. Zhang, I.P. O'Halloran, C.S. Tan, Q.C. Hu, and D.K. Reid. 2012. Soil tests as risk indicators for leaching of dissolved phosphorus from agricultural soils in Ontario. Soil Sci. Soc. Am. J. 76:220–229. doi:10.2136/sssaj2011.0175

Weld, J.L., D.B. Beegle, W.J. Gburek, A.N. Sharpley, R.B. Bryant, and P.J.A. Kleinman. 2007. The Pennsylvania phosphorus index. Version 2. CAT UC 180 Rev5M1/07mpc4591. Publications Distribution Center, Pennsylvania State Univ., University Park.

Wolfe, M.L., J. Pease, L. Zelazny, L. Daniels, and G. Mullins. 2005. Virginia Phosphorus Index Version 2.0: Technical guide. Revised Oct. 2005. http://p-index.agecon.vt.edu/Virginia%20P-Index%20V%202.0%20Technical%20Guide.pdf (accessed 16 Sept. 2012).

Zhang, H., and B. Raun. 2006. Oklahoma soil fertility handbook. 6th ed. OSU Extension Publication, Oklahoma State Univ., Stillwater.

Zhang, H., G. Johnson, D. Storm, N. Basta, and M. Smolen. 2005. Oklahoma phosphorus assessment worksheet. http://www.animalwaste.okstate.edu/application-rates/OKPAssess_REVISED_0812.xls/view (accessed 16 Sept. 2012).