

**SERA-17 PHOSPHORUS MANAGEMENT AND  
POLICY WORKGROUP:  
POSITION PAPERS ON KEY SCIENTIFIC ISSUES**

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## Phosphorus Indices to Predict Risk for Phosphorus Losses

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**Purpose of this publication:** Phosphorus-Indices (P-Indices) have been developed by scientists to help producers and nutrient management planners evaluate and rank potential risk for P loss from agricultural fields. However, the general public and many of our policy makers may not have a complete understanding of the concept or the potential use of the P-Index as a tool in phosphorus management. Therefore, this reader friendly “**position paper**” was developed on the concept and science behind P-Indices, as well as the benefits and limitations of their use.

### Introduction

Phosphorus (P) losses to surface waters (rivers, streams and lakes) are a serious concern in some regions, as elevated P concentrations can cause water quality problems in P-sensitive water bodies. Point sources of pollution such as municipal sewage treatment outlet pipes are relatively easy to identify. However, “non-point” or “diffuse” sources such as agricultural fields that may generate P runoff are much more difficult to identify, as their contribution to environmental pollution can vary greatly with time and can enter surface waters over a wide area. The US Department of Agriculture-Natural Resources Conservation Service (NRCS) has proposed three strategies for improving P management and controlling P losses from agricultural fields. These three strategies for P application management, contained in the NRCS conservation practice standard for nutrient management (590), are: either an agronomic or an environmental soil test P threshold above which no more fertilizer or manure P may be applied, or third a P-Index based assessment. Soil testing for P is commonly used to predict the likelihood of a crop response to additions of fertilizer or manure P. Soil testing alone cannot predict environmental P losses, as many other factors (such as rainfall, erosion, drainage, etc. ) will influence the concentration of P in runoff and leaching waters. Field management strategies such as crop rotations, tillage, and establishment of conservation buffers, can also impact P losses. Much research has been conducted over the last decades on how P moves from soils to surface waters, with most of this research concentrating on understanding individual P release and transport processes or pathways. In the P-Index, best available knowledge about the individual processes is put together to create one numerical P-Index score. The process takes into account the source and transport for P in order to conduct a comprehensive assessment of the risk of P runoff loss from a site. Once the assessment has been made, if a “High” risk of P loss is calculated, it is then necessary to alter the management of the site to reduce the risk of P losses. Many states (49 states to date) have developed P-Indices by modifying the basic components to make it suitable for local conditions (Sharpley et al., 2003). Such widespread adoption of this indexing concept shows the consensus among scientists, the fertilizer industry and

policymakers with regards to the validity of the P-Index approach (Sharpley et al., 2003; Snyder et al., 1999).

### Common Structure of Phosphorus-Indices

Most P-Indices require similar input data such as soil test P, P fertilization (inorganic and organic P) rates, method and timing of application, soil erosion, and distance to streams. If a source of P exists at a particular field (such as high soil test P, or recent fertilizer or manure applications), but there is no significant transport pathway for this P to leave the field and enter a stream, then the site does not represent a high risk for environmental P loss. Similarly, if there is a high risk of transport from a site (such as moderate runoff and/or erosion), but there is no large source of P at the site (i.e. low soil test P, or only small or no applications of fertilizer and/or manure), this site also will not represent a high risk for P loss. This is the basic concept of all P Indices, they identify two important categories that can generally be defined as ‘source’ and ‘transport’ factors for P loss, which together identify *critical source areas* (Sharpley et al., 1993).

Phosphorus-Indices rank fields according to risk of P loss in unit-less categories such as “Low”, “Medium”, “High”, and “Very High”. These categories describe whether or not improved management of P is required, and how stringent the P management needs to be, although recommendations vary by state. For example, “Low” and “Medium” indexed sites may continue nitrogen-based manure applications. This most often leads to more P being applied than the soil test recommends or a crop can remove, therefore most states suggest that some P management remediation efforts take place at “Medium” sites. For the “High” sites, the recommendation is generally to limit P applications to no more than what can be removed by the crop, while for “Very High” sites, no additional P may be added in an attempt to lower the P-Index scores (and soil test P) over time (Leytem et al., 2003; Sharpley et al., 2003). Most states also suggest the implementation of best management practices (BMPs) that can reduce the risk for P loss from “Very High” ranked fields (Weld et al., 2001; SERA17, 2005). Such BMPs will vary depending on site specific criteria, but can include options such as reduced fertilizer and manure P applications, changes in the timing and method of application, soil conservation (erosion reduction through reduced tillage and/or cover crop use), installation of conservation buffers, etc.

### Science Underpinning the Phosphorus-Indices

All P-Indices were developed and modified using the best available professional knowledge and documented in a wide range of scientific literature. For example, the North Carolina version of the P-Index lists approximately 150 publications in its supporting scientific literature (NC PLAT Committee, 2005). The scientific literature generally reports on individual research studies that investigate and quantify relationships between source and/or site characteristics and P losses in runoff and/or leaching. Phosphorus-Indices consolidate these individual studies into a comprehensive tool that links major transport and source characteristics to rank the risk of P loss. Some validation of P-Indices has occurred showing that higher P-Index rankings correspond to greater P losses, but more validation work is desirable (Veith et al., 2005).

The P-Index was not originally developed to quantify actual (lbs/acre) P losses from fields (Lemunyon and Gilbert, 1993). However, with the increasing number of studies

being reported in the scientific literature and with additional P-Index validation studies, some of the currently implemented P-Indices may in the future be modified to allow for quantification of P loss at the field scale. An extension of the risk assessment and indexing procedure will lead to a P model that uses site-specific data and processes to quantify actual P losses.

## Benefits of Phosphorus-Indices

The use of P-Indices in the field to assess P loss risk requires a number of site-specific characteristics. The field data have to be readily assessable in order for the field technician or producer to do the index. Some of the data can come directly from the producer (e.g., timing, rate, and method of P application). Other site characteristics may be found in soil surveys and soil test results, while others may require some preliminary planning, like making erosion predictions using RUSLE2 for water or the wind erosion equation.

Many studies have demonstrated good relationships between soil test P values and particulate and soluble P losses in runoff when all other conditions are equal (e.g. Pote et al., 1996). However, soil test P alone does not take site management into consideration. Lemunyon and Gilbert (1993) reported that in general, cultivated fields lost most P in the particulate form while forest and grassland lost most P in the soluble form. Torbert et al. (2005) observed dissolved P losses increased with increasing rate of manure application, but that incorporation of manure decreased P losses. Phosphorus-Indices incorporate soil test P as one variable, but a comprehensive P-Index considers individual site and management characteristics instead of soil test P value alone and is far superior for determining potential runoff risk. Phosphorus-Indices can show that some fields with high soil test P have little risk of P losses due to minimal risk of transport from the field, and therefore do not strictly limit P additions to these fields. Limiting P applications on soil test P alone is therefore generally more restrictive than implementing a P-Index. In situations where livestock producers have to dispose of excess manure, a P-Index would be less restrictive than application of manure P based on a soil test P threshold. This may be a benefit to the producer in the short term, but may lead to problems in the long run as soil test P may increase further in these fields until it causes the site to be ranked “High” by the P-Index.

Phosphorus-Indices generally identify only relatively small numbers of fields within watersheds as needing improved management of P, allowing producers to continue with their normal practices outside of these critical source areas (Leytem et al., 2003). Flexibility in management is a key asset to implementation of P-Indices. With the soil test P threshold approach, P application would be restricted once soil test P values reach the threshold. However, P-Indices allow producers or other land users to select from many strategies that will reduce the risk for P loss, including changing the method and/or timing of fertilizer or manure application, changing crop rotations and tillage practices to reduce erosion, or installing vegetated buffers or application setbacks to increase flow distances. This flexibility will help the producers search for the best methods to maintain profitability while protecting the environment.

Computer models, such as the Soil and Water Assessment Tool (SWAT), can give detailed output on P losses at the watershed scale. However, such models require large quantities of detailed input data as well as knowledge on how to run the computer software and interpret results, and do not necessarily represent P loss processes any better than P-Indices (Veith et al., 2005). Producers, regulators and other stakeholders normally require a

more user-friendly and simple tool to evaluate the risk of P loss. Phosphorus-Indices are much easier to use and obtain input data, yet are good planning alternatives to the use of complex computer models.

### Limitations of Phosphorus-Indices

As already discussed, soil test P is not as good at predicting P losses in runoff as P-Indices. However, soil test P is often routinely measured on agricultural fields. Regulating P applications above a certain level of soil test P does have the advantage of being a cheap and easy way to limit P applications (since it can be done as part of agronomic fertility soil sampling and testing guidelines anyway). As P-Indices require field input information such as slope steepness and length, a site visit is needed for the first year of an assessment of the P-Index. Therefore, P-Indices are more costly to initially determine and implement than a soil test P threshold. Advances in spatial analyses technology and database management may greatly reduce P-Index costs in the future. In the interim, due to the cost of implementation of a P-Index approach, some states have implemented a screening tool to quickly identify sites that are likely to have a high risk of P loss, and only on these sites are the full P-Index evaluations run (Sharpley et al., 2003).

Where inorganic fertilizers are used as the main P source, P-Indices will be effective at reducing P losses as reductions in P fertilizer rates in combination with better site management are relatively simple. However, for most animal feeding operations land application of manure is the only economic path for use / disposal and in some situations the amount of manure generated contains more P than local crops require. In these situations P-Indices will serve to move manure applications away from sites with a high risk for P loss to those with a lower risk, or to change management to reduce risk of P loss. This improved management of manure-P will reduce P losses in the short term. In the long term, the shift in manure application to lower risk fields will cause soil test P levels to increase. This is acceptable if soil fertility levels need to be built up, yet can be unsustainable over the long-term when soil test P reaches unacceptable levels across the farm. There may be no other options for manure application other than export from the farm. Therefore, in areas of intensive animal production, the long term goal must be to match manure P production with local crop P requirements, or to find alternative uses for the manures outside the farm boundary.

### Position of SERA17 on Phosphorus-Indices

Predicting P loss from the landscape based on soil test P alone is not feasible. Phosphorus-Indices represent the “state of the science”, incorporating P source and transport components, and are valuable tools to rank fields based on their relative risk of P loss. These Indices are excellent decision support tools that offer the farm planner and producer a method to identify site characteristic and management techniques that impact the potential for P loss. These identified site conditions can be modified or altered with BMPs and management practices.

It is the position of SERA17 that P-Indices are preferable to soil test P threshold values or any other current risk assessment techniques, in situations where P loss assessment must be carried out by a variety of personnel and stakeholders. However, it should be understood that the implementation of P-Index based management only addresses short-term P loss issues. For long-term sustainability, applications of P must approach a balance with crop removal.

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# Predicting Phosphorus Losses

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## Background

In July 2003, the city of Tulsa, OK reached an agreement with six Arkansas poultry integrators and the city of Decatur to reduce P loading into the Lake Eucha-Spavinaw reservoir complex. As part of the agreement, poultry growers in the watershed were forbidden from land application of litter until a new phosphorus index (P-Index) could be developed and used in the watershed in both states. The court specified that the P-Index should be designed to produce a numerical risk for each field. The P-Index was to be developed jointly by scientists from Oklahoma State University (OSU) and the University of Arkansas (UA). The deadline was 1 January, 2004. Scientists at OSU and UA could not agree on a common approach within the time period and submitted separate approaches. Two questions have arisen in regards to predicting P losses: 1) how accurately can indices or models be used to predict the long-term relative risk of P loss or actual P loss at the edge of a field and 2) what is the need for long-term monitoring of edge-of-field P loss. In this section, we discuss how modeling can and should be used in predicting P losses in the Eucha-Spavinaw watershed, but the discussion is applicable to watersheds throughout the nation.

## Edge-of-Field P Loss Predictions

There are some similarities between the way scientists at OSU and UA have approached predicting P losses in the Lake Eucha-Spavinaw watershed (Table 1). Both groups are using the same spatial scale which is field-scale. UA scientists are using a P-Index approach to estimate a relative risk (Daniel, 2004). The P-Index is based on the previously developed Arkansas P-Index for Pastures (DeLaune et al., 2004a) and the new P-Index is called the Eucha/Spavinaw P-Index (ESPI). It considers risk from source factors, transport factors, and best management practices (BMPs) and multiplies these to obtain an overall risk index (the higher the index, the higher the risk). Runoff risk is estimated based on the curve number and slope. Erosion risk is estimated using the Revised Universal Soil Loss Equation. The overall risk is modified based on the time of manure application. ESPI is designed to be simple and easy to use, especially for managers working in the field. It accounts for an extensive list of BMPs including streamside buffers and fencing cattle out of streams. The final output is a rating of low, medium, high, or very high risk for P movement beyond the edge of the field.

Scientists at OSU developed a P-Index using a modified version of the Soil Water Assessment Tool (SWAT) (Arnold et al., 1998; Neitsch et al., 2002). SWAT is designed for use at the scale of a watershed. The modified program is called the Phosphorus Pasture Management (PPM) Calculator and it estimates the average annual and monthly

P loss at the edge of a field (Storm et al., 2004). The PPM Calculator runs on a daily time step and simulates plant growth and nutrient uptake, grazing, fertilizer and manure applications, erosion (based on the Modified Universal Soil Loss Equation), and runoff (based on the curve number approach). No predictions are made beyond the edge-of-field (there is no channel routing of sediment or P). Like the ESPI, it is designed to be simple and easy to use in the field. A user interface contains a series of input blocks for entering readily available inputs such as STP and monthly stocking rates. Since SWAT is a watershed-scale model, it requires specification of a large number of parameter values. In the PPM Calculator, nine hydrologic parameters that can't be expected to be known by field users were determined using calibration in a representative watershed and given fixed values. These include parameters related to soil evaporation, percolation to groundwater, and curve number adjustments. The PPM Calculator requires specification of a "P allocation threshold" in lb/acre-yr as an input and one can test the effect of different thresholds on field-scale P losses. Future work will include adding more BMPs such as buffer strips and alum treatment, a delivery ratio that will extend P loading to receiving water bodies, economics, and row crop and small grain fields.

Both groups are using the same temporal scale which is a long-term multi-year average. The ESPI approach developed by UA scientists estimates a risk for average annual P loss. The PPM Calculator runs SWAT at a daily time step with a 15-year weather record for the Lake Eucha-Spavinaw basin and then calculates the annual and monthly averages.

In our opinion, accurately predicting P loss or relative risk at these spatial and temporal scales (long-term and edge-of-field) is an appropriate goal given the state of the science. A limited number of studies have shown the P-Index approach can identify fields with a high risk for P loss at these scales. Sharpley (1995) tested a P-Index approach on 30 grassed and cropped fields in the Southern Plains where long-term P losses had been measured. There was a good relationship between the P-Index and the log of the total P loss ( $r^2 = 0.70$ ). DeLaune et al. (2004b) compared a P-Index to P concentrations in small plots receiving simulated rainfall and to annual P losses from two 0.4-ha fields. The P-Index was correlated with dissolved reactive P (DRP) concentrations in runoff from small plots ( $r^2 = 0.66$ ) and annual P loss from the fields ( $r^2 = 0.83$ ). Harmel et al. (2005) evaluated P-indices from TX, AR, and IA using three years of measured data from Riesel, TX, and found relatively poor agreement between the measured P losses and P-Index ratings ( $r^2 \leq 0.31$ ). The field conditions were cultivated row crops or grassland receiving either poultry litter or inorganic fertilizers, which, as noted by the authors, was beyond the limits of some P-index intended applications. However,  $r^2$  values improved to as high as 0.90 when models were adjusted for measured sediment losses.

A limited number of studies have shown that dynamic models are also reasonably accurate at these scales. Storm et al. (2004) have compared the PPM Calculator to data from a study by Edwards et al. (1994) on four fields (ranging in size from 0.56 to 1.46 ha) in the Illinois River watershed in Arkansas. Runoff was measured under natural rainfall for 33 months. Half of fields received manure and were stocked with cattle and half had no cattle or manure and received fertilizer. The observed and predicted P loads for each field are shown in Table 2. The relative error ranged from 12 to 66%.

Pierson et al. (2001a) used the Erosion Productivity and Impact Calculator (EPIC) to predict event and annual runoff and P loads from six paddocks in the Piedmont region of Georgia. The paddocks ranged in size from 0.72 to 0.79 ha. All of the paddocks received broiler litter and were grazed. The relationship between predicted and observed DRP was relatively poor on an event basis ( $r^2 = 0.42$ ) but stronger on an annual basis ( $r^2 = 0.56$ ). Edwards et al. (1994) also found reasonable correlation ( $r^2 = 0.80$ ) between EPIC predictions and observed annual P losses from pastures receiving either inorganic P fertilizer or poultry litter.

Even at these scales (field and annual), there are gaps in our scientific knowledge about P processes, be they implemented in P indices or dynamic models. One question is where are the areas in a field that produce runoff? A study by Gburek and Sharpley (1998) on the same small watershed in Pennsylvania reported in Srinivasan et al. (2005) used small sensors to detect the areas where runoff occurred. They estimated that only 14% of the watershed (mostly low-lying areas near the stream) produced runoff. Chaubey et al. (2004) used similar devices to identify runoff areas in a field in Arkansas and found that subsurface features caused runoff in the mid-slope region. In Iowa, they have recognized that there are major differences in risk of P loss within fields (Mallarino et al., 2001). Nutrient management planners can zone fields for P index calculations based on characteristics relevant to P loss. Another question is the effectiveness of common best management practices (BMPs) in reducing P losses. The P subroutines in models such as SWAT were developed for EPIC nearly thirty years ago and have not been improved much since, despite advances in research.

In our opinion, watershed-scale predictions of loadings to lakes are not reliable unless extensive, site-specific calibration is used. The same can be said for short-term (daily) predictions at the edge-of-field scale. These types of predictions remain in the research development stage. The capability to make predictions at this scale is, however, an appropriate long-term goal. US EPA policy is committed to a watershed approach (US EPA, 2005). It is also at this scale that the public and courts want answers. This is particularly true with P, where the primary concern is usually loading to lakes (the case in the Eucha Spavinaw watershed).

To make accurate predictions at the watershed and short-term scales, many research questions need to be answered (including those already mentioned regarding runoff areas and BMPs). One question is how long does the manure pool act as source of P separate from soil test P (STP) in farming systems where manure is not incorporated (the typical practice in the Eucha-Spavinaw watershed)? DeLaune et al. (2004a) showed that the manure pool dominated STP as a source for up to 14 days after application of broiler litter, but it is not known how much longer these pools remain separate. Vadas et al. (2004, 2005) have suggested modifications to existing models to account for these two pools. Another area that needs to be addressed is in-stream processes for P including interaction with suspended sediment, bed sediment, and aquatic biota. Dynamic watershed-scale models differ in the manner and number of processes included. Parameter values for these processes are especially difficult to determine. As a consequence, sources, sinks, and travel times for P in streams are largely unknown. Finally, we need to be able to put confidence limits on model predictions.

The approaches taken by scientists at UA and OSU have different strengths that would complement each other if combined. The strength of the P-Index approach is that

it includes important field-scale processes such as P loss from a separate manure pool and BMPs, which are not currently part of SWAT. Also, the P-Index approach is relatively easy to develop for a given watershed in that calibration is not required. Weaknesses of this approach are that it is not easily expanded beyond the edge-of-field spatial scale and adjusted towards short-term time scales and that it predicts a relative risk instead of a P load, which is desired by the court. A weakness of the dynamic model approach (based on SWAT) is that it needs an updated P process that includes separate STP and manure pools and that accounts for BMPs. Another weakness is that some of the model parameters must be calibrated using data representative of the watershed in which it is to be applied. Its strengths are that it predicts a P load at average annual and average monthly intervals and has the potential to predict transport at the watershed-scale.

### Long-term Monitoring of Edge-of-Field P Loss

Models of various forms and complexities, ranging from process-based models to simplistic empirical models, have proven useful for the advancement of scientific knowledge by the comparison of land management practices on resulting water quality, runoff, and crop production. Models have also been valuable tools for educating the general public on issues related to P loss from agricultural lands and its impact on water quality. Many of these models have undergone scientific scrutiny and varying levels of validation to ensure the integrity of information gleaned from their use. These review and validation measures have proven satisfactory for the intended uses of the models; education and advancement of scientific understanding. Recently, field-scale P loss predictions from various models have been used to regulate individual producers. Models initially designed for education and scientific studies of relative impact may be well suited for broader applications, including legal regulation. However, caution must be used when models are applied for these expanded purposes. For example, because of the potential for model results to inflict direct economic harm on individual producers, models should undergo additional validation and subsequent refinements prior to regulatory application.

A major obstacle to extensive model validation is the lack of complete datasets that can be used for validation. Many of the datasets used for the development of models and study of P transport mechanisms have been produced under simulated rainfall (Edwards et al., 1995; Sauer et al., 2000; Kleinman et al., 2002). Rainfall simulation studies are helpful in determining relative differences in controlled settings, investigating nutrient loss processes, and isolating effects of individual variables. Although relative P loss trends observed under simulated rainfall are also observed in field studies, the predictive relationships developed from simulated rainfall are not always directly transferable to natural rainfall conditions (Cox and Hendrix, 2000). Because of the differences between P losses observed under simulated rainfall vs. natural rainfall, models should be validated with datasets derived from natural rainfall studies. Datasets that quantify P losses from both natural rainfall and irrigation-induced runoff and erosion should be used to validate models predicting P losses from irrigated agriculture. Phosphorus loss from agricultural fields acquired under natural rainfall is subject to considerable variability during and among runoff events as well as between sites (Harmel et al., 2004; Kurz et al., 2005). Therefore, long-term datasets from a variety of sites are particularly useful to capture this variability.

Furthermore, in-stream processes (including biological uptake, mineralization, adsorption, desorption, and sedimentation) alter nutrient forms, transport, and eventual impact

on larger receiving waters. Datasets that include both edge-of-field P losses and down-stream watershed P losses are uniquely suited to assess the relationship between P losses at the field edge and P delivery to sensitive water bodies.

Because field-scale studies quantifying P losses under natural rainfall require large land areas, have high equipment and personnel expenses, and generate large numbers of samples, there are relatively few datasets available (Harmel et al., 2003). Furthermore, there are even fewer datasets quantifying both field-scale P losses and down-stream watershed-scale P losses. However, several research locations have quantified or are currently monitoring field-scale P losses. Selected characteristics from these research locations and associated publications reporting measured P losses appear in Table 3. These studies have focused on P losses from fields receiving either poultry litter or inorganic fertilizers, for the most part. The wide range of P losses reported by these studies indicates a need for additional investigation of factors contributing to observed losses. Further research is needed to incorporate a wider range of cropping practices, P sources, and landscape/climate factors.

Studies listed in Table 3 can serve as examples of experimental design and sampling protocols for future studies. Ideally, future edge-of-field studies should be nested within larger watershed studies to allow for a more robust validation of the model predictions, as demonstrated at the Riesel, TX research location (Harmel et al., 2004). If possible, watershed studies should be set up in a paired design to allow for statistically sound data analysis independent of model results (Spooner and Line, 1993). Collection of both flow rate and water quality data is vital; however, recommended data collection protocols depend on field size and location, runoff intensity and volume, sampling equipment, sample collection and processing capabilities, and research objectives. Therefore, these variables should be carefully considered so that flow monitoring and sampling procedures are appropriately designed to meet research objectives (Harmel et al., 2003). Surface runoff from natural rainfall and irrigation events should be measured, ideally with a pre-calibrated flow control structure, and recorded on a 2-15 minute interval depending on watershed size. Water quality samples should be collected frequently during each runoff event. Sampling infrequently or only selected storms provides less useful data and introduces considerable uncertainty into annual P load estimates (Harmel and King, 2005). At a minimum, collected water samples should be analyzed for total suspended solids, total P, and dissolved reactive P.

Soil P concentration is an integral input in many models. Furthermore, datasets documenting management induced changes in soil P concentration offer another level of model validation for process-based models. Therefore, studies should closely monitor soil P concentration as well as document all field practices affecting soil P concentration and distribution. Because field-scale P loss is highly dependant on climate variability, studies should be conducted for a minimum of 4 to 5 years to capture variability and allow for statistical analysis of results from paired watersheds.

## Position of SERA-17 on Modeling Phosphorus Losses

The Eucha Spavinaw watershed court case poses a number of vexing scientific issues on modeling P losses and has forced the scientific community in this region to address

controversial policy issues. Based on our assessment, we make the following observations and recommendations regarding the science supporting P transport modeling:

- The two approaches for predicting P loss developed by scientists at OSU and at UA share a common spatial scale (edge-of-field) and temporal scale (annual or longer-term). They differ in that the UA approach predicts a relative risk for P loss and the OSU approach predicts a specific P loss.
- These are the appropriate scales for making predictions, given the current scientific understanding, and both approaches have been shown in a limited number of studies to provide reasonably accurate predictions.
- Making watershed-scale predictions of P loading to lakes or short-term (daily) P losses at the edge-of-field cannot be done reliably without extensive and site-specific calibration of watershed-scale models.
- The strengths of the P-Index approach are that it treats manure and soil P as separate sources, includes a number of BMPs, and is readily adapted to different watersheds. The strengths of the dynamic model approach are that it predicts a load rather than a risk and has the potential to predict loadings to a lake.
- Since the approaches taken by scientists at UA and scientists at OSU have complementary strengths, the two groups are encouraged to strive for a common approach.
- Further research is needed to study P source and cropping system effects on edge-of-field P losses. Field-scale studies should be conducted under natural rainfall or irrigation conditions for greater than 3 years. USDA-ARS is particularly well suited to conducting such long-term studies.
- Preferably, long-term field-scale studies should be nested within watershed-scale studies to better evaluate the relationship between edge-of-field P loss and down-stream P inputs to sensitive water bodies. Datasets from these studies would be a valuable resource for model validation thereby allowing for extended model applications in the regulatory area.

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Table 1. A comparison of the P-Index (ESPI) and Dynamic Model (PPM Calculator) approaches.

<b>Feature</b>	<b>P-Index Approach (ESPI)</b>	<b>Dynamic Model Approach (PPM Calculator)</b>
Output	Risk of losing P	P load lost
Spatial Scale	Edge of field	Edge of field
Temporal Scale	Long-term annual average	Long-term annual and monthly averages
Estimation of runoff	Index based on NRCS curve number and slope	Daily runoff based on NRCS curve number
Soluble P concentration in runoff	Based on STP and adsorption coefficients from rainfall simulation studies and P solubility in manure	Based on soil labile P and adsorption coefficients; does not consider manure
Manure as a P source	Treats manure as a separate source of P	Does not treat manure as a separate source
Erosion	Based on RUSLE	Based on MUSLE
BMPs	Accounts for buffers, time of application and cattle access to streams (10% reduction in risk if cattle do not have access)	Accounts for time of application
Number of input parameters	Few	Many but most of these are pre-calibrated
Row crops	Does not address	Does not address
User interface	Easy to use in field	Easy to use in field

Table 2. Observed and predicted total P loads in four fields from two sites. Unmanaged fields (RU and WU) received litter and managed fields (RM and WM) received commercial N fertilizer. Site WM received both litter and commercial N fertilizer. Observed loads were measured in a study by Edwards et al. (1994). The PPM Calculator was used to make the predictions of total P (Storm et al., 2004).

Field	Observed	Predicted	Relative Error
	Total P	Total P	
	kg/ha/yr		%
R Site Unmanaged (RU)	4.6	5.7	-25
R Site Managed (RM)	0.77	0.54	29
W Site Unmanaged (WU)	2.0	2.2	-12
W Site Managed (WM)	2.7	0.91	66

Table 2. Studies reporting edge-of-field phosphorus losses from natural rainfall (*adapted from: Harmel et al., 2004*).

Site location	Land use	Applied P sources	Dates	Area (ha)	P forms monitored at field edge <sup>†</sup>	Mean annual P loss (kg ha <sup>-1</sup> )	Down-stream monitoring	Published data
Iowa	Corn	poultry manure	1998–2000	0.40	PO <sub>4</sub> -P	0.2–0.3 <sup>‡</sup>	no	Chinkuyu et al., 2002
Arkansas	grazed fescue	poultry manure poultry litter none	1992–1994	1.06–1.23	PO <sub>4</sub> -P	1.58–4.34 <sup>‡</sup>	no	Edwards et al., 1996
Alabama	corn-winter rye	poultry litter inorganic fertilizer	1991–1993	0.11	sediment P, dissolved P, total P	0.99–2.42	no	Hall (1994) Wood et al., 1999
Georgia	grazed fescue	poultry litter cattle manure	1995–1996	0.75	DRP <sup>§</sup>	7.40 <sup>‡</sup>	no	Pierson et al., 2001b Kuykendall et al., 1999
Arkansas	Cotton	poultry litter none	1996–1998	0.60	PO <sub>4</sub> -P, total P	3.0	no	Vories et al., 2001
Georgia	Bermuda-fescue	poultry litter composted litter	1995–1996	0.45	DRP, total P	0.1–0.4	no	Vervoort et al., 1998
Texas	Corn pasture	poultry litter inorganic fertilizer	1984–1989 2000–2003	1.2–8.4	dissolved P, sediment-bound P	0.15–6.25	yes	Chichester and Richardson, 1992 Harmel et al., 2004 Harmel et al., 2005
Arkansas	Fescue	poultry litter alum-amended litter	1995–2000	0.405	soluble reactive P, total P	0–3.1	no	Moore et al., 2000 DeLaune et al., 2004b
Missouri	corn/soybean rotation	inorganic fertilizer	1991–1997	1.65–4.44	total P	0.13–0.18	no	Udawatta et al., 2004
Ireland	grazed pasture	inorganic fertilizer	1996–1998	0.46–1.54	DRP, total dissolved P, total P	0.70–4.76 <sup>‡</sup>	no	Kurz et al., 2005
Oklahoma	native grassland wheat	inorganic fertilizer	1977–1992	1.6	total P	0.20–2.98	no	Sharpley, 1995

<sup>†</sup> P forms as reported in published data

<sup>‡</sup> Does not represent total P losses due to lack of data

<sup>§</sup> dissolved reactive phosphorus

# Soil Phosphorus Threshold Levels

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**Purpose of this publication:** In an effort to reduce phosphorus (P) losses from agricultural areas to the environment, there are three approaches to address phosphorus (P) manure application rates for concentrated animal feeding operations (CAFOs) (EPA, 2000; Sharpley et al., 2003). These methods included the Phosphorus Index (P-Index), soil test P threshold level, and soil test P level. This paper was developed to determine states currently using a P threshold, how the P threshold was determined and developed, how the P threshold is being used, and to develop a systematic strategy for developing and using a P threshold.

## Introduction

Water quality issues from algal blooms have been related to excess nitrate-nitrogen (N) and P transported into surface water bodies. Many discussions among state Extension and Experiment Station, Agricultural Research Service (ARS), Natural Resources Conservation Service (NRCS), state regulatory, and federal regulatory personnel have taken place to evaluate and determine the best method for estimating the potential for P to be transported from the land surface into surface water bodies. One of the methods under discussion is the use of a soil test P threshold. A soil test P threshold can be defined as a concentration at which no additional P may be added from an organic or inorganic source or, the upper environmental critical level. It can also be defined as a soil P concentration where more stringent regulations are imposed to reduce the addition of P, such as crop uptake or removal.

Listed in Table 1 are states that use the P threshold method alone or in combination with soil test P and the P-Index. States not listed have made the decision to not use the P threshold as part of their tools to estimate the potential for P to be transported from the field. The information in Table 2 describes the methods used to establish the P threshold and how it is being used. As the information presented in Table 2 indicates, there is variability in the P threshold and how it was developed and is being used. The most common threshold is 200 mg P kg<sup>-1</sup> soil (ppm) (400 lbs P acre<sup>-1</sup>) using Bray PI or Mehlich 3 as the soil P extracting solution.

Most states used soil test information to arrive at their respective thresholds. When states have used this method to arrive at their respective P threshold, it was either an estimated P concentration where additional P application would not give a crop yield response or an explanation of why soil test P should be allowed to increase beyond the agronomic range and evidence of P leaching at these soil test P concentrations. The P threshold is often estimated to be three to four times the soil test P concentration rated as High in that state's soil testing P rating system. The High rating for a nutrient is usually considered the concentration at which additional nutrient would not give a response to crop yield. As an example, in Texas, the High soil test P rating based on the Mehlich 3 extract is 50 mg kg<sup>-1</sup>. A multiplication factor of 4 was used to obtain the 200 mg kg<sup>-1</sup> concentration currently used in Texas (Table 2).

McDowell and Sharpley (2001) and Sharpley et al. (2001) used a split-line model that describes two linear relationships whose slopes are significantly different to estimate threshold P concentrations for five soil series. Equations 1 and 2 describe the line below and the line above the P threshold, respectively:

$$\text{Dissolved P} = m_1(\text{Mehlich-3 P}) + c$$

[1]

$$\text{Dissolved P} = m_1(\text{Mehlich-3 P}) + m_2(\text{Mehlich-3 P} - \text{Mehlich-3 P threshold}) + c$$

[2]

where  $c$  is the intercept,  $m_1$  is the slope of the linear relationship for values of Mehlich 3 extractable soil P less than the threshold, and  $m_2$  is the difference in slopes after the threshold compared with  $m_1$ . The point at which the two linear relationships crossed was determined to be the P threshold. The P threshold varied from 185 to 190 mg/kg and was established at 200 mg/kg for Pennsylvania.

### Benefits of the Phosphorus Threshold

There are two underlying assumptions for the P threshold. First, manured fields with the greatest soil test P will transport the greatest P concentration in runoff/erosion. Second, transferring manure from high soil test P fields to lower soil test P fields will reduce the transport of P to surface water bodies. The strengths of the P threshold are that it is a simple criterion for regulation, it is a single soil analytical P test that can be determined quickly and be cost effective, and it is assumed to be based upon water quality criteria.

Table 1. States using the phosphorus threshold approach to evaluate the potential for phosphorus transport to surface water bodies.

<b>State</b>	<b>Soil P Threshold</b>	<b>Soil Test P</b>	<b>Phosphorus Index</b>
Arkansas - Eucha Spavinaw	yes		yes
Arkansas- Rest of State	yes		yes
Indiana	yes	yes	yes
Kentucky	yes		
Oklahoma	yes		yes
Pennsylvania	yes		yes
Texas	yes		yes

Table 2. Development and use of the phosphorus threshold.

State	Org/Inorg Fertilizer	Developed By <sup>†</sup>	Scientific Data Used	Soil Test P Method	Threshold Soil Test P	How It Is Used If P Threshold
Arkansas - Eucha Spavinaw	Both	Court Order	Yes	Mehlich 3	300 mg/kg on 0-4 inch sample	No P application
Arkansas- Rest of State	Both	Experiment Station, Extension, and ARS	Yes	Mehlich 3	500-600 mg/kg depending on hydrologic conditions on 0-4 inch sample >600 mg/kg	Apply manure at P crop uptake, incorporated into PI  No P application
Indiana	Both	Extension, NRCS, IDEM	Yes	Bray P1 / Mehlich 3	0-50 mg/kg on 0-8 inch sample 51-100 mg/kg 101-200 mg/kg >200 mg/kg	N-based 1.5X P removal 1.0X P removal No P application
Kentucky	Both	Extension, Experiment Station, NRCS	Yes	Mehlich 3	400 lb/A on a 0-6 inch sample	Apply P based on NRCS general guidelines or according to KY P-Index
Oklahoma	Both	NRCS, Ext., Exp. Stn., ARS, State Agencies	No	Mehlich 3	300 lbs/A on 0-6 inch sample ≥400 lbs/A on 0-6 inch sample Severe Soil Test Rating	Nutrient impaired water body segment, P crop removal Rest of state, P crop removal No P application
Pennsylvania	Both	ARS, Ext., and Exp. Stn.	Yes	Mehlich 3	200 mg/kg on a 0-6 inch sample	Component of PI, if PI rating is very high, no P application
Texas	Both	Ext., Exp. Stn., TCEQ	No	Mehlich 3	≥200 or 350 mg/kg on a 0-2 and 2-6 (pasture) or 0-6 (incorporated) inch sample 200 mg/kg 500 mg/kg	If CAFO, must manage according to PI and NMP (200 mg/kg East Texas, 350 mg/kg West Texas) Bosque River, P crop removal Bosque, P soil test reduction component

<sup>†</sup>IDEM - Indiana Department of Environmental Management; Ext. - Extension; Exp. Stn. - Experiment Station; TCEQ - Texas Commission on Environmental Quality.

## Weaknesses for the Phosphorus Threshold

There are numerous weaknesses for the P threshold approach. First, it considers only one aspect of P source and does not necessarily consider P transport, potentially hampering its ability to accurately identify management practices leading to high P transport as surface runoff and/or leaching.

Second, it is only one number and no other factors are considered in its derivation. Since soils are heterogeneous and the application of manures, litters, biosolids, and other organic sources of nutrients are not as consistent across the field as commercial fertilizer (see Fig. 1), the variability in soil sampling results for P can be greater than 50%. For example, if we assume the average Mehlich 3 soil test P level is  $200 \text{ mg kg}^{-1}$  and the variability is 50%, then the range in soil test P would be 100 to  $300 \text{ mg kg}^{-1}$ .

There are numerous reasons for variability in soil test P values. Soil test P variability comes from the variability in manure application methods, lack of manure consistency, and inconsistent P distribution in the manure. Most soil test P extractions do not extract most of the organic forms of P, but are good extractants of inorganic forms of P. Thus, as mineralization occurs over time, the soil test P will change as the organic P is converted to inorganic P that the soil test extractant will extract. Research in Texas on small plots where manure has been applied by producers and through grazing animals indicates up to 60% variability between representative samples from four plots (15 subsamples per  $1.5 \times 2 \text{ m}$  plots) within a 20 m area (Jacoby, 2005). Thus, if soil testing is so variable, it is not a good criterion on which to base regulatory compliance.

Third, a soil P threshold assumes that moving manure application from high testing fields to low testing fields will reduce P transport to surface water. This depends on when the precipitation event that causes runoff/erosion occurs relative to the application date. The longer manure is in contact with the soil, the greater number of light rainfall events incorporating the manure, and the longer the exposure to microbial activity, the less potential for P transport in surface runoff.

Fourth, a soil P threshold fails to address management of high testing fields that do not receive manure or management of other fertilizer sources in addition to manure. Finally, extensive research must be done to establish estimated P thresholds for all soil series. With sufficient research, this may be extrapolated to soil associations.

## Position of SERA-17 on the Phosphorus Threshold

Because the P threshold is a single soil test P concentration, the lack of correlation between a single soil test P concentration and P being transported from a field, and the high variability of representative soil samples from fields where manure, litter, biosolids, or other organics have been applied, we recommend that the P threshold not be used as the sole regulatory criteria for compliance. It may be used in conjunction with the P- Index, other transport models, or as a component in those models to trigger additional P management, including no additional P application until the soil test P has decreased to a pre-determined threshold level. We further recommend that the P-Index and other models developed and being developed be used as the primary tool to estimate the potential for P transport from a

field.

It is recommended that the P threshold be two tiered. When the first tier is reached, reductions in the amount of P applied will be put in place. If the soil test P continues to increase, the second tier will be the upper environmental critical P threshold where no additional P will be applied.

There should be an upper environmental critical threshold P point at which no additional P should be applied. This upper environmental critical concentration will differ for different soil associations because different soils have different P retention capacities. Therefore, there is not a single extractable soil P concentration that can be determined where the next addition of P will be detrimental to surface water quality (Sharpley et al., 1996; Daniels et al., 1998). Research completed in Arkansas (Burch, et al., 2001) and Texas (Jacoby, 2005) indicates that at approximately 700 mg kg<sup>-1</sup> Mehlich 3 soil test P, additional soil test P does not contribute to dissolved runoff P. Even at this soil test P, the runoff P can vary from less than 1 mg kg<sup>-1</sup> to greater than 1 mg kg<sup>-1</sup>. This soil test P concentration is probably due to P solubility in the natural environment of soils. This concentration, however, should not be used as the concentration at which no additional P should be applied across the U.S. It is doubtful that any areas should be greater than this; however, areas susceptible to erosion or leaching should have a lower upper environmental critical concentration.

It is recommended that when this upper environmental critical concentration is reached, manure, litter, biosolids, or other sources of organic or inorganic P application will cease. It is recommended that Fe and Zn be monitored in soils due to the potential for P induced Fe and/or Zn deficiencies when the P/Fe (from 100:1 to 300:1) and P/Zn (30:1) ratios are very high, especially in calcareous soils. There may be a need for application of organic sources of nutrients at the P crop removal rate every two to four years depending on the susceptibility of the watershed to nutrient impairment.

When a federal or state regulatory agency or NRCS makes the decision to establish and use a threshold P, it is recommended that either the procedure of Sharpley et al. (2001) or the estimation calculated by multiplying the High soil test P rating by three or four be followed. Because the Sharpley et al. (2001) methodology requires an extensive amount of research, it is highly recommended that the research be funded by the regulatory agency and/or NRCS and that the research be done by State Extension and/or Experiment Station personnel responsible for soil testing, soil fertility, and nutrient management related to CAFOs.

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Figure 1. Phosphorus distribution in a commercially fertilized field in West Texas. Data from Kevin Bronson, Texas Agricultural Experiment Station, Lubbock, TX.

# Phosphorus Determination in Waters and Extracts of Soils and By-Products: Inductively Coupled Plasma Spectrometry versus Colorimetric Procedures

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## Introduction

The ability to measure phosphorus (P) concentrations in soils, water, and by-products is important from both an agricultural and an environmental perspective. One of the purposes underlying the development of soil testing was to identify soils that would likely have increases in crop yield with additions of P fertilizer. That use continues today and the procedures developed for identifying soils that would be responsive to additions of P fertilizer are also used to identify soils that have excessive amounts of P that might contribute to eutrophication of surface waters. The analysis of by-products, mostly animal manures, for P is important in our efforts to effectively manage P from concentrated animal feeding operations to minimize potential environmental impacts.

The methods used to measure P concentrations require that the P be contained in a liquid matrix. Therefore, for solid samples such as soils or by-products, the P must be brought into solution through a digestion procedure using acids or by extraction with a liquid such as water, weak salt solutions, or weak acids. Prior to analysis these solutions must be filtered to remove solid particles that would interfere with the analytical procedures. In the case of water, the sample may also be filtered through a specific type of filter and any P that passes through the filter is considered to have been dissolved in the original water sample. The water sample may also be digested prior to filtration and any P that is measured is considered an estimate of the total amount of P in the original sample.

The issue of filtration is important in P analysis. Filters are characterized by a pore size whereby particles in a liquid that are smaller than the pore size of the filter paper will pass through the filter paper. Even filter papers with a very small pore size will allow some solid particles to pass (sometimes called colloidal material) and P attached to those particles may or may not be measured in the analysis step. In general, the P contained in a filtered sample would exist as soluble inorganic or organic P species and P adsorbed to any colloidal material that has passed through the filter.

The possibility that P concentrations in extracts, digests, and water samples might be different when measured with inductively coupled plasma spectrometry (ICP) as compared to colorimetric procedures has been debated since the introduction of ICP instruments. The ability of ICP to measure several elements simultaneously has increased interest in multi-element extracts for routine soil testing and likely reduced the use of the colorimetric approach. However, colorimetric procedures offer some advantages, such as increased sensitivity and lower instrumentation costs, and it is unlikely that ICP will completely displace colorimetric procedures. The commonly held

belief is that ICP would measure greater P concentrations than colorimetric procedures because the high temperature environment of the plasma would allow the measurement of organic P compounds or other soluble P complexes that would not be measured colorimetrically. Differences in P concentrations measured by these two methods may have implications for agronomic and environmental P testing. The purpose of this paper is to discuss potential differences in P determination by ICP versus colorimetric procedures.

## Magnitude and Characteristics of the Difference between ICP and Colorimetric P Analyses

The most common P colorimetric procedure in use, because of its high sensitivity, was developed by Murphy and Riley (1962). For purposes of this paper, colorimetric analysis refers to the Murphy and Riley method. The literature has sufficient examples of direct comparisons between ICP and colorimetric P determination to demonstrate that differences can clearly exist. Many of these papers discuss the Mehlich-3 (M3) method, which has been widely adopted in the eastern half of the U.S. The M3 extract is used as a multi-element soil extractant that matches well with the multi-element capabilities of ICP, although there are significant concerns about differences between ICP and colorimetric procedures with water samples as well as water or weak salt extracts of soils and manures. Most of the examples indicate that ICP will measure greater P concentrations than colorimetric methods, although examples can be found where ICP values are less than P concentrations obtained via a colorimetric procedure. For the sake of brevity, select examples are presented here to illustrate the differences in various sample types.

Pittman et al. (2005) compared ICP and colorimetric P determination in M3 extracts of 6400 soil samples from Oklahoma. A significant correlation was found between the two methods (Fig. 1a) and the difference between the two methods was greater when considering only soils with  $<60 \text{ mg kg}^{-1}$  M3 P (Fig. 1c). The intercepts of the lines shown in Figure 1 are close to zero and the slopes indicate that P concentrations determined colorimetrically will be 80 to 90% of those determined by ICP. The difference between the two methods is proportionally larger when the extractable P concentration in the soil sample is low ( $<20 \text{ mg kg}^{-1}$ , Fig. 2). Mallarino (2003) also found M3 results to be greater in Iowa soils when P was measured with ICP as compared to a colorimetric approach. Differences were large as indicated by a larger intercept and smaller slope (0.779), and the differences were also proportionally larger at low P values. Sikora et al. (2005) found the slopes of correlations between ICP and colorimetric P determination in M3 extracts of Kentucky soil soils were much closer to 1 (1.02 and 0.968 for two data sets) as compared to Pittman et al. (2005) and Mallarino (2003). However, when M3 extractable P was low and P fertilizer would be recommended, P concentrations determined by ICP were greater than colorimetric values more frequently than the reverse.

Jacoby (2005) evaluated 23 fields where manure had been applied either via a manure spreader or grazing cattle or both on feedyards and dairies. He compared Mehlich-3 P to colorimetric P and found a  $R^2$  of 0.76 at  $p < 0.01$  with a  $47 \text{ mg kg}^{-1}$  P intercept (Fig. 3). The colorimetric P was 55% of the P determined by ICP. The pH values ranged from 4.9 (only one below 5.5) to 8.6, with 14 of the 23 fields having a pH from 5.5 to 7.5. The range in colorimetric-P was from 31 to  $472 \text{ mg kg}^{-1}$  and ICP-P from 40 to  $772 \text{ mg kg}^{-1}$ .

Wolf et al. (2005) compared ICP and colorimetric determination of P in water extracts of manures and found that colorimetric P analyses were significantly greater, by an average of 7%,

than ICP analyses for swine, dairy, and broiler poultry manure samples (Fig. 4). Similar results were reported by Choate (2004) for 0.01 M CaCl<sub>2</sub> extractable P in biosolids (Fig. 5). These samples covered a wide range of P concentrations and colorimetric analyses were 13% greater than ICP. In contrast, recent results from a study conducted by SERA-17's soil and manure testing workgroup (Fig. 6), indicate that for manure and biosolids water extracts, ICP measurements are approximately 20% greater than colorimetric measurements. When those manures and biosolids were broadcast to soils and subjected to simulated rainfall to generate runoff, runoff water samples revealed a similar difference in ICP versus colorimetric measurements (approximately 20%).

### Possible Causes for any Discrepancies between ICP and Colorimetric P Determinations

The possibility that ICP is able to measure organic forms of P that colorimetric procedures miss was investigated by Pierzynski et al. (2005). Standard organic P solutions containing glycerol 2-phosphate disodium salt hydrate, phytic acid, or 4-nitrophenyl phosphate bis(cyclohexylammonium) salt hydrate were analyzed by ICP and the Murphy and Riley procedure. Recovery from the solutions by ICP was essentially 100% for glycerol and phytic acid compounds and 88% for 4-nitrophenyl. Only 0 to 3.5 % was recovered by the colorimetric P procedure indicating that this approach was unable to detect P in the organic compounds (Table 1).

The standard solutions were digested in potassium persulfate in an autoclave, and the recovery of P by ICP was near 100% for 4-nitrophenyl and phytic acid while decreasing to 86% for glycerol. Upon digestion and determination of P with the colorimetric procedure, recoveries increased to between 56 and 93%. These results suggested that laboratory digestion is not sufficiently rigorous to completely oxidize the organic P such that the P can be measured by the colorimetric procedure. Thus, if the difference between ICP and colorimetric P determinations is related to organic P species, then the digestion of extracts, digests, or water samples followed by colorimetric analysis may not be adequate to account for all of the P that can be measured with ICP, and merely digesting solutions prior to colorimetric analysis will not bring the two approaches into agreement. This is illustrated in Figure 7, which shows the correlation between P in M3 extracts as determined by ICP or the colorimetric approach in undigested or digested solutions.

Digesting samples and determining P colorimetrically brings the slope of the correlation closer to one as compared to undigested samples, but does not completely compensate for the discrepancy. Incomplete digestion of organic P in the extracts cannot be ruled out based on the results shown in Table 1. Work coordinated by the NCR-13 soil-testing committee with Iowa, Minnesota, and Missouri soils (R. Eliason, G. Rehm, and A. Mallarino, unpublished data; Nathan et al., 2002) also showed that ICP determined near 100% of various organic P species added to M3 extracts while the colorimetric method recovered only trace amounts. These studies do indicate that ICP is fully capable of measuring P in some organic forms but do not allow us to determine with certainty if the presence of organic P species in extracts accounts for all of the difference between ICP and colorimetric P determinations.

Pierzynski et al (2005) also investigated the possibility of spectral enhancement of the P signal using ICP by measuring spectral emission intensity in a scan across the P wavelength in P standards and unknowns. Spectral enhancement would artificially increase P concentrations measured by ICP. No evidence of spectral enhancement was found.

Other possible explanations for the higher values obtained by ICP over colorimetric procedures in soil extracts include the presence of P-containing particulates (colloidal materials) not removed during the filtering process and/or the presence of soluble P complexes with iron (Fe),

aluminum (Al) and/or calcium (Ca). The higher temperature environment of the ICP plasma could potentially result in the measurement of some fraction of these soluble or suspended P components that would not be measured by colorimetric procedures. However, we are not aware of any published studies that have specifically evaluated these effects.

Pittman et al. (2005) characterized 100 soil samples in greater detail that were then used to study relationships between other soil chemical characteristics and the difference between ICP and colorimetric P determination. Within this group, the slope of the correlation between ICP-P and colorimetric-P was 0.87 for all soils, 0.96 for soils with pH <5.5, 0.83 for soils with pH 5.5 – 7.5, and 0.88 for soils with pH > 7.5. Therefore, soil pH plays a role in the relationship between the two methods but does not explain the difference between them. This study also examined the potential influence of M3 extractable Al, Fe, and Ca; clay content; and soil organic carbon (C) content on the difference between colorimetric and ICP determination of P; but no significant relationships were found. Mallarino (2003) found a weak ( $r^2 = 0.32$ ) negative relationship between M3-ICP minus M3-color and soil pH suggesting that the difference between the two methods increased as pH decreased. This is in contrast to the findings of Pittman et al. (2005). Similarly, the difference between the two methods decreased when soil organic C increased ( $r^2 = 0.16$ ), which suggests that organic P may not account for all of the difference between ICP and colorimetric approaches if one assumes that extractable organic P would increase with increased soil organic C. Studies in Minnesota showed the difference between the methods tended to be smaller with increased pH but did not change significantly with increased organic C (Ellison et al., 2001). Studies in Missouri found no consistent relationships between the additional P measured with ICP and manure applications or soil organic C (Nathan and Sun, 1998; Nathan et al., 2002).

The colorimetric procedure determines the P concentration by measuring the amount of light at a specific wavelength that is absorbed by a colored complex formed with P. Greater absorption corresponds to a greater P concentration. Reports of colorimetric analyses being greater than ICP are thus far confined to water extracts of organic by-products and it is not known if this situation exists with other sample types or extracts. Wolf et al. (2005) hypothesized that substances were extracted with the manure also absorbed light at the specific wavelength and that did not contain P. Such substance would induce a positive bias in the colorimetric analyses as compared to ICP. The findings of SERA-17's soil and manure testing workgroup (Fig. 6), where colorimetric and ICP determinations were run by the same laboratories as in Wolf et al. (2005), indicate that the role of color interference in inflating colorimetric P measurements is not universal.

The possibility of human error cannot be discounted and there are a variety of ways in which human error can induce a positive or negative bias in results. Preparation of standards, calculation errors, and dilutions are three common factors that can influence results.

It is likely that organic P species play a role in the discrepancy between ICP and colorimetric P analyses when ICP results are greater and that other as yet unidentified factors may also play a role. We currently have little insight into what may cause colorimetric P analyses to be greater than ICP results for water extracts of organic by-product materials. Overall, this is an area of needed research from an academic point of view. On the practical side, the cause of the discrepancy is less important than the magnitude of the discrepancy.

## Practical Significance

Phosphorus analyses of soils, waters, and manures can be used for a variety of purposes including making P fertilizer recommendations; estimating the risk of P loss in runoff; or assessing actual P losses from the landscape. The interpretation of the results may be based upon P analyses determined colorimetrically or by ICP. A common example would be soil test calibrations which have historically been based on colorimetric P analyses. Clearly, if a method other than the one used as a basis for the interpretation is employed, then significant errors may occur.

A reasonable worst case scenario would be a decrease in recommended P fertilizer proportional to the enhancement of the soil test P results measured by ICP as compared to recommendations based on colorimetric analyses. To avoid misinterpretation of soil fertility results obtained by ICP, it has been suggested that equations, such as those shown in Figure 1, be used to convert ICP data back to colorimetric analyses. However, obtaining the appropriate correction factors or equations is no trivial matter as these relationships are potentially influenced by soil type, and factors such as soil pH or organic matter content. Until the specific factors contributing to the higher values obtained by ICP over colorimetric procedures have been more clearly defined, a regression approach for converting ICP to colorimetric-equivalent values is not recommended.

An alternative approach is to develop separate calibration sets for colorimetric versus ICP determinations as recommended by Mallarino (2003). Noting that the differences between ICP and colorimetric P determinations were not constant across Iowa soils and that they were only weakly correlated to soil organic matter and pH, Mallarino demonstrated that a different field response-based calibration for M3 colorimetric versus M3 by ICP was merited (Fig. 8). Additional unpublished research for other crops resulted in the publication of Iowa soil-test interpretations for colorimetric and ICP versions of the M3 extractant (Sawyer et al., 2002). Iowa considers the M3 extractant with ICP or colorimetric determination of extracted P as two, clearly different soil tests.

The issue is less clear when using P analyses as part of a determination of the risk of P loss from the landscape. The common tool for this purpose would be one of the P Indices used in the U.S., where P analyses may be a factor in varied ways including soil test P data or water extractable P for manures (Sharpley et al., 2003). If the method of P analysis is not specified for a given P Index, then it is not possible to correct for any possible discrepancies as may be possible for fertilizer recommendations. The typical output from a P Index is a relative ranking of risk for P loss from the landscape in categories of very low, low, medium, high, and very high. It is possible that the use of one method for P determination over another may result in a shift up or down one category and that change may have important ramifications.

For example, a lower category may allow a producer to apply animal manures on a N basis instead of a P basis. If the method of P analysis is specified for a given P Index, then it may be possible to correct any P analyses to the specified method and avoid any possible variations in the P risk loss category that is determined for a given site. The freedom to use any method of P analyses or the specification of a particular method are means to build flexibility and varying degrees of conservatism into the process. Not specifying a method may allow a shrewd producer to select the method that is to his or her greatest advantage. Specifying a method may force the most or least conservative interpretation of the P Index. A recent modification of the Iowa P Index specifies that both the M3-colorimetric and M3-ICP soil tests can be used as source factors for the index but different equations are used for these tests when estimating P in surface runoff or subsurface drainage (Mallarino et al. 2005).

If one assumes that ICP would indicate greater P concentrations in samples of surface runoff

as compared to the colorimetric approach, then using ICP would present the worst case scenario with regard to runoff losses of P. It is difficult to interpret the potential ramifications of the method of P analysis beyond this given our lack of ability to interpret edge of field P losses on a larger watershed scale. Samples of water collected from streams or lakes may be used to estimate compliance with total maximum daily load (TMDL) requirements or the degree of impairment from P, and would also present a worst case scenario if ICP were the method employed.

Some states or regions have heavily relied on soil test P threshold values to decide whether animal waste is allowed to be applied or not. It is particularly important to specify a method of sampling and analysis to minimize unnecessary confusion.

## Summary and Conclusions

The method of P determination used in water samples and extracts of soils and by-products can influence the reported concentrations. For most sample types, ICP is slightly greater than colorimetric analyses, but the two methods are well correlated for high P samples. However, extreme caution needs to be used for samples with low P concentrations (e.g., 60 mg/kg extractable P), as the difference may be as great as 5 fold. Water extracts of manures analyzed using colorimetric procedures may be greater than ICP by as much as 15%. The reasons for the differences have not been fully investigated. When ICP results are greater than colorimetric values, it appears that the ability of the ICP to measure organic P species plays a role.

The difference between the two methods can be important when interpreting results. Most fertilizer recommendations are based on colorimetric P analyses and the use of ICP may produce different recommendations. The use of correction factors needs further investigation. The impact is less obvious when using P analyses as part of a P Site Index. The use of one method may cause the estimated risk of P loss to be slightly greater or less than that predicted using another approach. For water samples from surface runoff, lakes, or streams, the use of ICP would likely estimate the worst-case scenario in terms of the potential loss or impact of P.

The SERA-17 Committee supports the following recommendations:

- The method of P analysis should always be clearly stated when presenting analytical results.
- If P data collected with a particular method supports subsequent interpretation of P analyses, then that method should be clearly identified.
- More research is needed to determine the sample types and range of P concentrations for which significant differences in results might be obtained with ICP and colorimetric methods.
- More research is needed to identify the reasons for discrepancies between ICP and colorimetric P analyses.
- The use of regression analysis to convert ICP to colorimetric-equivalent values needs further evaluation for a variety of conditions. Until additional research is completed, extreme caution is warranted whenever such conversion procedures are used.

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Table 1. Recovery of P from undigested or digested solutions of organic P compounds using ICP or the Murphy and Riley method. Solutions contained either 15 or 20 mg P/L. Source: Pierzynski et al. (2005).

Compound <sup>†</sup>	Digestion/Analysis Method, % recovery			
	Undigested/ICP	Undigested/Color	Digested/Color	Digested/ICP
4-nitrophenyl	88	0	78	100
Glycerol	101	0	56	86
Phytic acid	96	3.5	93	101

<sup>†</sup> 4-nitrophenyl = 4 nitrophenyl phosphate, bis (cyclohexylammonium) salt hydrate; glycerol = glycerol 2-phosphate disodium salt hydrate.

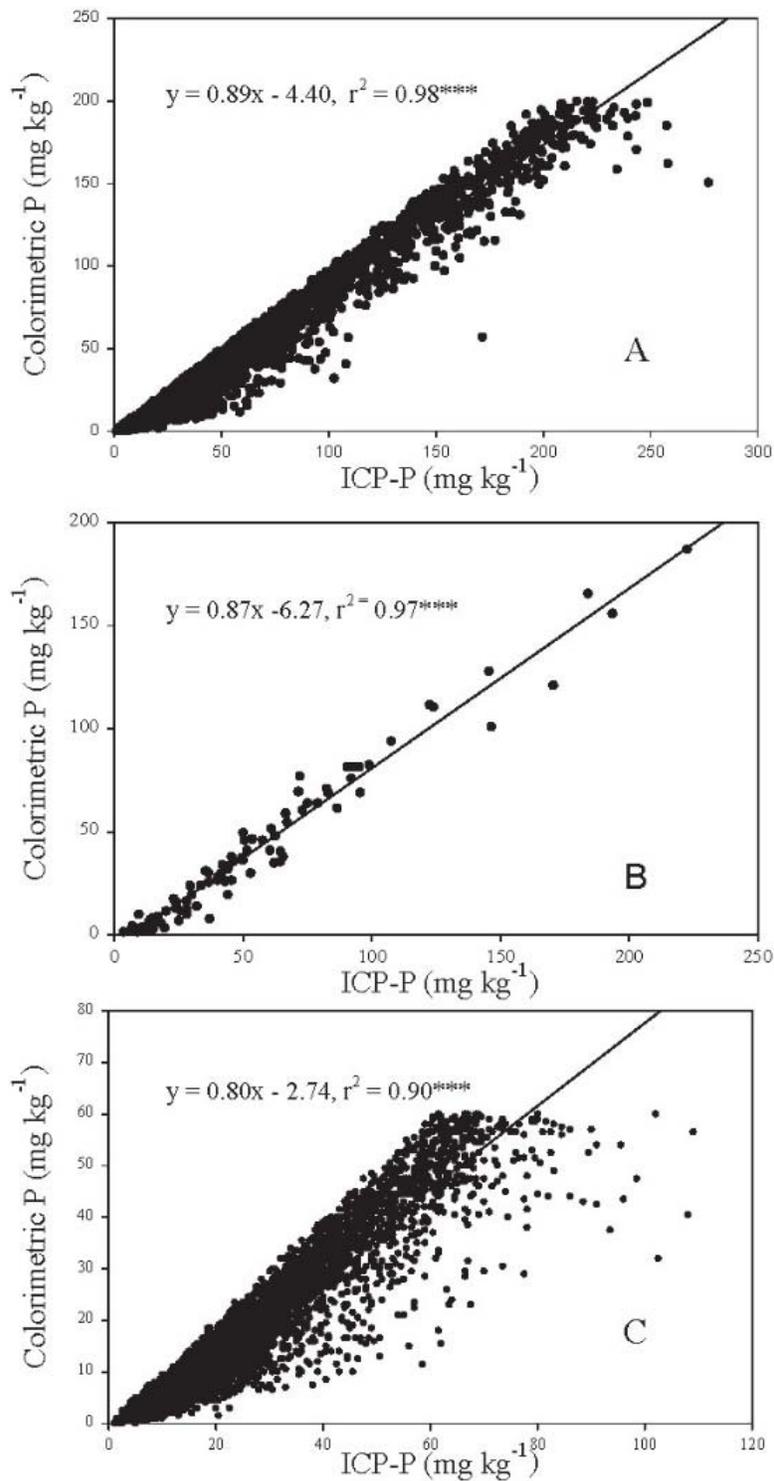


Figure 1. The relationship between Colorimetric P and ICP-P for (A) 6400 soil samples received by Oklahoma State University Soil Testing Laboratory (B) 100 characterization soils and (C) 5400 soils with colorimetric P < 60 mg kg<sup>-1</sup>. \*\*\*\*p < 0.001. From Pittman et al. (2005).

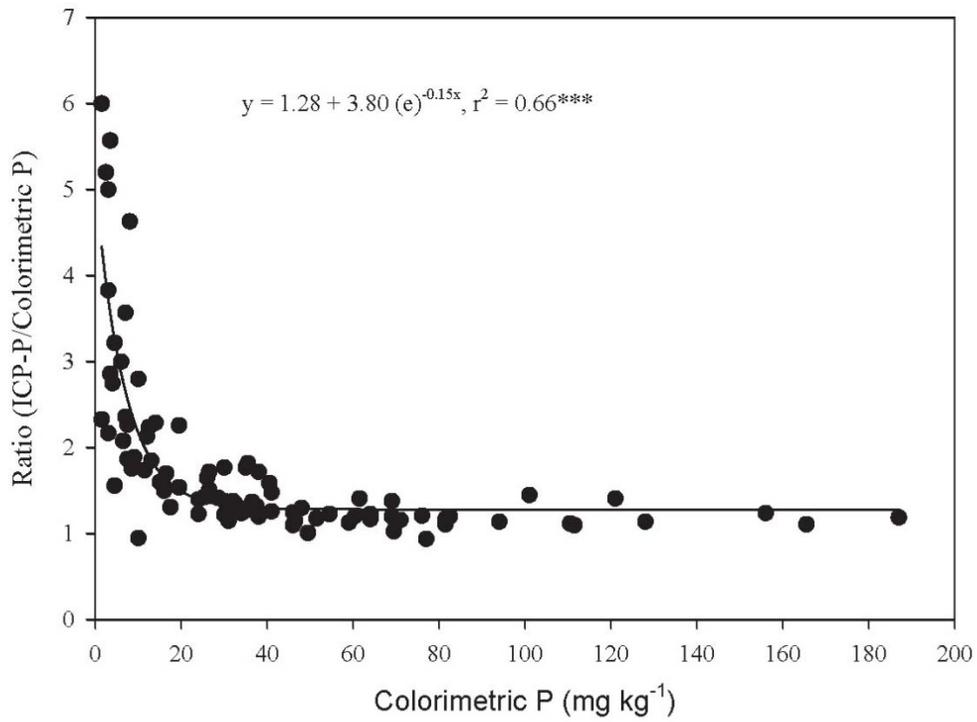


Figure 2. The relationship between the ratio of ICP-P and Colorimetric P and Colorimetric P for the 100 characterization soils. \*\*\*p < 0.001. From Pittman et al. (2005).

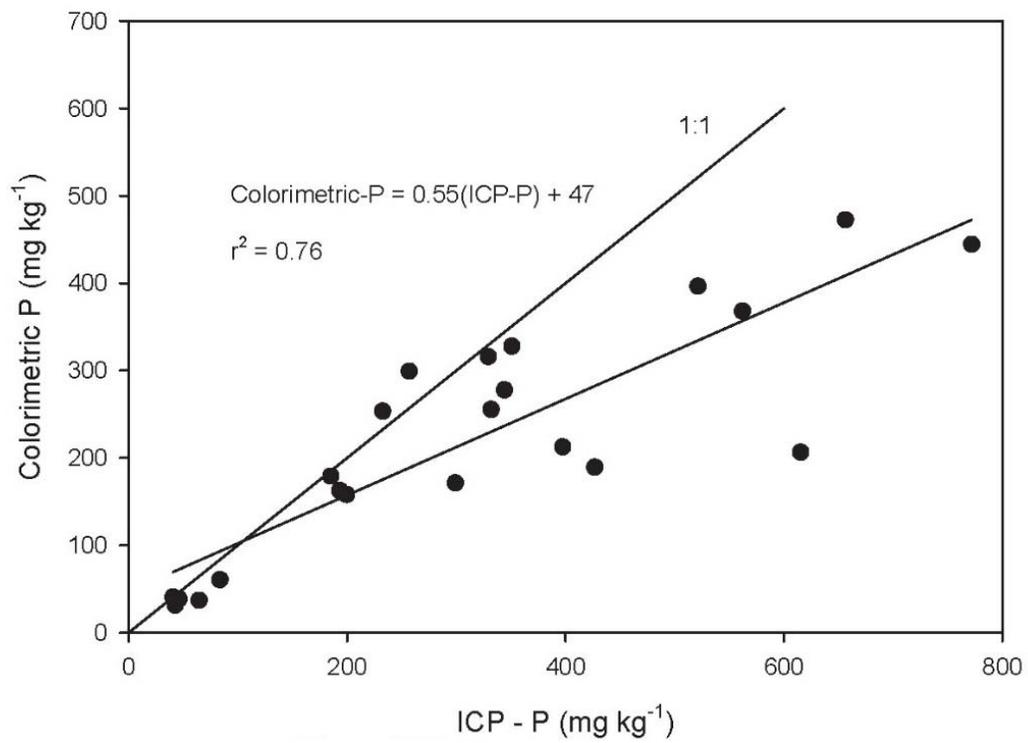


Figure 3. ICP versus colorimetric P analysis for Mehlich-3 extracts of manure-amended soils in Texas. Source: Jacoby (2005).

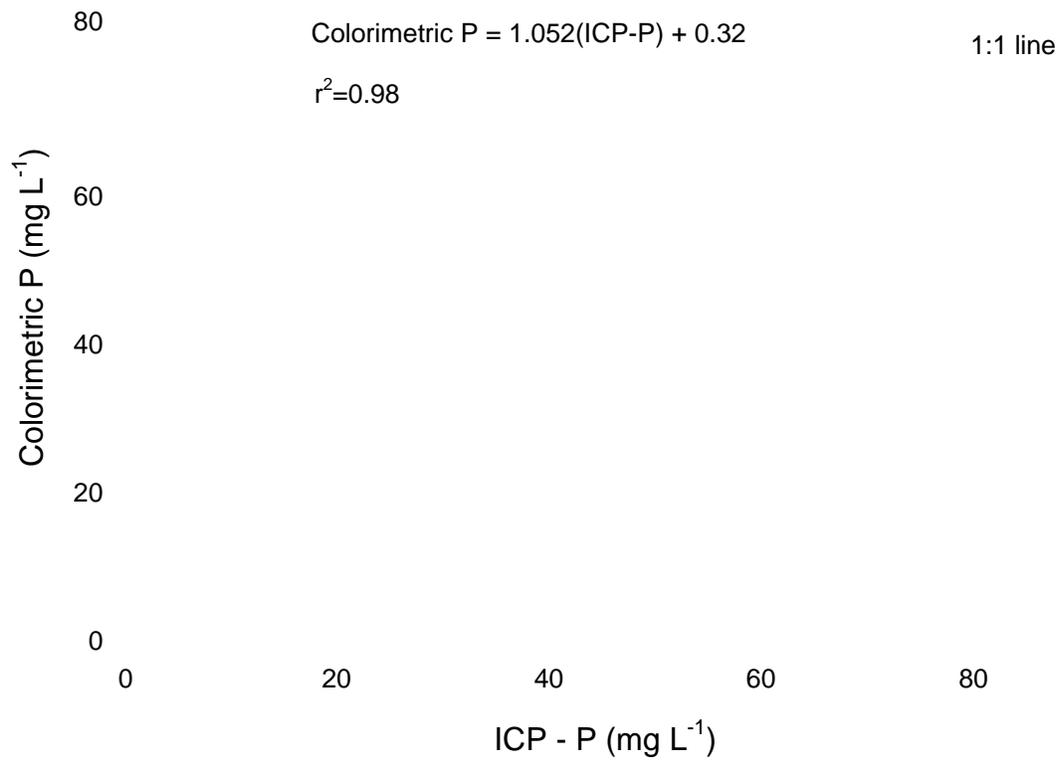


Figure 4. ICP versus colorimetric determination of P in water extracts of manures. The solid/solution ratio was 1:200. Redrawn from Wolf et al. (2005).

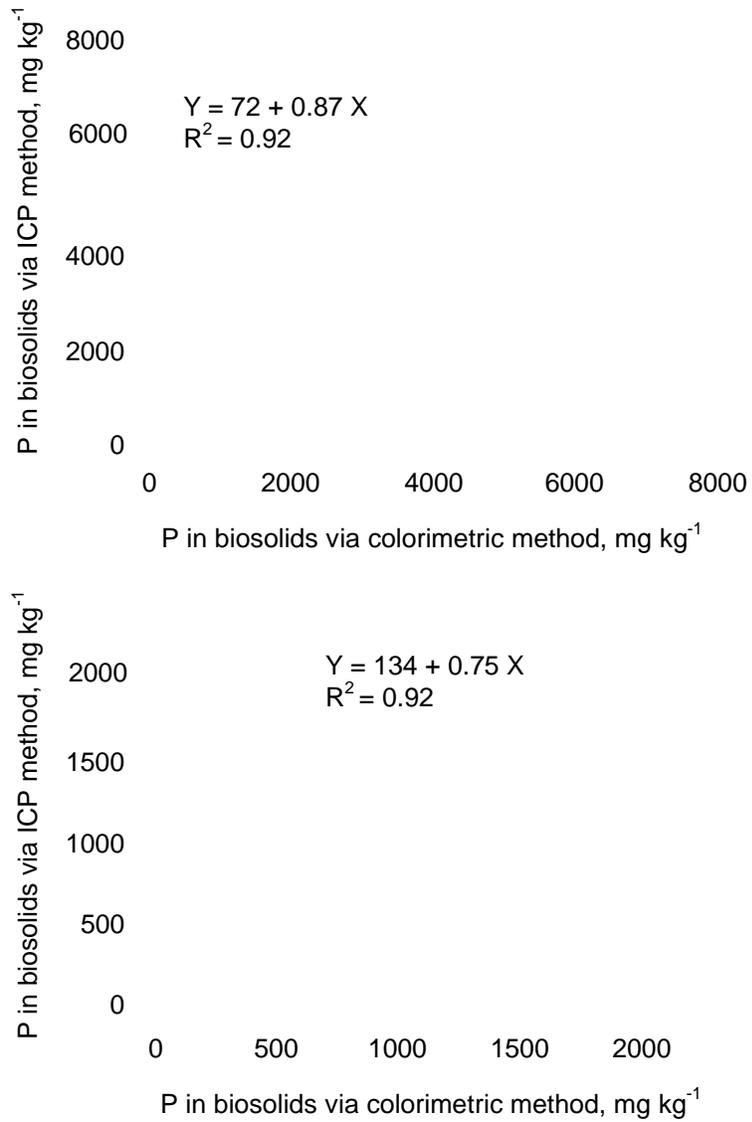


Figure 5. Phosphorus extracted with 0.01M CaCl<sub>2</sub> from 30 samples of oven-dried municipal biosolids. Source: Choate (2004). Only difference in graphs is scale (0 to 8000 above and 0 to 2500 below)

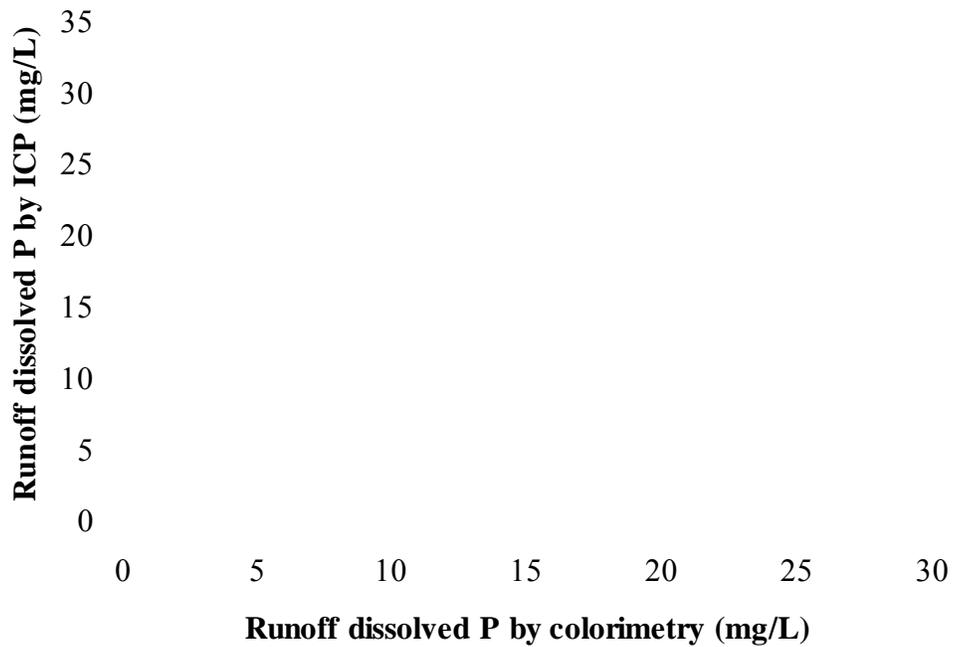
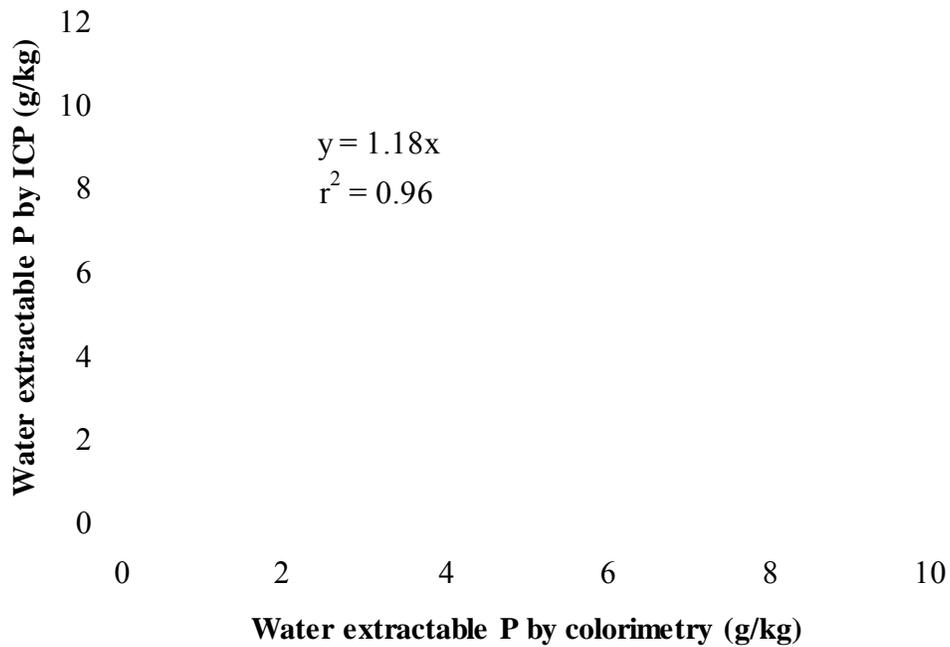


Figure 6. Relationship of P determined by colorimetry and ICP in manure and biosolid water extracts (a) and runoff water from soils broadcast with manures and biosolids (b). Note that regressions have been forced through the origin to counter effect of outliers on slope. Source: SERA-17 soil and manure testing workgroup, unpublished data.

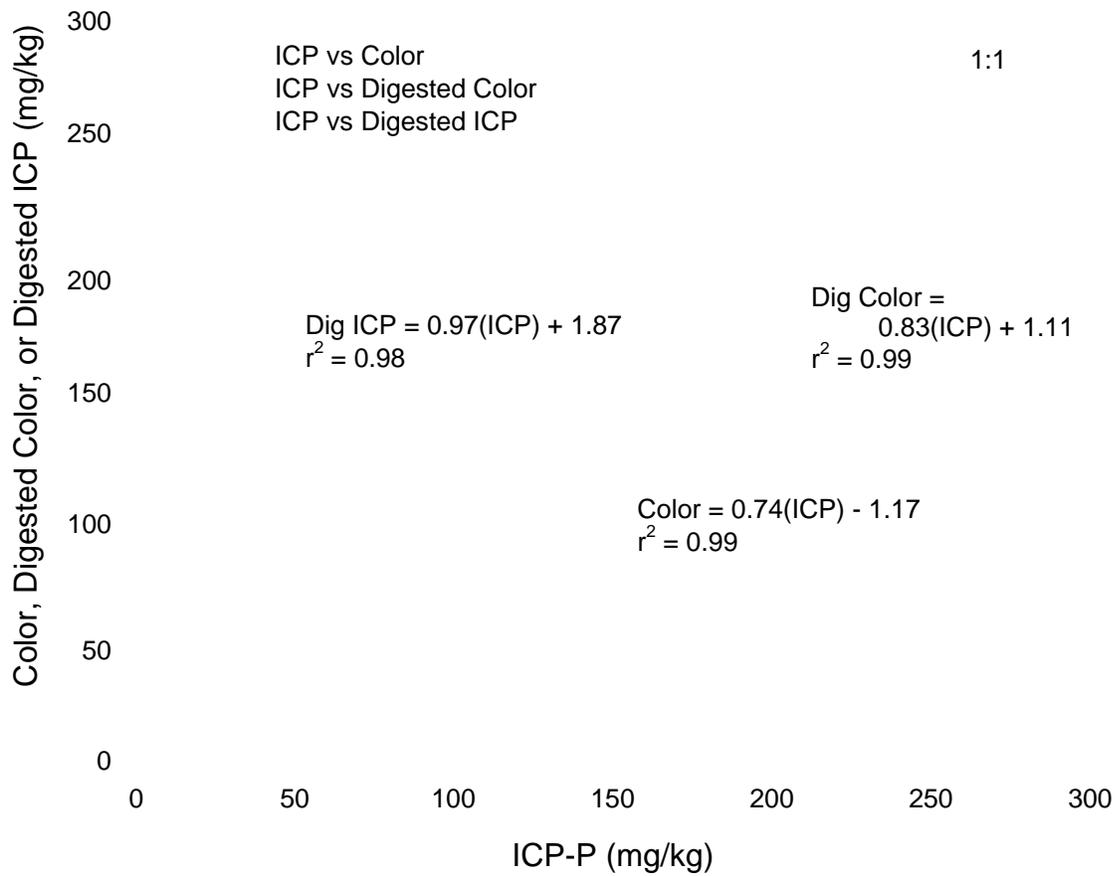


Figure 7. Phosphorus in the Mehlich-3 extracts of 50 Kansas soils, with or without persulfate digestion, as measured by ICP or colorimetric procedures. Source: Pierzynski et al. (2005).

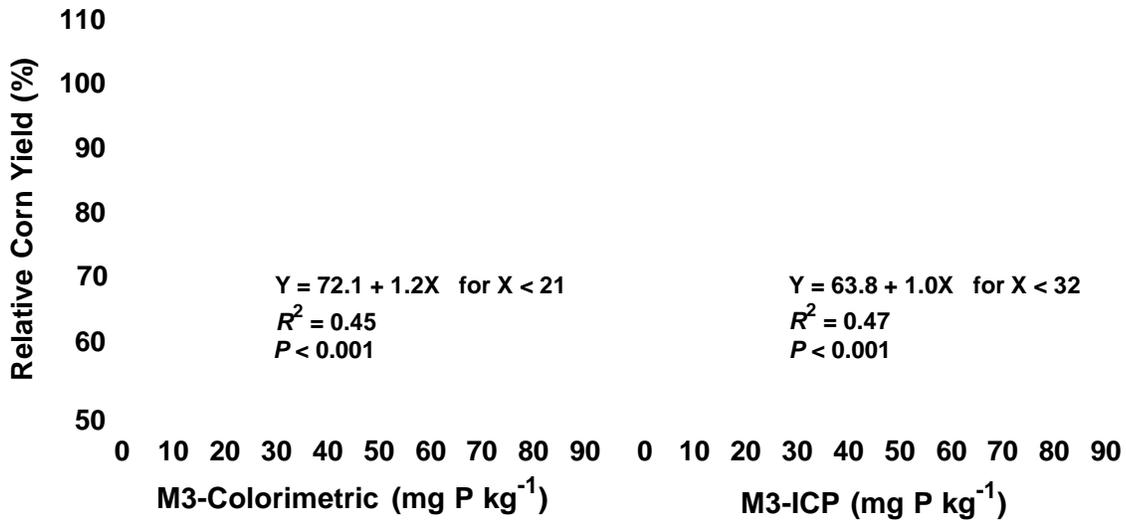


Figure. 8. Relationships between relative yield response of corn and soil-test P in Iowa soils measured using the Mehlich-3 extractant and determining extracted P with colorimetric and ICP methods (adapted from Mallarino, 2003).

# The Importance of Sampling Depth when Testing Soils for their Potential to Supply Phosphorus to Surface Runoff

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## Purpose of this publication

Soil-test phosphorus (P) results are an inherent part of agricultural nutrient management, both agronomically and environmentally (Thom and Sabbe, 1994). Historically, soil testing has been conducted for agronomic production, but is now being used as an environmental parameter to assess the risk of P transport in runoff. Interest in environmental soil sampling has been evolving since only the late 1980s and early 1990s (Sharpley and Menzel, 1987; Sims, 1993). While the relationship between soil P and runoff P has been well researched and discussed since then, a clear statement on the importance of sample depth in environmental soil testing for P has not been put forward. Soil samples for estimating nutrient sufficiency for crops usually are taken from 0-15 to 0-20 cm deep, where a large proportion of the active root zone is. Surface runoff in most cases interacts with only the top few cm of soil. Therefore, the issue of sampling depth is important when using soil-test P results for environmental purposes. This position paper presents the current scientific understanding of the effect of sampling depth when using soil samples for environmental purposes and recommends appropriate environmental soil sampling practices.

## How Plants Get Their Phosphorus and Agronomic Soil Testing

Phosphorus is essential for crop growth and development. Crops obtain P entirely from the soil, but soils have a finite capacity to supply P. When that capacity is depleted, fertilizer P must be added to the soil to replenish it. Agronomic soil sampling and testing is designed to estimate the amount of soil P that is potentially available to plants over a growing season and to determine if and how much fertilizer is needed.

Phosphorus forms strong chemical bonds with soil, and is not nearly as mobile in the soil profile as other nutrients, like nitrate-nitrogen. With the exception of phenomena like rapid macropore flow in precipitation events that closely follow P applications, downward vertical movement of P is generally a slow, gradual process. In regularly fertilized soils, most P is thus in the topsoil, which is usually from 0-15 or 0-20 cm deep. There is typically much less P deeper in the soil profile. This pattern of vertical soil P distribution is routinely observed (Grant and Bailey, 1994; Guertal et al., 1991; Lucero et al., 1995; Malhi et al. 2003; Rechcigl et al., 1985) (Fig. 1). Plant roots extract the majority of their P from the topsoil because that is where the most soil P and greatest root density are. It is therefore recommended that agronomic soil samples intended to assess P availability to plants be taken from the top 15 to 20 cm of soils, although specific recommended depths may vary by crop and tillage practices.

## How Tillage and Phosphorus Application Practices Affect Soil Phosphorus Distribution

In consistently and well-tilled soils, P is fairly uniformly distributed in the topsoil because tillage mixes soil and fertilizer P well (Andraski et al., 2003a) (Fig. 2a, b). The depth of uniform P distribution depends on the tillage implement used. For these soils, most guidelines recommend that agronomic samples be taken from 0-15 or 0-20 cm or the depth of tillage, but most often 0-15 cm.

For no-till or pasture systems, P fertilizers are not mixed well into soils, and P is not evenly distributed throughout the topsoil (Crozier et al., 1999; Howard et al., 1999). Instead, there is often a distinct vertical P stratification, with most P in the top 5 to 7 cm and decreasing amounts of P with depth (Andraski et al., 2003a; Gaston et al., 2003) (Fig. 2c, d). In these soils, a soil sample taken to 15 or 20 deep will not show this P stratification, but will show an average P concentration throughout the depth sampled (Schroeder et al., 2004; Torbert et al., 2002) (Table

1). Because plants absorb P from the entire topsoil zone and because research sometimes shows no advantage of shallower sampling for predicting P fertilizer needs in no-till or pasture soils, many guidelines still recommend taking agronomic soil samples from 0-15 cm. However, a few guidelines recommend soil samples from shallower depths, such as 0-10 cm, to better estimate P availability to plants.

The P application method also influences soil P stratification. Besides broadcasting, P fertilizers and manures can be banded at a shallow depth with the planter, or banded (fertilizer) or injected (liquid manure) deeper into the soil. Shallow banding of P with the planter in tilled soils should distribute P uniformly throughout the topsoil because bands are seldom placed deeper than 5 to 7.5 cm and because tillage mixes the fertilizer well into topsoil. However, banding P fertilizers with the planter in no-till soils applies little or no fertilizer to the soil surface. This practice should result in more P concentrated in a 5-10 cm depth than in a 0-5 cm depth, but research has provided inconsistent evidence for such a pattern. This may be because of continued soil and band mixing over time or the inability of sampling depth methods to show patterns of P stratification (Eckert and Johnson, 1985; Tyler and Howard, 1991). Deep-banding P fertilizer or manure may concentrate P deeper than 10 cm.

The intensity or effectiveness of tillage will also affect the pattern of P distribution in tilled soils. Moldboard plows and heavy disk harrows will uniformly mix P fertilizer with topsoil, unless the fertilizer is placed below tillage depth. However, commonly used chisel plows, light disk harrows, or field cultivators may not uniformly mix P fertilizer into topsoils. Data in Fig. 3 from Mallarino and Borges (2005) illustrate vertical P stratification after banding P fertilizer from 12.5 to 17.5 cm deep during four years of no-till or chisel-plowing. Soil P concentrations were similar for both tillage systems across the 0-15 cm depth. Therefore, both tillage and P fertilizer placement method influence P distribution in the topsoil.

## Using Soil-Test Data to Determine Phosphorus Available to Runoff

Transfer of P in surface runoff from agricultural soils has been implicated in the process of accelerated eutrophication of surface waters, which limits water quality for recreation, industry, or drinking (Carpenter et al., 1998). Concentrations of P in runoff, both dissolved in runoff water and attached to eroded sediment, increase as concentrations of soil P increase (Sharpley et al., 2001; Vadas et al., 2005). In an effort to minimize P transfer from soils to surface waters, it is critical to be able to identify those soils in the landscape that have the greatest potential to supply P to runoff. Therefore, the traditional practice of soil testing is now

being used for this environmental purpose.

Studies have consistently shown that traditional agronomic soil samples taken for P fertility recommendations can also reliably assess a soil's potential to release P to runoff (Vadas et al., 2005). There are several reasons why it is attractive to use P results from agronomic soil samples to determine potential soil P transfer to runoff. Agronomic soil testing is a well-established practice that uses sound chemical and physical techniques to estimate soil P availability. There is already an infrastructure established to sample and analyze soils and to process and deliver results. There are historical databases available to determine regional trends in soil-test P results over years and decades. Using agronomic samples for environmental purposes also eliminates extra labor, cost, and education required to take and process separate environmental soil samples. Finally, soil-test P results will most likely be used in P indexes or models to assess the risk of P transport in runoff. Such P indexes often recognize that changes in sediment loss and potential P losses from unincorporated manure and fertilizer are more important in determining risk of runoff P loss than variability in soil-test P. Therefore, soil-test P results from agronomic samples may be adequate for intended uses.

However, there are some important differences in determining soil P that is available to plants and soil P that is available to runoff. As mentioned above, plants take P out of the entire topsoil zone. In most cases, surface runoff interacts with only the top few cm of soil (Ahuja et al., 1981; Sharpley, 1985), although this may not be true for situations of emerging flow on longer slope lengths (Sanchez and Boll, 2005). Soil P data used to estimate P available to runoff should thus accurately represent the P in the surface 5 cm of soil. For well-tilled soils where P is evenly distributed throughout the topsoil, the concentration of soil P from 0-5 cm should be about the same as the P concentration from 0-15 cm (Butler and Coale, 2005; Table 2). Therefore, an agronomic soil sample from 0-15 cm should give the same assessment of P available to runoff as a sample from 0-5 cm. In P stratified soils, P concentrations are greater from 0-5 cm than from 5-15 cm, and an agronomic soil sample from 0-15 cm or deeper usually shows less soil P than a shallower sample (Butler and Coale, 2005; Table 2). For example, if a soil has P in the top 5 cm of 150 ppm and P from 5-15 cm of 20 ppm, a soil sample taken from 0-15 cm might give a result around 70 ppm. From an environmental perspective, a soil-test P result of 70 ppm from a well-tilled soil is not the same as 70 ppm from a P stratified soil when similar

0-15 cm samples are taken in both soils. The P stratified soil is likely to have more P in the top 5 cm and greater concentrations of P in runoff (Vadas et al., 2005). Therefore, sampling depth is important when using soil-test P results for environmental purposes.

### How Sampling Depth Affects the Relationship between Soil and Runoff Phosphorus

Studies have usually shown a linear relationship between concentrations of soil-test P and dissolved P in runoff. However, the slope of the linear relationship for P stratified soils can vary depending on the depth of soil sampling (Jacoby, 2005; Torbert et al., 2002). Data from Andraski et al. (2003b) in Fig. 4 and 5 illustrate this well. Their soil P data in Fig. 4 show that varying degrees of P stratification occurred in no-till and chisel-plowed soils at three different locations in Wisconsin that had similar tillage and fertilization treatments. Figure 5 shows that when soil-test P was related to dissolved P in runoff with data from 0-15 cm soil samples, the slope of the linear relationship was the same at the Arlington and Lancaster sites where there was little soil P stratification, but was much greater at the Fond du Lac site where soil P stratification was greater

(Fig. 4). However, when soil-test P was related to runoff P with data from 0-2 cm soil samples, the slopes of the relationships were more similar at all locations because the effect of soil P stratification was minimized. Even though shallow samples did not provide a more accurate prediction of P in runoff, they did provide a more uniform prediction relationship across the different soil types and P stratification conditions. Vadas et al. (2005) reviewed the literature and combined data from 17 studies representing 30 soil types from throughout the U.S (Fig. 6). When data for soil samples taken from 0-15 or 0-20 cm in well-tilled soils were combined with data from samples taken from 0-5 cm of no-till and pasture soils, there was a consistent linear relationship between soil-test P and dissolved P in runoff for the majority of soils. Therefore, shallow soil samples from P stratified soils give an assessment of soil P available to runoff that is the same as that from deeper samples in well-tilled soils.

However, it could be argued that as long as there is a predictive, linear relationship between soil-test P and runoff P, the depth for collecting soil samples is not critical if a consistent sampling depth is used. Agronomic guidelines could continue to recommend 0-15 cm samples for no-till and pasture soils with P stratification. Environmental guidelines would then use these samples for runoff P assessment, but would simply develop different interpretation systems for tilled soils and for no-till/pasture soils, accounting for P stratification in the no-till/pasture soils. This separate environmental interpretation approach is already being investigated or implemented for P indices in some states, with Wisconsin and Missouri as examples, and represents one alternative in dealing with the soil P stratification issue. Further, soil P variability between samples may be less for deeper, agronomic samples than shallower (0-5 cm) samples due to less relative interference from thatch layers in pastures, residues on the soil surface, or seasonal variability in soil-test results (Keogh and Maples, 1967; Lockman and Malloy, 1984; Peck and Sullivan, 1993). However, more subsamples for composite samples collected within a given field or field zone could help improve accuracy of P assessments in shallow samples.

However, separate interpretation systems based on tillage, fertilization, or soil properties may be difficult for environmental soil sampling because the degree of soil P stratification can be highly variable. Data from Andraski et al. (2003b) and Mallarino and Borges (2005) demonstrate this possibility. Mallarino and Borges (2005; Fig. 3) showed that similar soil P stratification can exist between no-till and chisel-plowed soils. Data from Andraski et al. (2003b; Fig. 4) show that varying degrees of P stratification occurred between no-till and chisel-plowed soils at their three Wisconsin locations. Reasons for variable P stratification are sometimes unclear, but may be controlled by combinations of soil properties and tillage and fertilization practices. Data from Andraski et al. (2003b) and Mallarino and Borges (2005) suggest that it may be difficult to develop variable environmental soil interpretation systems because soil P stratification may vary across locations in ways that are difficult to predict. In these cases, shallow soil samples may provide the most accurate and consistent assessment of the potential for soil P transfer to runoff. Further, with each addition of P fertilizer to a P stratified soil, soil P concentrations in the 0-5 cm layer are likely to increase more than in the 5-15 cm layer. Therefore, shallow sampling offers the opportunity to make a more certain measure of soil P available to runoff, to monitor changes in soil P more closely, and to intervene with timely and appropriate management practices before P transfer to runoff increases significantly.

## Recommended Soil Sampling Depth to Assess Soil Phosphorus Available to Runoff

A single, national recommendation for environmental soil sampling for P is difficult given differences in soil properties, site hydrology, management practices, and practical, logistical, or economic circumstances of different states and regions. However, the SERA-17 Committee supports the following recommendations:

- 1) In soils that are consistently well-tilled and have little P stratification, a traditional agronomic soil sample taken from 0-15 or 0-20 cm, or to the depth of tillage, should accurately assess soil P that is available to runoff.**
- 2) In no-till, pasture, or lightly tilled soils where distinct P stratification is likely, soil testing that accounts for soil P stratification will likely improve assessments of soil P available to runoff.** Below, we briefly discuss two possible options to account for soil P stratification.

Option a. Collect soil samples for environmental P assessment from depths shallower than the traditional 0-15 to 0-20 cm agronomic depth: Because most states currently have either no guidelines for environmental soil sampling or guidelines that are the same as agronomic sampling, this option means taking separate agronomic and environmental samples. At least one state has already implemented separate agronomic and environmental sampling protocols. Existing knowledge discussed above indicates that a sampling depth of about 0-5 cm may provide the best and most consistent assessment of soil P available to runoff in P stratified soils. A different environmental interpretation system should not be needed when shallow samples are used for P stratified soils and deeper samples are used for tilled soils. Separate environmental sampling will increase soil testing costs and required resources. However, it is already recommended in several states that 0-5 to 0-10 cm samples be taken in no-till and pasture fields for agronomic P, K, lime, or herbicide recommendations. These same shallow samples could be used for runoff P assessment.

It is possible that shallow samples could also be used for agronomic recommendations. In at least one state, for example, 0-10 cm samples are used for both agronomic and environmental purposes in pasture soils. While it was recognized that 0-5 cm samples best represent the risk of P transport in runoff, the 0-10 cm sample was a best compromise between P loss assessment and the desire to avoid taking separate samples. Although some research indicates no advantage of a shallow soil samples for agronomic uses, there is no evidence to suggest that sampling depths such as 0-5 or 0-10 cm predicts nutrient sufficiency for crops more poorly compared to 0-15 or 0-20 cm depths. Use of shallow samples both agronomically and environmentally implies developing field research to recalibrate both agronomic and environmental interpretations of soil P tests in some states. This process takes time and is costly.

Option b. Continue to use the traditional 0-15 to 0-20 cm agronomic sampling depth and account for soil P stratification by developing different interpretation systems for P stratified soils: For this option, there is no need to implement a new soil sampling system. However, separate soil-test interpretation systems should be developed for P stratified soils to improve the ability of soil-test P results from 0-15 or 0-20 cm samples to assess runoff P. Detailed research will be required to develop these different interpretation systems. Such research is currently being conducted in a

few states and attempts to use data from surveys of soil P stratification and (or) factors such as soil management and physicochemical properties to correct results for P stratification. However, soil P stratification may be quite variable across fields of a region, so that different interpretation systems may or may not be accurate for all soils suspected of having P stratification.

Although ultimately a shallow sampling depth would probably provide the best and most consistent assessment of soil P available to runoff across most conditions, it is to individual states to decide which is sampling option is best based on local research and needs. However, further research is needed on the agronomic and environmental impacts of soil sampling depth for P stratified soils, which involve crop production systems of forages, pastures, and no-till or minimum tillage management.

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Table 1. Soil test P (Mehlich-3) in four pasture soils from Texas showing a decrease in soil P concentrations with depth in the topsoil. Data are from Torbert et al. (2002).

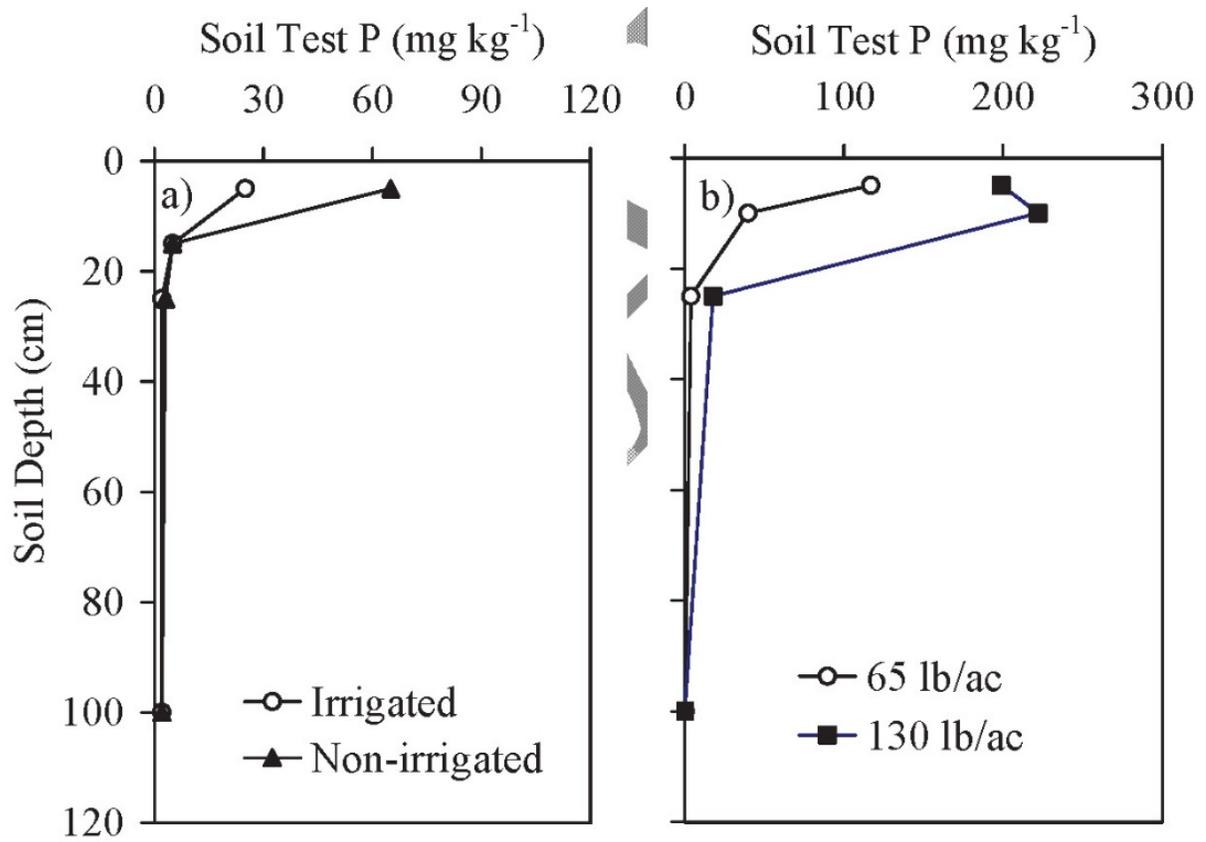
Soil Depth, cm	Soil Test P, mg kg <sup>-1</sup>			
	Blanket	Windthorst	Houston	Purves
0-2.5	525	250	600	525
0-5	350	175	300	275
0-15	125	50	75	75

Table 2. Soil test P (water-extractable) in three tilled and no-till soils from Maryland showing the effect of tillage on soil P concentrations with depth in the topsoil. Data are from Butler and Coale (2005).

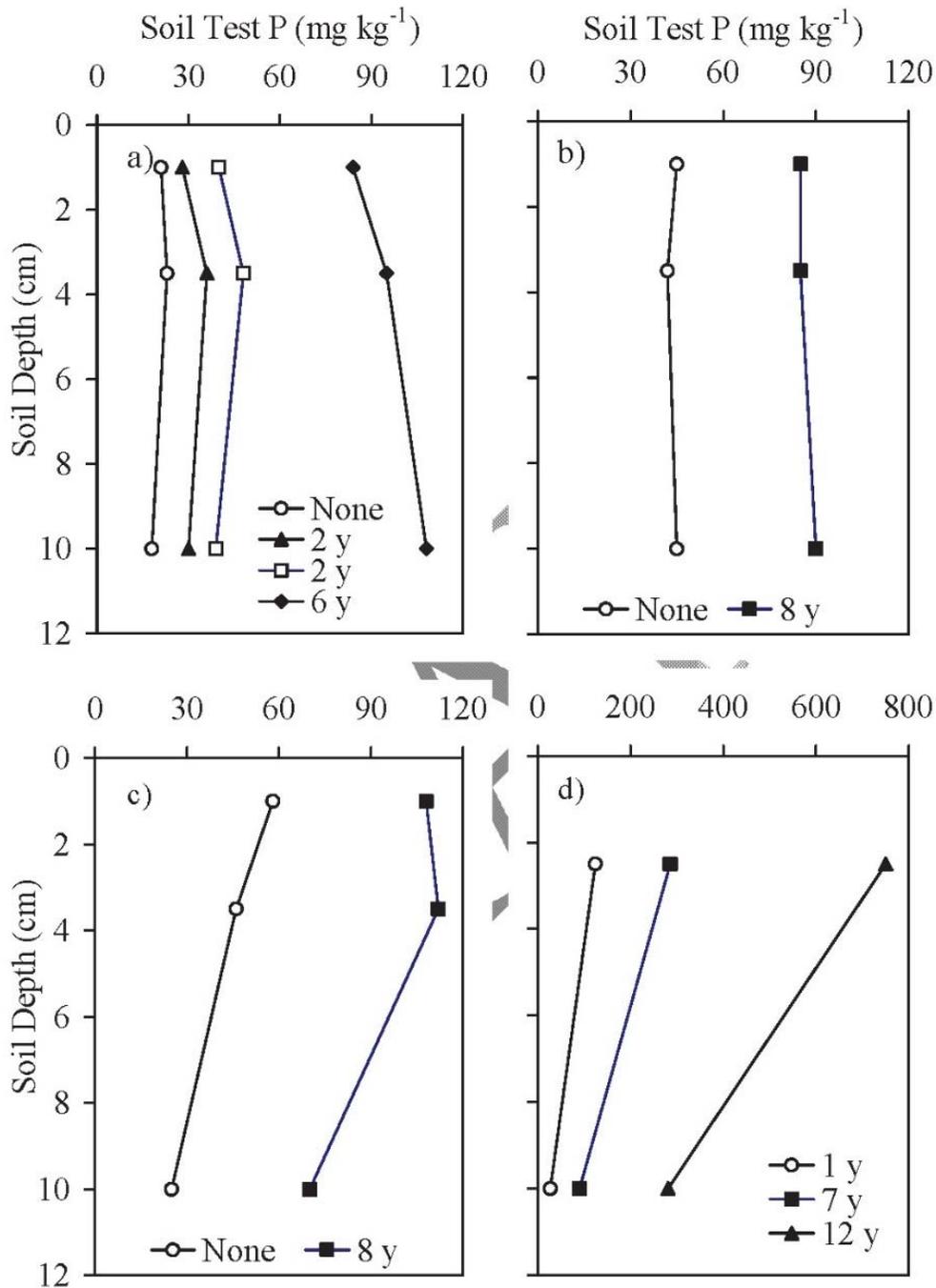
Soil Depth, cm	Soil Test P					
	Beltsville		Marlboro		Queenstown	
	Chisel Plow	No-till	Chisel Plow	No-till	Chisel Plow	No-till
0-2.5	64	120	54	54	35	52
0-15	48	47	57	38	40	40
15-30	8	8	7	4	2	3

Table 3. Soil test P (Bray-1) in three tilled and no-till soils from Wisconsin showing a greater degree of soil P stratification at the third Fond du Lac location. Data are from Andraski et al. (2003).

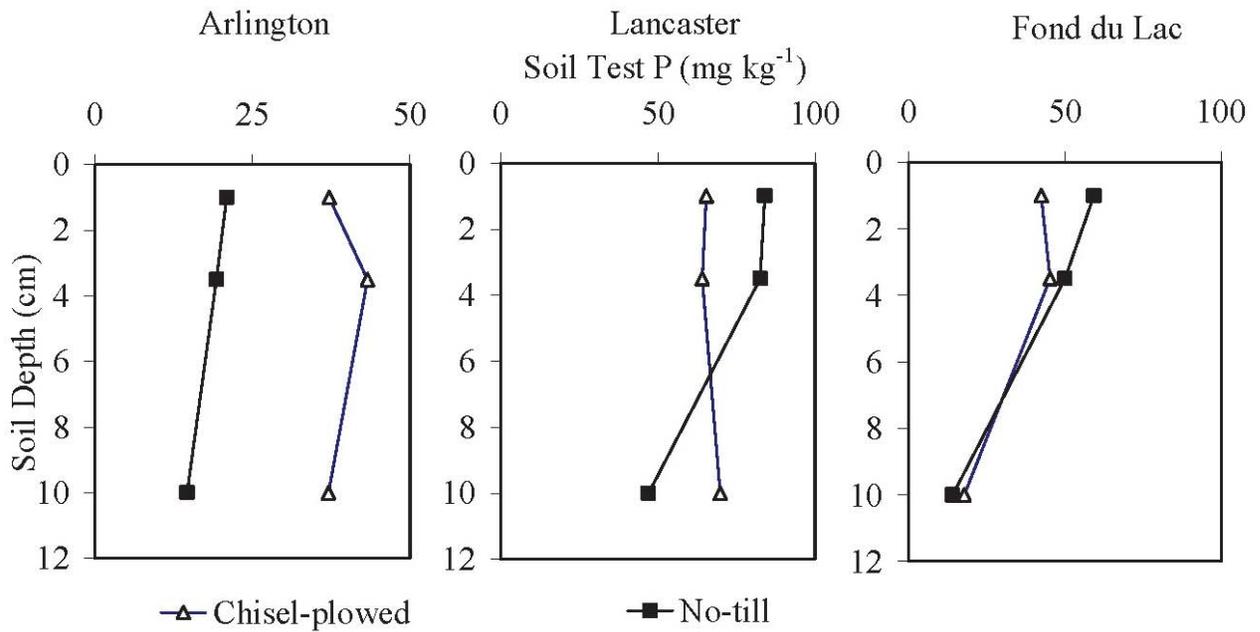
Soil Depth, cm	Soil Test P					
	Lancaster		Arlington		Fond du Lac	
	Range	Mean	Range	Mean	Range	Mean
0-2	36-138	82	5-213	34	18-274	65
0-5	36-144	80	4-195	33	18-222	59
0-15	24-152	67	3-132	27	11-89	31



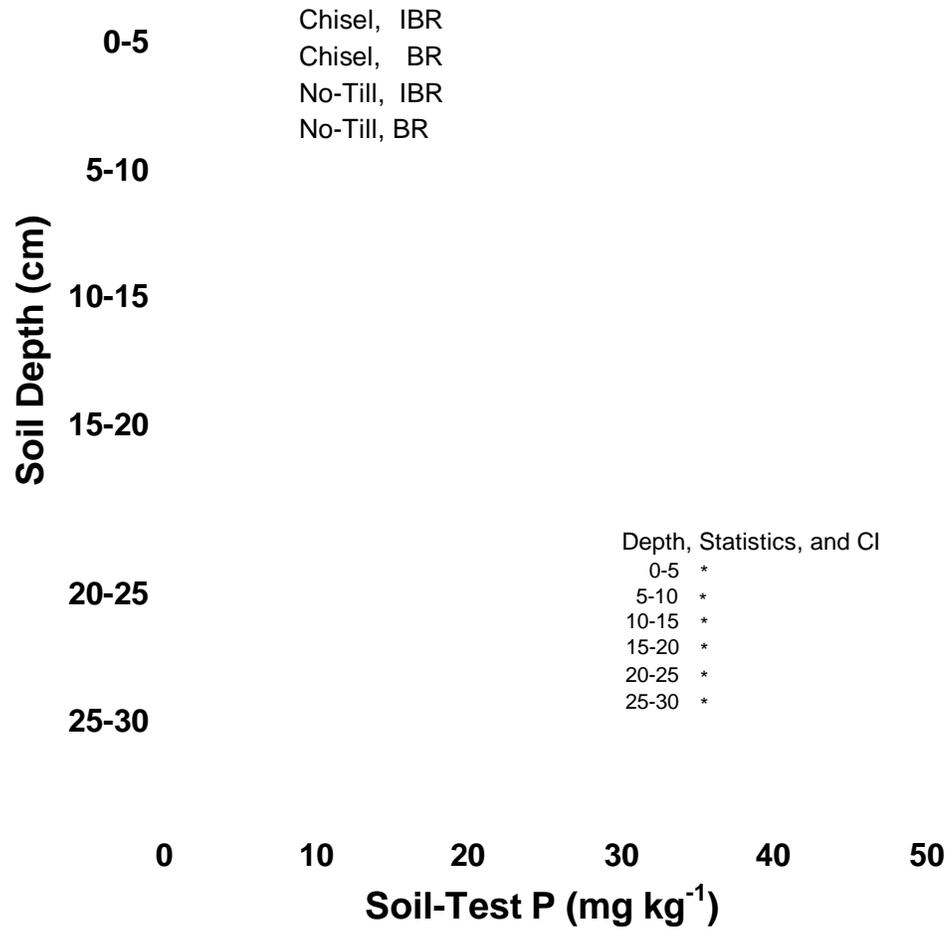
**Fig. 1.** Soil-test P showing common distribution of soil P with depth in agricultural soils from (a) Virginia (soil P extracted with NH<sub>4</sub>OAc) and (b) Alberta, Canada (soil P extracted with NH<sub>4</sub>F + H<sub>2</sub>SO<sub>4</sub>). Data are from Mahli et al. (2003) and Rechcigl et al. (1985).



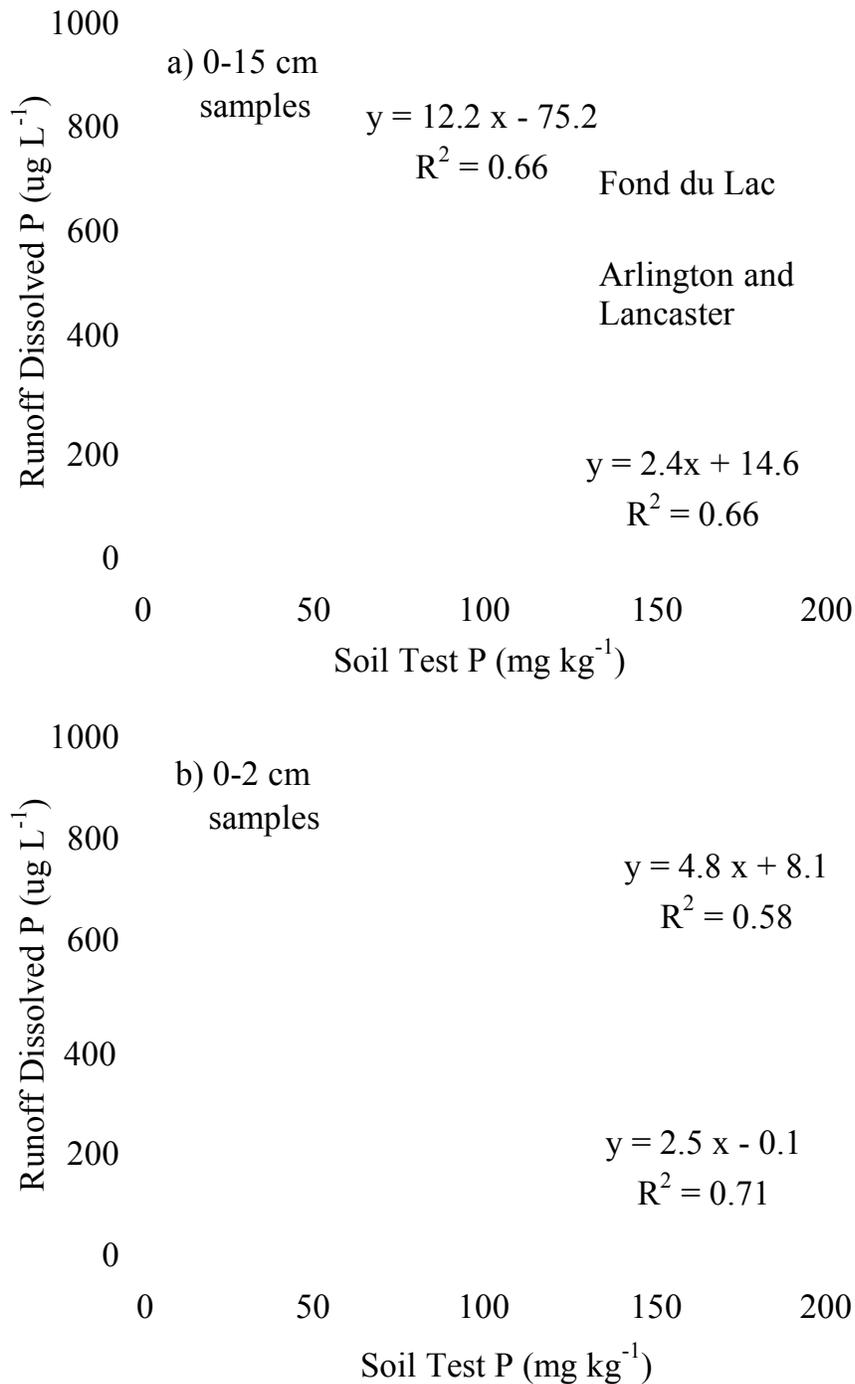
**Fig. 2.** Soil-test P showing (a and b) uniform distribution of soil P with depth in tilled soils from Wisconsin (Bray-1) and (c and d) decreasing soil-test P with depth in no-till and pasture soils from Wisconsin (Bray-1) and Louisiana (Bray-2). Legends indicate number of years P was applied to soils as fertilizer or manure. Data are from Andraski et al. (2003a) and Gaston et al. (2003).



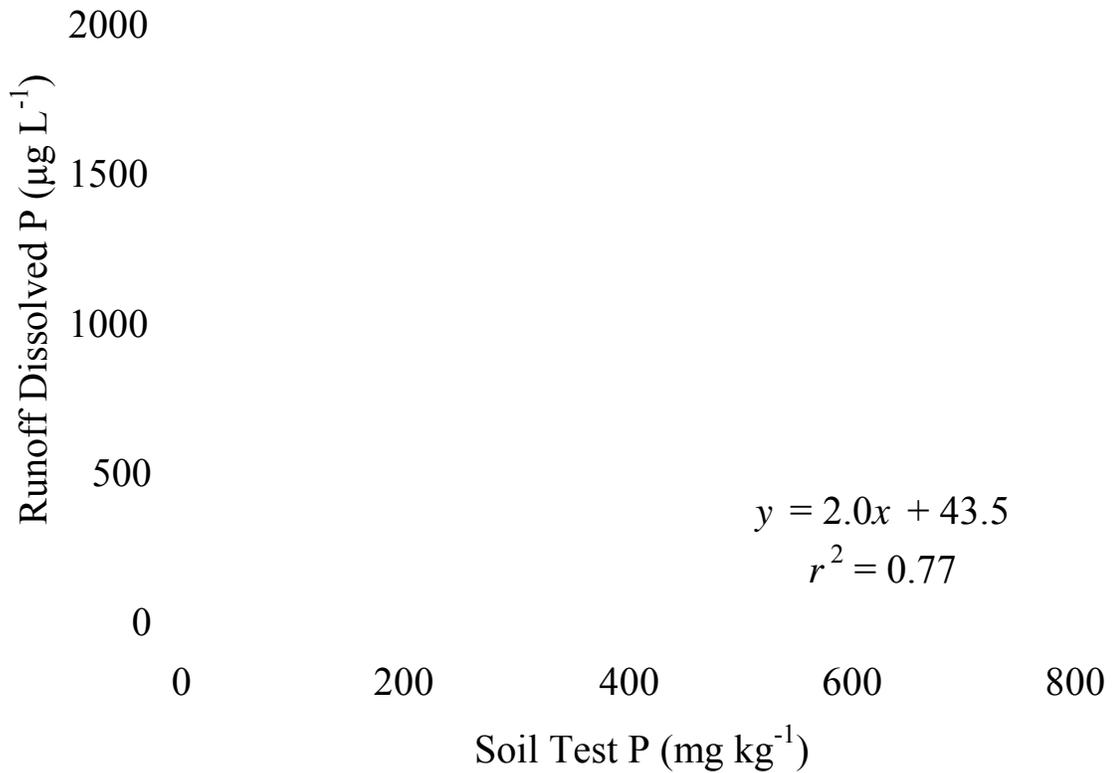
**Fig. 3.** Mean soil-test P (Bray-1) across five sites after 4 years of no-till or chisel-plow tillage and deep-band P fertilization (13 to 18 cm depth and spaced 76 cm) for row/band (BR) and inter-row/inter-band (IBR) sampling zones. \*, significant tillage or sampling zone differences ( $P \leq 0.1$ ). CI, confidence interval of a mean.



**Fig. 4.** Distribution of soil-test P (Bray-1) with depth in no-till and chisel plowed soils. Data are from Andraski et al. (2003b) from three sites in Wisconsin with similar fertilizer and tillage practices.



**Fig. 5.** Linear relationships between soil-test P (Bray-1) and dissolved P in runoff for a) 0-15 cm samples and b) 0-2 cm samples. Data are from Andraski et al. (2003b) from three sites in Wisconsin with similar fertilizer and tillage practices. Data from the Arlington and Lancaster sites with little soil P stratification behaved similarly, while data from the Fond du Lac site with greater P stratification behaved much different.



**Fig. 6.** The commonly observed linear relationship between soil-test P (Bray-1 and Mehlich-3) and dissolved P in runoff. Data are from a survey by Vadas et al. (2005) and represent 14 independent studies and 24 soil types. Data are a combination of samples taken from 0-15 or 0-20 cm in well-tilled soils and from 0-5 cm in P stratified soils, showing a consistent relationship between the two sampling depths.