FIELD-SCALE TOOLS FOR REDUCING NUTRIENT LOSSES TO WATER RESOURCES

Larry G. Bundy, Department of Soil Science, University of Wisconsin-Madison
Antonio P. Mallarino, Department of Agronomy, Iowa State University, Ames
Laura Ward Good, Department of Soil Science, University of Wisconsin-Madison

Introduction

Phosphorus (P) loss in runoff from cropland is a water quality concern because this P often promotes algae and other vegetative growth in lakes and streams (Carpenter, et al., 1998; Correll, 1998). When this vegetation decomposes, dissolved oxygen levels in the natural waters are depleted. This can cause death or damage to fish and other aquatic organisms as well as odors and a general degradation of the aesthetic and recreational value of the environment. Some evidence also exists that certain blue green algae in eutrophic waters can produce toxins which contribute to taste and odor problems and may pose a health hazard to livestock and humans if these waters are used for drinking purposes (Kotak et al., 1993; Sharpley et al, 1994).

Phosphorus entry into natural waters from point sources such as industrial discharges and municipal sewage treatment facilities are currently regulated under the provisions of water quality protection legislation. Nonpoint or diffuse sources of P entry into natural waters, such as that occurring in runoff from managed and natural landscapes, is more difficult to quantify and manage. Since cropland receives frequent P additions from fertilizers and manures, and sediment-bound P losses can occur through soil erosion, runoff from agricultural fields can contribute substantial amounts of P to water resources. Initially, P was not identified as a key nutrient influencing the extent of Gulf of Mexico hypoxia (Rabalais et al., 2001). More recently, an EPA (Region 4) paper suggested that controlling both nitrogen (N) and P loading into the Gulf of Mexico could be beneficial in minimizing hypoxia. However, the emphasis in this paper will be on addressing local surface water quality concerns.

Specifically, this paper will focus on use of field-scale tools to manage and reduce P losses from cropland. Since the development of P indices has occurred in essentially every state in the USA, these products are among the most promising approaches to predicting the risk of P losses from agricultural fields and developing appropriate management practices to control or reduce these losses (Maguire et al., 2005; Sharpley et al., 2003). The P indices developed are intended primarily to assess risk of P loss from fields and, therefore, for use as planning tools for agronomic P management. The high level of activity in development of P indices in the USA is largely in response to USDA and/or EPA proposals that all animal feeding operations (AFO's) have a nutrient management plan (addressing both N and P) in place by 2008 to address water quality concerns related to nutrient management (Heathwaite et al., 2005).

Field-Scale Tools for Assessing P Losses

National policy and general guidelines on nutrient management issued by USDA-NRCS

(1999) recognized the need for enhanced P-based nutrient management in agriculture to control nonpoint source losses of P. Three risk assessment tools were proposed in the NRCS national policy: agronomic soil test P interpretation categories; soil test P threshold values resulting in a critical runoff P concentration; or a comprehensive P loss risk assessment tool (P-index). The soil test P category option is appealing because soil test information is widely available for many agricultural fields and this parameter can be readily obtained at low cost. However, soil test P is not a reliable predictor of P loss risk because it does not consider the transport component required for P losses in runoff and subsurface drainage. Use of optimal soil test P levels for crop production as an upper limit to minimize risk of P loss from fields would be reasonable only when both animal production economics and the transport component contributing to P loss are ignored. Likewise, the soil test P threshold value option considers primarily the level of P source and not the many variables involved in transporting P from the field. In addition, this method would necessitate a massive data collection effort to determine the soil test P value associated with a critical runoff P concentration. Because soils may differ in runoff P concentrations at a given soil test P value (Pote et al., 1999; Cox and Hendricks, 2000; Andraski and Bundy, 2003) these relationships would need to be determined on many agriculturally important soils in each state. In addition, there is no consensus on what critical runoff P concentration should be used as the threshold value. A concentration of 1 ppm P, which is the typical threshold value used for point sources has been suggested (Sharpley et al., 1996). It seems likely that the critical P concentrations would need to be determined for individual receiving waters depending on the sensitivity of water quality to P additions in each case.

Of the alternative strategies proposed in the NRCS national policy, the P index risk assessment tool is most likely to provide realistic estimates of P loss risks because it can consider both source and transport components involved in P runoff losses. Most P indices in use or under development consider various source and transport factors affecting the risk of P loss (Mallarino et al., 2002). These factors typically include soil erosion potential, site characteristics affecting runoff, soil test P, and fertilizer or manure P application rates and methods.

Structure of P Indices

Initially, Lemunyon and Gilbert (1993) proposed a P index structure that involved assigning a numerical value to each major source or transport factor likely to influence P loss. In addition, a weighting coefficient reflecting the relative importance of each factor in influencing P loss was assigned. A P index value was calculated by multiplying the factor P loss rating by its weighting coefficient and summing these products across the source and transport factors considered. Index values for individual fields were categorized using a general P loss risk ranking (low to very high), and nutrient management recommendations appropriate for the level of P loss risk were made.

In P indices based on this initial design, the influence of factors affecting P losses were additive, which often did not accurately reflect the interaction of P source and transport contributions to P losses. Subsequent P indices continued with the matrix structure proposed by Lemunyon and Gilbert (1993), but included additional factors affecting P loss potential, grouped P loss factors into separate P transport and P source categories, and employed a multiplicative approach to calculating the P index value. Multiplying the P source loss potential value by the corresponding P source value allowed the P loss risk index value to indicate the strong interdependence of source and transport factors. For example, low P index values were produced when either source or transport factors were low even when the corresponding source or transport loss potential factor was very high.

The P-indices currently in use in Delaware (Leytem et al., 2003), Pennsylvania (Weld et al., 2002), and Maryland (Coale et al., 2002) are examples of the matrix or row and column P index structure described above. These indices provide a numerical or categorical rating of P loss potential on a field scale, but do not attempt to provide a quantitative estimate of annual P loss in runoff. The P index used in Pennsylvania illustrates the P source (Table 1) and transport (Table 2) factors typically included in P indices along with the weighting factors assigned to various components.

Several states in the North Central Region of the USA have developed P indices using semi-quantitative modeling approaches that attempt to estimate annual P losses on a field by field basis. In the Eastern USA, North Carolina has developed a P index using a generally similar modeling approach (NC PLAT Committee, 2005). These indices are sensitive to the need to utilize input data that is available or easily obtainable by users and are much less data intensive than more complex process-based research P loss models. The P indices developed in Iowa (Mallarino et al., 2002) (http://www.ia.nrcs.usda.gov/technical/Phosphorus/phosphorusstandard.html), Minnesota (Minnesota Phosphorus Site Risk Index, 2005), Missouri (http://www.nmplanner.missouri.edu/), and Wisconsin (http://wpindex.soils.wisc.edu/) (http://www.snapplus.net/) using a semi-quantitative modeling approach were independently constructed based on available data within each state. Informal interaction and information exchange among the four states allowed comparisons of techniques for estimating P index parameters and probably promoted commonality among the individual indices. While some distinct differences remain among the P-indices in the three states where the index is at the most advanced stages of development and implementation, there are many similarities in the approaches used to estimate P loss potential on a field-by field basis. These similarities are apparent in the general formulae used to calculate P index values in the three states (Table 3).

In all cases, the P indices seek to estimate the amount of annual P load (lb P/acre/year) lost on a field-by-field basis. The Iowa P index suggests distinct P index calculations for different “Conservation Management Units” within a field. This approach is useful for identifying areas within fields that may be sources of high P loss and for targeting soil conservation and/or crop management practices to these areas to minimize losses. All three indices estimate particulate P (PP) and soluble P (SP) separately and sum these values. The separate estimates of PP and SP are useful indicators of the mechanism of P losses in a given field and the management options that may be effective in lowering the P loss. For example, if PP is the major contributor to P loss, modification in cropping systems and tillage to control sediment loss would likely reduce overall P loss.

Alternatively, a high SP contribution to the PI total suggests losses from surface applications of P sources, high soil test P levels, or winter runoff.

While the general approach for calculating annual P loads in runoff is similar among states, the specific algorithms for calculating individual components needed to estimate P loss are often different. Some of the similarities and differences in the Iowa, Minnesota, and Wisconsin P indices are summarized in Table 4. All three states use RUSLE2 to estimate sediment delivery. Iowa and Minnesota calculate a field-to-stream sediment delivery ratio using the distance from field to stream. Wisconsin takes into account both sediment-bound and dissolved P transport from field to stream in its total P delivery factor which is based on distance and slope of the drainage path. The influence of vegetative buffers is accounted for by somewhat different approaches in Iowa and Minnesota while a process to account for buffer influences is under development in the Wisconsin index. Particulate P loss estimates are adjusted for recent P applications (since the last soil test P measurement) in Minnesota and Wisconsin, but not in Iowa. Similar approaches are also employed in the three states for estimating the dissolved or soluble P component of P loss with runoff volume estimates being based on runoff curve numbers and precipitation data. Soil test P values from several recommended tests for crop production are uniformly employed to calculate dissolved P concentrations in runoff, and adjustments for recent P additions are accomplished using soil P buffer capacity information. Dissolved P loss in runoff from recent surface P applications from rainfall and snowmelt events are accounted for through use of time and method of applications factors in the Iowa P index. Minnesota and Wisconsin use somewhat different processes to estimate soluble P from winter runoff. However, all states use information on amount of P applied, expected percentage of applied P lost in runoff, tillage, and application time in their estimates.

In the Iowa P index, a separate internal drainage component considers the impacts of subsurface tile drainage systems, water flow volume to tile lines, surface water recharge from subsurface flow, and the soil P level on the amount of total dissolved P delivered to surface water resources through flow to tile lines or surface water recharge from subsurface flow. It uses existing databases for soils and landscape forms, an estimate of water flow as a proportion of historic county precipitation data, and a two-class soil P factor based on soil test P and empirical data.

Validation of P Indices

Validation of P indices as tools for predicting the risk of P runoff from agricultural landscapes requires measurement of actual annual P runoff losses from field-scale areas where P index values for the same fields can be obtained. Currently, little information is available confirming the relationship between P index values and measured annual P runoff losses from individual fields.

Several reports have compiled information on the relative proportion of agricultural fields in a designated region that would be assigned to various interpretive categories for the P index being evaluated (Coale et al., 2002; Leytem et al., 2003). While these studies provide valuable information on the magnitude of management changes needed to bring most fields into an acceptable interpretive category, no information on the relationship between P index values and actual P losses is obtained. Usually the P index interpretive categories used are not directly tied to environmental criteria for P loss, and the need for field validation is recognized by the authors (Coale et al., 2002; Leytem et al., 2003).

Veith et al. (2005) recently compared measured P runoff losses from a south-central Pennsylvania watershed with losses from this watershed predicted by the Soil and Water Assessment Tool (SWAT). The SWAT model is a complex watershed-level research-based simulation model (Arnold et al., 1998). Direct measurements of runoff P were conducted during a 7-month period (April through October) during four years (1997-2000), thus the runoff P measurements did not include winter runoff contributions. In addition, field-level P loss predictions from SWAT for 22 fields within the monitored watershed were compared with values from the Pennsylvania P index for the same fields. Results showed that watershed P loss measurements for dissolved and total P were of the same magnitude as SWAT P loss predictions. The P index and SWAT categorized P loss risk similarly for 73% of the 22 fields evaluated, and P loss assessments by the two methods were well correlated. The authors concluded that the P index can be reliably used to assess where P losses occur in a watershed and where management practices are needed to control losses and ultimately provide for improved water quality.

In Wisconsin, (Good et al., 2005, unpublished) annual (12 month) measurements of P runoff losses were obtained from 21 crop years at a field or sub-watershed scale, and these measurements were compared with the Wisconsin P index values for the same areas. The 21 sites represented 18 fields on 7 farms in 4 major topographic areas of the state. Soil textures included silty clay loam, silt loam, and loam, slopes ranged from 4 to 13%, crops included alfalfa, alfalfa/brome, corn grain, and corn silage, and manure was applied (4 incorporated, 7 surface) in the monitoring year in 11 of the 21 sites. Eight of the runoff monitoring stations utilized passive interception devices with drainage areas of 0.04 to 2.5 acres. The remaining 13 sites were equipped with H-flumes and USGS automated gauging stations with drainage areas of 9 to 40 acres. Runoff volumes and analyses of runoff for sediment, total P and dissolved P were compiled for each site.

Data in Figure 1 show that measured annual edge-of-field P loads from the monitored areas were well correlated ($r^2 = 0.79$) with the Wisconsin P index edge-of-field values calculated for the same areas. This finding indicates that the Wisconsin P index is a reliable predictor of actual P runoff losses from cropland. As expected, no relationship was found between annual runoff P loads and field average soil test P values, since soil test P alone indicates only the level of P source and does not reflect the transport component involved in runoff P losses (Figure 2).

Little information is available to evaluate the performance of matrix or row and column P indices relative to indices using a semi-quantitative modeling approach. Figure 3 shows the relationship between index values calculated using the Pennsylvania P index and measured annual P runoff loads from the same 21 locations as used in Figures 1 and 2. Comparison of Figures 1 and 3 indicate that the Wisconsin P index values are much more closely related to measured P losses than the P-index values calculated with the Pennsylvania P index. Since the P indices used in Wisconsin and Pennsylvania were developed from local information available in each state, part of the difference in performance may be due to state-specific influences that are reflected in the P index calculations. Specifically, the Pennsylvania P index may not reflect measured P losses under Wisconsin conditions because this index was developed using information specific to factors affecting P losses in Pennsylvania. Alternatively, the site-specific quantitative consideration of factors affecting P runoff losses that can be obtained with the modeling approach used in the Wisconsin P index may have better capability to predict runoff P losses.

Summary and Conclusions

Field-scale tools for predicting the risk of P losses have potential for identifying areas most likely to contribute P to water resources and for focusing management practices to control these losses. Phosphorus loss assessment tools function by evaluating factors known to affect the extent of P losses and using these results as the basis for nutrient management planning. Ideally, these tools will consider both source and transport components involved in P losses. Currently used field-scale tools for assessing the risk of P losses to water resources include mainly soil test P and P indices. The extent of loss identified by these tools is expressed as a categorized risk level (eg. low to high), or as a semi-quantitative estimate of annual P loads in runoff. Limited validation work indicates a good relationship between measured field-scale P losses and edge-of-field index values from P indices used in several states.

The field scale assessment tools available are intended for use as planning tools to identify appropriate management practices that will lower P losses. As such, the quantitative reduction in P loss that could be achieved by application of these tools will vary on a field by field basis and will depend on the factors influencing these losses and the practices selected to reduce the losses. Field scale P loss assessment tools are useful for identifying cropland that could benefit from improved management to control losses. Some P-indices may also have potential for identifying high P loss areas within fields and for targeting practices to control these losses. Application of these tools should have limited impact on crop yields and may enhance long-term productivity by minimizing soil erosion. Effective application of these tools will require user training.

Evaluation of field scale tools indicates that field average soil test P levels have little value in predicting P loss because this parameter considers only P source components and does not consider P transport factors. A good relationship was found between annual field-scale measurements of P loss and P index values derived from a semi-quantitative model P index in Wisconsin. Less favorable relationships were found between these measured P runoff losses and P index values from the matrix-type P index used in Pennsylvania. Additional validation of field-scale tools against measured annual P losses is needed.

Interpretive Summary

Practices Recommended

- Use P indices developed with local data to provide the best assessment of the risk of P losses from cropland.
- P indices using a semi-quantitative modeling approach may have advantages since they provide site-specific quantitative consideration of factors affecting P runoff losses.
- Do not use soil test P alone as a predictor of P loss risk, since this parameter does not consider the transport component of P loss.

Important Considerations

- P indices reflect both source and transport factors involved in P runoff losses.
- Limited validation data shows good relationships between measured field scale P runoff losses and P index values.
- P indices based on semi-quantitative models can evaluate alternative practices for controlling P losses.
- Alternative management practices suggested by P indices provide users with flexibility in selecting an approach to controlling P losses.

Limitations

- Substantial research data bases on the effects of site and management factors on the risk of P losses in runoff are needed to construct reliable P indices.
- Effective application of P indices as nutrient management planning tools will require user training.
- Some of the management alternatives suggested by P indices may have significant implementation costs and could reduce crop yields in specific production situations. Users must evaluate the range of management options to select those providing the greatest benefit.

Potential

- Phosphorus indices have potential for identifying the mechanisms of P loss in specific runoff situations and for suggesting appropriate management options for lowering these losses.
- Improved management practices identified by P indices can often be implemented at low cost and may improve crop yields and long-term productivity.

Additional Information Needed

- Additional validation of field scale tools such as the P index are needed to confirm their reliability as risk assessment tools

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Table 1. The Pennsylvania P Index: Source factors (Weld et al., 2003).

Contributing Factors	Risk Levels				
	Very Low	Low	Medium	High	Very High
Soil test P risk	Risk value = Mehlich-3 soil test P (mg kg^{-1} P) × 0.20				
Loss rating for P application method and timing	Placed with planter or injected more than 2 in. deep	Incorporated <1 week after application	Incorporated >1 week or not incorporated following application in spring - summer	Incorporated >1 week or not incorporated following application in autumn - winter	Surface applied on frozen or snow-covered soil
	0.2	**0.4**	**0.6**	**0.8**	**1.0**
Fertilizer P risk	Risk value = Fertilizer P application rate (lbs P_2O_5 acre^{-1}) × Loss rating for P application				
Manure P availability	Based on organic P source availability coefficients [a]				
Manure P risk	Risk value = Manure P application rate (lbs P_2O_5 acre^{-1}) × Loss rating for P application × P availability coefficient				
Source factor = Soil test P risk + Fertilizer P risk + Manure P risk					
[a] The appropriate phosphorus availability coefficient to use in developing a nutrient management plan is determined based on the organic P source: 1.0 = swine slurry; 0.9 = layer, turkey, duck, liquid dairy; 0.8 = broiler, bedded pack dairy, beef, biological nutrient removal biosolids; 0.5 = alum-treated manure; 0.4 = alkaline-stabilized biosolids; 0.3 = conventionally stabilized and composted biosolids; and 0.2 = heat-dried and advanced-alkaline stabilized biosolids.					

Table 2. The Pennsylvania P Index: Transport factors (Weld et al., 2003).

Characteristics	Risk Levels				
Soil Erosion	Risk value = Annual soil loss = ____________ tons acre $^{-1}$ year $^{-1}$				
Runoff Potential	Very Low	Low	Medium	High	Very High
	0	**1**	**2**	**4**	**8**
Subsurface Drainage	None		Random		Patterned [a]
	0		**1**		**2**
Contributing Distance	>500 ft.	500 to 350 ft.	350 to 250 ft.	250 to 150 ft.	<150 ft.
	0	**1**	**2**	**4**	**8**
Transport sum = Erosion + Runoff potential + Subsurface drainage + Contributing distance					
Modified Connectivity	Riparian buffer *Applies to distances <150 ft.*		Grassed waterway or none		Direct connection *Applies to distances >150 ft.*
	0.7		**1.0**		**1.1**
Transport factor = Transport sum × Modified connectivity / 22 [b]					
P Index = 2 × Source sum × Transport sum					

[a] Or a rapidly permeable soil near a stream.

[b] Transport value is divided by 22 (i.e., the highest value obtainable) in order to normalize transport to a value of 1, where full transport potential is realized

Table 3. General structure of P-indices in Iowa, Minnesota, and Wisconsin.

State	P-index formulae
Iowa	PI = PP + SP + Subsurface P
Minnesota	PI = PP + rainfall SP + snowmelt SP
Wisconsin	PI = (PP + SP + event losses) x TP delivery ratio

PI = P index value; PP = particulate P; SP = soluble P; TP = total P

Table 4. Comparison of components used in the Iowa, Minnesota, and Wisconsin P indices.

P index component	Iowa	Minnesota	Wisconsin
Particulate P:			
Sediment delivery	RUSLE2	RUSLE2	RUSLE2
Sediment delivery ratio	Distance to stream	Dis. field to stream	Distance & slope on TP
Buffer factor	Buffer width	Sediment trap factor	Under development
Sediment P content	Calc. from soil test P	Calc. from soil test P& organic matter	Calc. from soil test P & organic matter
Adjust. of PP for recent P additions	None	Optional based on soil P buffer cap.	Soil test P adjusted based on buff. cap.
PP enrichment factor	1.1-1.3 depending on mgmt. practices	None	Under development
Dissolved/soluble P:			
Runoff volume	From runoff curve nos. & % of precip.	From runoff curve nos. & % of precip.	Ave. precip., runoff curve nos. + winter runoff
Dissolved P in runoff	From soil test P	From soil test P	Soil soluble P from soil test P x extraction efficiency
Adjust. of DP for recent P additions	From buffer cap. & method & time factor	Optional based on soil P buffer cap.	Soil test P adjusted based on buff. cap.
Dissolved P from surface P applications	Included in adjust. of DP for recent P additions (above)	From amount of P applied, timing, and tillage	Included in soil test P adjust. (above) + single event P loss
P in snowmelt and from winter applied manure	Included in adjust. of DP for recent P additions (above)	From snowmelt runoff volume, tillage, % of applied P, and residue P	Est. worst-case loss from: manure soluble P, % P loss, slope, and tillage

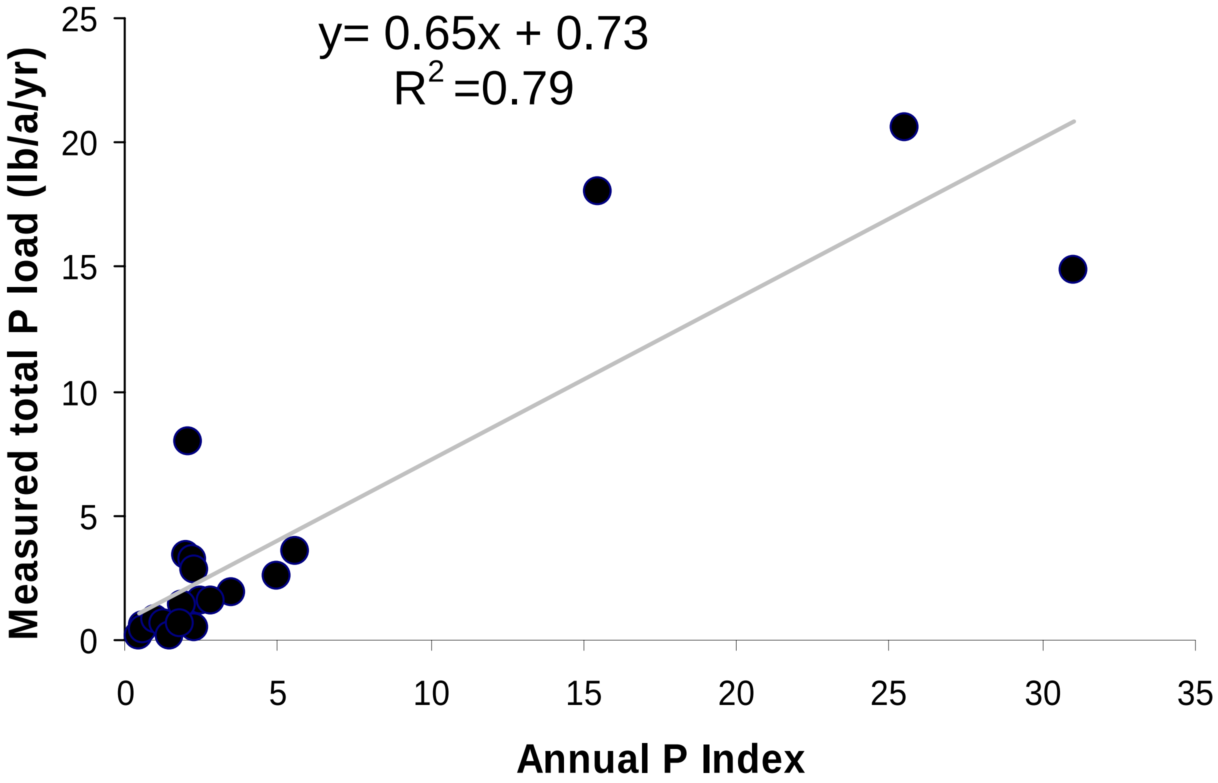

Figure 1. Relationship between measured annual runoff P loads and Wisconsin P index values for 21 field locations in Wisconsin.

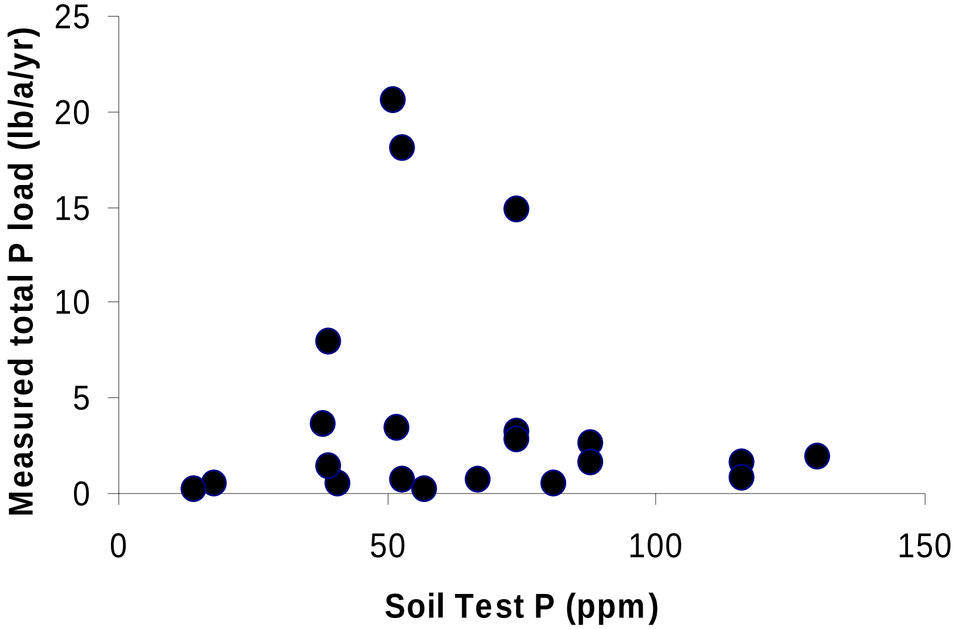

Figure 2. Relationship between measured annual runoff P loads and Bray P-1 soil test values for 21 field locations in Wisconsin.

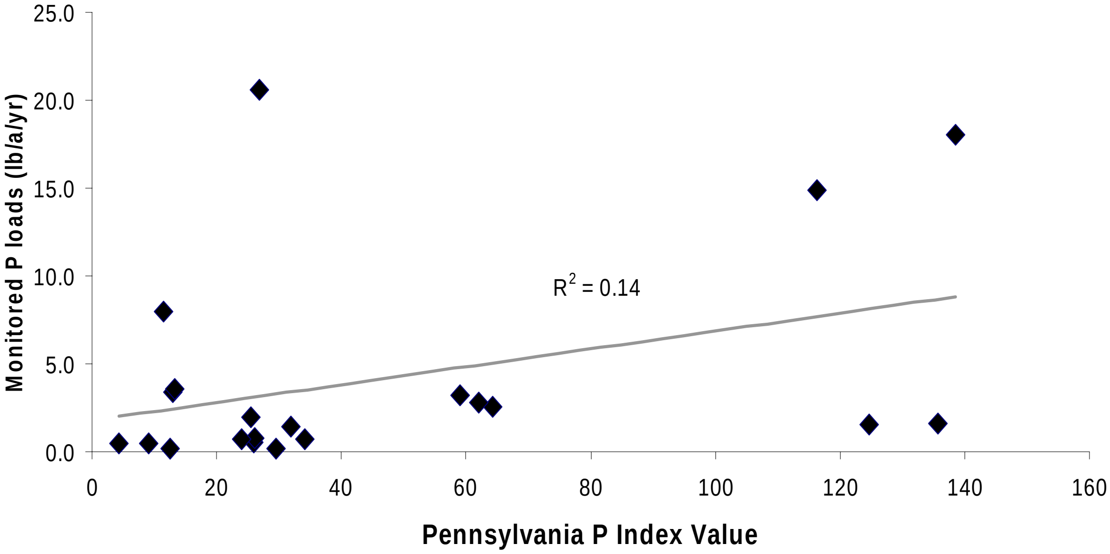

Figure 3. Relationship between measured annual runoff P loads and P index values calculated using the Pennsylvania P index for 21 field locations in Wisconsin.

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