On-farm evaluation of a phosphorus site index for Delaware

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ABSTRACT: The contribution of phosphorus (P) to non-point source (NPS) pollution of surface and groundwaters is a serious environmental problem in Delaware. In 1999, the Delaware Nutrient Management Act was passed limiting application of P on "high" P soils to a "three year crop removal" rate or to the amount recommended by a University of Delaware P site index. The Delaware P site index was developed and evaluated on seven farms in Delaware, through a joint effort between the universities of Delaware and Maryland. Results showed that 78% of fields evaluated were in the "low" risk category, with the remaining 22% falling into the "medium" (6%), "high" (7%), and "very high" (9%) risk categories. The components of the index found to have the greatest influence on P site index ratings were soil erosion, subsurface drainage, leaching potential, distance from field to surface water, soil test P and organic P application rates and methods. P site index ratings were found to vary by year, depending on manure applications, suggesting a need for yearly P site index evaluations or averages over a cropping rotation. The P site index worked well for identifying fields with differing relative potential risks of P loss; however, validation of these P loss assessments is needed to ensure that the risk categories assigned are sufficiently protective of water quality. Continual monitoring, analysis, and improvement of the P site index are needed to ensure that it remains a useful tool for P based nutrient management planning in the future.

Keywords: Delmarva, phosphorus, phosphorus site index

Nonpoint source pollution of surface waters and groundwaters by agricultural nutrients has been a serious environmental problem in Delaware for more than 30 years (Cabrera and Sims, 2000; Hamilton and Shedlock, 1992; Ritter and Chirnside, 1984; Shedlock et al., 1999; Sims and Coale, 2002). The issues of greatest long-standing concern have been, and continue to be, groundwater contamination by nitrate-nitrogen (NO_3-N) and surface water eutrophication by nitrogen (N) and phosphorus (P). Numerous factors have contributed to these water quality problems, including soil properties, topography, hydrology, climate, nutrient management, and the nature of Delaware agriculture. Due to the relatively flat topography in most of the state, soil erosion and surface runoff are not necessarily the dominant transport pathways of P loss to surface waters. Many Delaware soils are sandy, low in organic matter and thus are susceptible to P leaching. Groundwater aquifers are often shallow and interconnected with surface waters and rainfall is plentiful (39 in per yr or 100 cm per yr).

Agriculture in Delaware is nutrient intensive, dominated by a large and geographically concentrated poultry industry and grain and vegetable crop production. Poultry production in Delaware has nearly tripled since the mid-1950's now producing about 260,000 million broiler and roaster chickens annually. Most of the increase has occurred primarily in Sussex County, which is one of the largest poultry producing counties in the United States (DDA, 2001). During this same time period, the number of farms and hectares of cropland available in Delaware to efficiently use the by-products created by the poultry industry has decreased. Intensification of animal agriculture in this manner has created farm and regional nutrient surpluses, primarily in the form of animal manures that traditionally have been land applied because of the absence of any other economically viable options. Compounding the situation has been the use of commercial fertilizers on some farms when excess manure nutrients were available from other farms in the region, usually because of the costs and logistical problems associated with transporting manures more than a few miles from the site of their generation. In 1998, a statewide mass balance for N and P indicated that there was a yearly N surplus of 73 lbs acre^{-1} yr^{-1} (83 kg ha^{-1} yr^{-1}) and a P surplus of 26 lbs acre^{-1} yr^{-1} (30 kg ha^{-1} yr^{-1})(Sims et al., 1998). The P surplus is particularly troubling given the fact that recent statewide soil test summaries by the University of Delaware showed that 85% of the soil samples tested from commercial cropland were either "optimum" (27%) or "excessive" (58%) in P, from an agronomic standpoint, and thus need little or no application of fertilizer or manure P to attain economically optimum crop yields.

In the past 30 years, much research has been conducted in Delaware and other Mid-Atlantic states to develop improved N and P management practices. At the same time, many voluntary technical assistance programs have been implemented, with mixed success, to foster improved nutrient management planning for water quality protection. However, in 1997, a series of events began that altered the approach used in Delaware for nutrient management, causing a movement away from the voluntary methods of the past and toward a more structured, regulatory approach.

First, in 1997, as a result of a lawsuit filed by environmental action groups, the U.S. Environmental Protection Agency (USEPA) negotiated a Total Maximum Daily Load (TMDL) agreement with Delaware's Department of Natural Resources and Environmental Control. The agreement mandated that the state establish TMDLs for N, P, sediments, and pathogens for all impacted water bodies and called for pollution control strategies to make these waters "fishable and swimmable" by 2007. The process of establishing TMDLs is now well

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underway in Delaware and assessments to date indicate that reductions in N and P loading to surface waters from 40-85% will be required from nonpoint sources to achieve the goals of the Clean Water Act.

Second, in response to intense public and media pressure associated with fish kills and algal blooms an "Agricultural Industry Advisory Committee on Nutrient Management" was appointed by Delaware's Governor in 1998 to address the issue of agricultural nonpoint source pollution. This committee issued a series of recommendations that led to the passage of the 1999 Delaware Nutrient Management Act that established a "Delaware Nutrient Management Commission" and charged them with the development and implementation of a state nutrient management program (Sims, 1999). A similar law had been passed in 1998 in Maryland (Simpson, 1998). Both the Agricultural Industry Advisory Committee on Nutrient Management and the Delaware Nutrient Management Act stressed the need to reduce nonpoint source P pollution of surface waters and groundwaters. In fact, the Delaware Nutrient Management Act specifically mandated that *"application of P to high P soils cannot exceed a three year crop P removal rate"*. The specific definition of a "high P" soil was left to the Delaware Nutrient Management Commission who were also charged with developing "P-based" nutrient management practices for fields and farms that were sufficiently "high" in P to be of environmental concern.

In 1999, researchers and extension specialists began working with the Delaware Nutrient Management Commission and others in Delaware and Maryland to develop a reliable means to identify "high P" soils based on the risk of P transport from fields to surface and shallow groundwaters, as a function of site properties (topography, drainage, leaching potential, proximity to surface water) and the management practices used for all P sources (e.g., fertilizers, manures, biosolids). The approach selected was the phosphorus site index, originally described by Lemunyon and Gilbert (1993) and previously evaluated in Delaware in the early 1990s (Sims and Ritter, 1993). This paper describes the on-farm evaluation of the Delaware P site index and the advantages and disadvantages associated with the use of this approach to guide the implementation of "P-based" nutrient management plans for agriculture.

The Delaware phosphorus site index. The Universities of Delaware and Maryland worked together to develop a common P site index for use in Delaware and Maryland because of the similarity in soils, cropping systems, agricultural nutrient management practices, and nutrient management laws in the two states. Details of the approach we followed are provided elsewhere (Coale et al., 2002; Sims et al., 2002). In brief, we modified earlier versions of the P site index (Lemunyon and Gilbert, 1993; Sims, 1996) through many discussions with scientists in the Mid-Atlantic region and with representatives of state and federal technical, advisory, and regulatory agencies (e.g., conservation districts, NRCS, Delaware Nutrient Management Commission, Department of Natural Resources and Environmental Control). We also reviewed and included concepts that were based on recent research on the factors controlling P loss from soil to water. In general, we believed that it was critical to target limited resources initially at areas where the interaction of P source, P management, and P transport processes result in the most serious risk of P losses to surface and shallow groundwaters.

We decided that any risk assessment process for the potential effect of soil P on water quality should include the following: (i) the concentration and bioavailability of P in soils susceptible to loss by erosion; (ii) the potential for soluble P release from soils into surface runoff or subsurface drainage; (iii) any characteristics of the P source (fertilizer, manure, biosolids) that influence its solubility and thus the potential for movement or retention of P once the source has been applied to a soil; (iv) the effect of other factors, such as hydrology, topography, soil, crop, and P source management practices, on the potential for P movement from soil to water; and, (v) the sensitivity of surface waters to inputs of P and the proximity of these waters to agricultural fields.

The final version of the Delaware P site index ultimately adopted by the Nutrient Management Commission in 2000 is provided in Table 1 and generalized interpretations of P site index ratings now used are given in Table 2. Note that we decided that the current P site index, unlike earlier versions, should be multiplicative in nature. In this approach the effects of site and transport characteristics on P loss (Part A) are determined first, in an additive manner and then multiplied by a scaling factor of 0.02 to express P transport potential on a scale of 0 to 1.0. Next, the effects of P source and management on P loss (Part B) are also determined in an additive manner, and the two sums are multiplied together to obtain the overall P loss rating for a site.

A multiplicative approach (Part A x Part B) was used to ensure that the highest P site index values were assigned to those fields that had both a high P transport potential (Part A) and a high potential for P loss due to P source management (Part B). We recognized that this approach will also tend to assign lower risks of P loss to fields that have high soil P values or high P source management loss factors but low risks of P transport to surface waters or shallow groundwaters. In doing this we assumed that other management practices, guidelines, or regulations would address the possible long-term environmental impacts of the accumulation of P to very high levels in soils with low risks of P transport to water.

Methods and Materials

The Delaware P site index was evaluated in 2000-2001 using 272 fields located on seven farms. Farms were selected to represent typical agricultural production operations in their region and ranged in size from approximately 200 to 6,000 acres (80 to 2,400 ha) (Table 3). The farms varied from cash grain operations, with no animal production on site, to small farms dominated by animal agriculture. In some cases the main form of P added was fertilizer while on other farms use of manure P dominated. To conduct P site index evaluations, we identified farm field boundaries using digital orthophotos. Information was then collected from the farm owner or manager on soil test P results (expressed in fertility index value units[1]), crop rotations, tillage, fertilizer and manure use, as well as application methods and timing for all P sources for each field. After the preliminary data were collected, each field was visited and information on slope, length of slope, proximity of the field to surface waters, and the nature (e.g., type of vegetation, length, width) of any buffers adjacent to surface waters was obtained. Slope measurements (% slope) were made in the field using a clinometer. The predominant slope in the field was measured except in instances where a stream, ditch or other surface water source bordered the field. In these cases, the main slope measured in the field was toward the surface water. Distance from edge of field

Table 1. The Delaware phosphorus site index.

Part A: Phosphorus loss potential due to site and transport characteristics.

Characteristics	***Phosphorus loss rating***					***Value***
Soil erosion	2 x [Soil erosion value from RUSLE* (tons/acre)]					
Soil surface runoff class	Very low **0**	Low **2**	Medium **4**	High **6**	Very high **8**	
Subsurface drainage	Very low **0**	Low **2**	Medium **4**	High **6**	Very high **8**	
Leaching potential	Low **0**		Medium **2**	High **4**		
Distance from edge of field to surface water	> 100 ft **0**	< 100 ft AND > 50 ft vegetated buffer ***OR*** < 100 ft AND > 25 ft vegetated buffer AND > 25 ft additional no P application zone **2**	< 100 ft AND > 25 ft vegetated buffer AND < 25 ft additional no P application zone **4**	< 100 ft AND < 25 ft vegetated buffer AND > 25 ft additional no P application zone **6**	< 100 ft AND < 25 ft vegetated buffer AND < 25 ft additional no P application zone **8**	
Priority of receiving water	Very low **0**	Low **1**	Medium **2**	High **3**	Very high **4**	

***Revised Universal Soil Loss Equation**

Sum of site and transport characteristics: ______

Scaling factor: χ **0.02**

Total site and transport value: ______

Part B: Phosphorus (P) loss potential due to P source and management practices.

Characteristics	***Phosphorus loss rating***					***Value***
Soil test P fertility index value (FIV)	[0.2] x [FIV from University of Delaware soil test]					
P fertilizer application rate	[0.6] x (lbs P_2O_5 applied per acre)					
P fertilizer application method and timing	None applied **0**	Injected/banded below surface at least 2" **15**	Incorporated within 5 days of application **30**	Surface applied March through November OR incorporated in > 5 days **45**	Surface applied December through February **60**	
Organic P source application rate	[***PAC***] x (lbs P_2O_5 applied per acre)					
Organic P source application method and timing	None applied **0**	Injected/banded below surface at least 2" **15**	Incorporated within 5 days of application **30**	Surface applied March through November OR incorporated in > 5 days **45**	Surface applied December through February **60**	

Total P source and management value: ______

Table 2. Generalized interpretation of the phosphorus (P) site index.

P site index	Generalized interpretation of phosphorus site index
< 50	***LOW*** potential for P movement from this site given current management practices and site characteristics. There is a low probability of an adverse impact to surface waters from P losses from this site. Nitrogen-based nutrient management planning is satisfactory for this site. Soil P levels and P loss potential may increase in the future due to N-based nutrient management.
51 - 75	***MEDIUM*** potential for P movement from this site given current management practices and site characteristics. Practices should be implemented to reduce P losses by surface runoff, subsurface flow, and erosion. Nitrogen-based nutrient management should be implemented no more than one year out of three. Phosphorus-based nutrient management should be implemented two years out of three during which time P applications should be limited to the amount expected to be removed from the field by crop harvest or soil test based P application recommendations, whichever is greater.
76 - 100	***HIGH*** potential for P movement from this site given current management practices and site characteristics. Phosphorus-based nutrient management planning should be used for this site. Phosphorus applications should be limited to the amount expected to be removed from the field by crop harvest or soil test based P application recommendations. All practical management practices for reducing P losses by surface runoff, subsurface flow, or erosion should be implemented.
> 100	***VERY HIGH*** potential for P movement from this site given current management practices and site characteristics. No P should be applied to this site. Active remediation techniques should be implemented in an effort to reduce the P loss potential from this site.

to water was determined by measuring the shortest buffer area from the edge of the field to the closest surface water source.

Once all field data and nutrient management information had been obtained, the P site index values were calculated. Specific details of the calculations used are available in the P site index technical manuals prepared for Delaware (Sims et al., 2002). In brief, an estimate of erosion for each field was calculated using the Revised Universal Soil Loss Equation (RUSLE). Information needed to estimate surface runoff class (slope, soil permeability), subsurface drainage class (depth to seasonal high water table, soil drainage), and leaching potential (depth to seasonal high water table, soil series leaching value) was obtained from county soil survey manuals or from U.S. Department of Agriculture-Natural Resources Conservation Service. Each field in Delaware was assigned a surface water priority of "very high" based on consultations with state water quality agencies. These data, in combination with information on the

Table 3. Overview of the properties of the seven Delaware farms evaluated using the phosphorus site index (PSI).

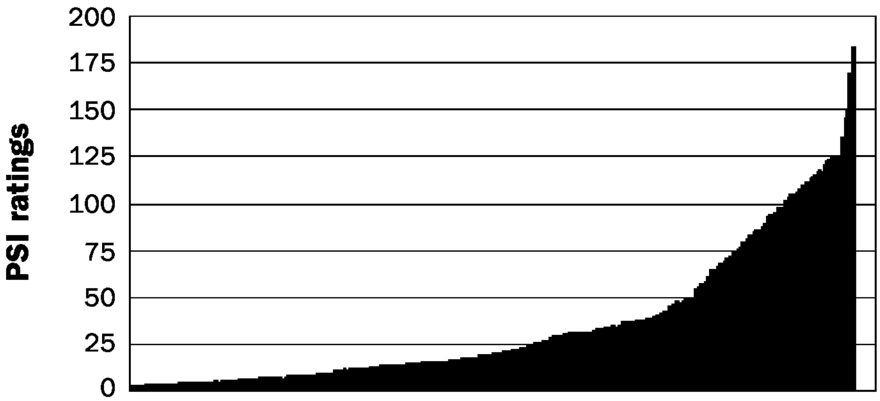
Farm number and location	Farm size	Number of fields evaluated for PSI	Major soil types	Major crops	Animal production
	— acres—				
#1: New Castle County	3000	53	Matapeake, Sassafras, Butlerstown	Corn, soybeans, small grains	None†
#2: Kent County	2500	38	Sassafras, Rumford	Orchard, vegetables, corn, soybeans, small grains	None
#3: Sussex County	6000	112	Evesboro, Fallsington, Kalmia, Pocomoke, Rumford, Sassafras	Corn, soybeans, small grains	Broilers, swine
#4: New Castle County	300	7	Matapeake, Fallsington	Corn, soybeans, small grains	None‡
#5: Sussex County	500	20	Pocomoke, Fallsington	Corn, soybeans, small grains, vegetables	Broilers
#6: Sussex County	1000	29	Evesboro, Rumford, Fallsington	Corn, barley, alfalfa, soybeans	Dairy‡
#7: Sussex County	300	13	Evesboro, Rumford, Sassafras, Woodstown	Corn, barley, alfalfa, lima beans, peas	Beef

† Farming operation is associated with large egg-laying operation but does not apply manure from that operation to fields on this farm. However, manure is sometimes imported from nearby broiler farms for use in crop production.

‡ Manure is imported from a nearby poultry operation and applied to some fields.

Figure 1

Summary of phosphorus site index (PSI) ratings for Delaware. Each bar represents the P site index value for a given field and fields are sorted in ascending order. Note that P site index categories used are: Low: < 50; Medium: 50-75; High: 76-100; Very high < 100 (see Table 2).



proximity of the field to water and buffer strips, were then used to calculate Part A (Total site and transport value) of the P site index. Soil test P data and information on the use of fertilizer and organic P sources (e.g., rate, method, and timing of application) for the most recent year available for each field were then used to calculate a value for Part B (Total P source and management value). Incorporated into the calculation of organic P source application rate is the concept of a phosphorus availability coefficient. This coefficient is used to distinguish between the relative P solubility and plant availability of fertilizer P and differing organic P sources. Research is now being conducted to determine appropriate phosphorus availability coefficient for the main organic P sources used in Delaware, however until these are compiled a single default value (0.6) is being used for all P sources. Parts A (transport) and B (source management) were multiplied to obtain the overall P site index rating for the field.

Table 4. Summary statistics (mean, standard deviation, range) for the phosphorus (P) loss rating values for each component of Part A and Part B of the phosphorus site index. Values are for the 272 fields evaluated on seven farms in Delaware.

Component	Mean	S.D.	Range
Part A: Phosphorus loss rating values			
Site and transport characteristics			
Soil erosion†	4.7	5.9	0.1 - 48
Surface runoff	1.0	1.3	0 - 4
Subsurface drainage	3.4	2.2	2 - 8
Leaching potential	0.9	1.0	0 - 2
Distance from field to water	3.2	3.5	0 - 8
Priority of receiving water‡	All fields assigned a value of 4		
Part A value§	0.34	0.15	0.13 - 1.2
Part B: Phosphorus loss rating values			
Source and management characteristics			
Soil test P†	31.2	29.1	3 - 156
P fertilizer application rate†	11.8	19.2	0 - 115
P fertilizer application method	9.8	12.2	0 - 45
Organic P application rate†	33.2	61.3	0 - 350
Organic P application method	10.6	17.4	0 - 60
Part B Value	97.1	86.7	8 - 483
Phosphorus site index rating	35	37	2 - 184

† **Values for these loss ratings are from the P site index calculations they are not expressed as actual values.**

‡ **The approach that will be used to prioritize receiving water bodies in terms of the impact of agricultural nonpoint P pollution has not been finalized in Delaware. All P site index calculations in this report assumed that the priority of all water bodies in close proximity to the fields on these farms was "very high" (P loss rating value = 4).**

§ **Part A value computed as sum of all Part A components multiplied times a scaling factor of 0.02.**

Results and Discussion

Interpretation of Delaware phosphorus site index evaluations. Figure 1 shows the distribution of P site index values for the 272 fields evaluated in Delaware. The average value for Part A was 0.34, for Part B was 97, and the average overall P site index rating was 35 (Table 4). We examined the distribution of P site index values among the four P loss categories (low, medium, high, and very high; Table 2) as well as the mean values of each component in the calculation (Table 5). Our results showed that most (78%) of the fields evaluated in Delaware were in the "low" risk category where N-based nutrient management planning would be appropriate, at least in the near term. Of the remaining 22% of the fields, 6% were rated "medium", 7% were rated "high", and 9% were rated "very high" in terms of the potential for P loss. Most, but not all, components of Part A and Part B of the P site index increased in magnitude as the risk of P loss increased from "low" to "very high" (Table 5).

The main components causing the increase in the Part A factor as the P site index rating increased from "low" to "very high" were soil erosion, subsurface drainage, leaching potential and distance from field to water. For Part B, the main components influencing the observed increases in the P site index were soil test P and organic P application rate and method. Overall there was a 50% increase in the average Part A value and a 340% increase in average Part B value for fields falling into the "very high" vs. the "low" categories. The increase in the average Part B value was much greater than the average Part A value indicating that the overall increase in P site index ratings was primarily due to P source and management practices. While the components of the average Part A value had increases of approximately 130%, the average values for organic P application rate and method increased by 1362% and 685% respectively.

The farm data was divided into three groups (poultry, dairy/beef, and vegetable/

Table 5. Mean values, by interpretive category (low, medium, high, and very high), for the phosphorus (P) loss rating value of each component of the phosphorus site index. Data are for all Delaware fields (n = 272).

	Phosphorus site index category			
Component of the phosphorus site index	Low	Medium	High	Very high
Number of samples (%)	212 (78%)	16 (6%)	18 (7%)	26 (9%)
Part A: Phosphorus loss rating values				
Site and transport characteristics				
Soil erosion†	4.3	8.1	7.4	4.0
Surface runoff	1.0	1.1	0.9	0.8
Subsurface drainage	3.0	4.1	4.0	6.0
Leaching potential	0.8	1.0	1.1	1.6
Distance from field to water	2.4	5.0	5.6	7.2
Priority of receiving water	4.0	4.0	4.0	4.0
Part A value‡	0.31	0.47	0.45	0.47
Part B: Phosphorus loss rating values				
Source and management characteristics				
Soil test P†	26.1	19.3	56.6	62.6
P fertilizer application rate†	10.6	22.18	19.0	12.2
P fertilizer application method	10.2	9.38	9.6	7.2
Organic P application rate†	10.5	69.9	97.5	153.5
Organic P application method	4.7	26.3	28.33	36.9
Part B value	62	147	211	272
Phosphorus site index rating	18	65	88	123

† Values for these loss ratings are from the phosphorus site index calculations they are not expressed as actual values.

‡ Part A value computed as sum of all Part A components multiplied times a scaling factor of 0.02.

orchard) to determine if there were any trends within particular production operations (Table 6). The two groups that had on-farm animal production (or applied manure to fields) had a higher percentage of fields falling into the "very high" risk category, compared to production using P fertilizer only. Of the two groups the dairy/beef operations had more fields in the "high" and "very high" risk category (29%) than the poultry operations (14%). The difference in P site index ratings in this case can be attributed to differences in farm operation. The dairy/beef operations used no-till or minimum till on many fields to which manure was applied, which gives a higher risk rating for manure application since the majority of the time the manure was surface applied. In addition, because of inadequate manure storage capacity, the dairy was required to spread manure year round (requiring surface application and application on frozen ground), while the poultry producing operations only had to dispose of manure after cleanout of the houses. One problem that was common to all farms utilizing manures was the over-application of P compared to crop requirements and the application of manure in close proximity to surface water sources.

The data was then further separated into two groups, those that received manure application and those that had fertilizer P applications only (Table 6). When these data groups were examined, 51% of the fields receiving manure fell into the "high" and "very high" risk categories compared to only 2% of the fields not receiving manure application. In contrast, there was little difference in the transport factors associated with manured and non-manured fields (Part A= 0.37 and 0.33, respectively). This indicates that it is the P source and management factors at these sites that are primarily influencing the P site index ratings. Further, the majority of fields receiving manure application already had excessive STP due to a past history of over-application of manure P and therefore had an average STP value 100% greater that of fields not receiving manure. The average planned P application rate for manure was approximately 700% greater than that of the planned fertilizer P application rate and the average application method rating was 200% greater than that for manure vs. fertilizer P.

Analysis of the Delaware phosphorus site index. In general, the Delaware P site index identified farm fields that would likely be identified by a nutrient management specialist as being the highest priority for immediate improvements in P management (Table 5). This is illustrated clearly in Figure 2, which provides data on soil erosion, soil test P, and planned organic P application rates for the 44 fields in the "high" and "very high" categories. Clearly, one or more of the following actions are needed in these fields: (i) reduce soil erosion; (ii) better manage organic P sources by reducing the planned rate or changing the planned time of application of animal manures; or (iii) prevent further buildup of soil test P or even deplete soil P from excessive to optimum values by using crop management strategies that enhance P removal in harvest.

However, as noted above, the P site index assessments in this state also suggested that 78% (212 fields) of the fields evaluated could continue to use N-based nutrient management, a practice that is known to increase soil P values with time (Cabrera and Sims, 2000; Sims, 1997; Sims and Coale, 2002). While following N-based management practices with these 212 fields will likely result in their eventual re-classification into the "medium"

Table 6. Distribution of phosphorus site index ratings by interpretive rating (low, medium, high, and very high) according to farm production operation and by manure usage.

		Phosphorus site index category			
Field category	No. of fields	Low	Medium	High	Very high
Poultry†	192	154 (80%)	11 (6%)	10 (5%)	17 (9%)
Dairy/beef‡	42	27 (64%)	3 (7%)	4 (10%)	8 (19%)
Vegetable/orchard	38	31 (82%)	3 (8%)	3 (8%)	1 (2%)
No manure applied	193	185 (96%)	4 (2%)	3 (1.5%)	1 (0.5%)
Manure applied	79	27 (34%)	12 (34%)	15 (19%)	25 (32%)

† Some farms receiving manure application do not have on-site animal production facilities.

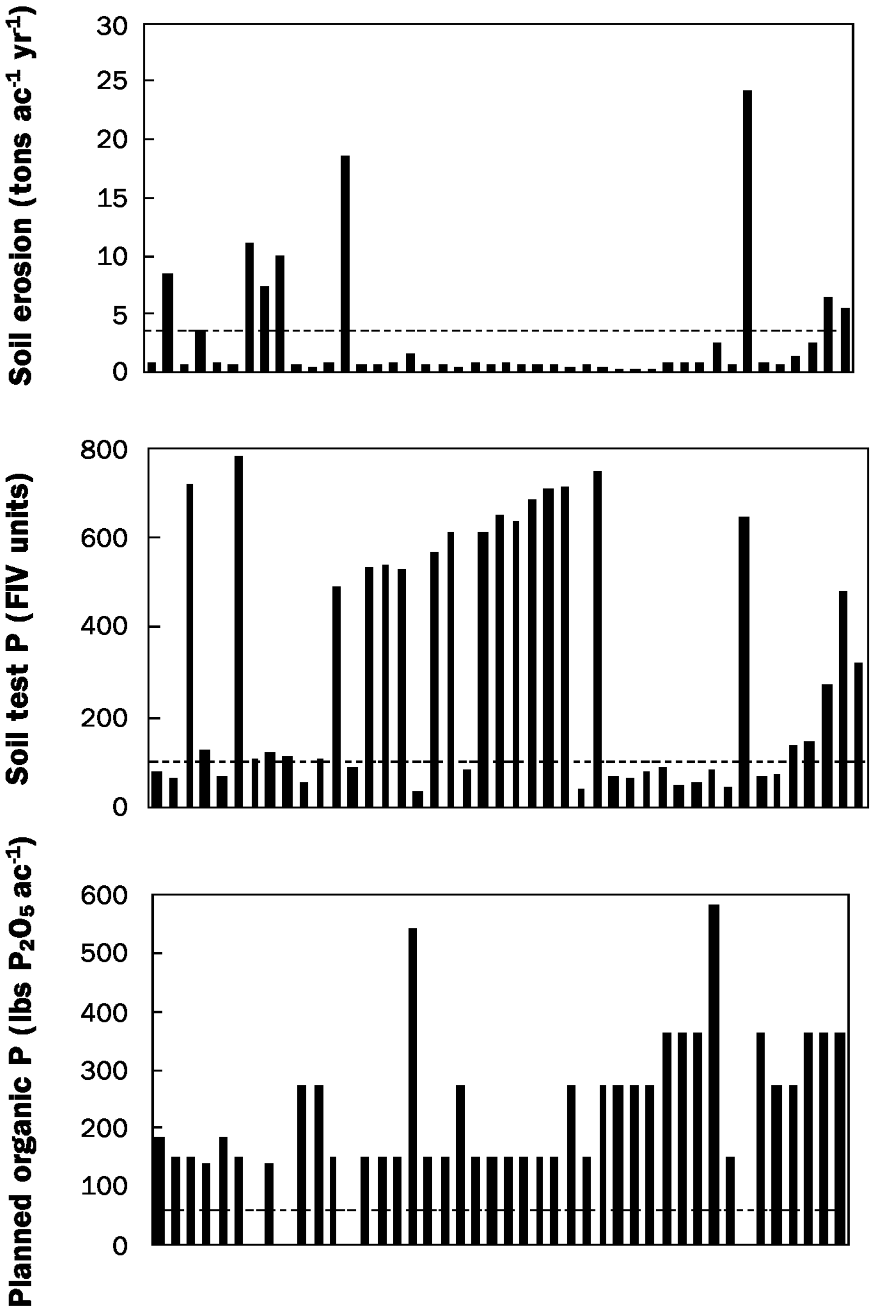
‡ Some fields operated by dairy have poultry litter applications periodically.

Figure 2

Actual values for (a) soil erosion (RUSLE*), (b) soil test phosphorus (P), and (c) planned organic P application rate for the 44 Delaware fields in the "high" and "very high" categories of the P site index. Note that dashed lines in figure correspond to values associated with the need for improved soil P management, i.e. (a) soil erosion of 4 ton ac^{-1} yr^{-1}; (b) excessive soil test P (>100 FIV**); and (c) organic P rates that exceed typical crop P removal values for corn, soybeans, and small grains in Delaware (~40-60 lb P_2O_5 ac^{-1} yr^{-1}).

*Revised Universal Soil Loss Equation

**Fertility index value



or higher categories of the P site index, where P-based management practices would presumably be implemented, it seems valid to question whether or not the P site index approach will be protective enough of water quality in the near term.

A review of the actual characteristics of these 212 fields with "low" P site index values points to some areas where further work on the P site index may be required (Table 7). First, within the transport component of the P site index (Part A), where soil erosion is arguably the most important transport mechanism of P from agricultural fields to surface water, approximately 14% of the fields in the "low" category had greater than 5 tons ac^{-1} yr^{-1} (11 Mg ha^{-1} yr^{-1}) of soil erosion. Acceptable rates of erosion for soils in this region are typically 3 to 4 tons ac^{-1} yr^{-1} (7 to 9 Mg ha^{-1} yr^{-1}) (USDA-NRCS, 1974). Thus, there are fields with unsustainable soil erosion losses each year that have not been identified as high priorities for improved P management. Second, when soil test P results were examined the results showed that 55% of the total fields evaluated had "excessive" soil test P values (>100 fertility index value), yet N-based nutrient management planning that would further increase soil test P was recommended based on the P site index (Table 7).

Of the 212 fields falling into the "low risk" category, only 10% were in the "low" or "medium" soil test P categories where recommendations for fertilizer or manure P applications would be made based on the probability of a crop yield response. Thus, P applications are being recommended via the P site index approach that are unprofitable and likely to increasingly saturate soils with P, because the risk of P transport from these fields is deemed to be low enough to be of little concern for water quality. Third, when planned P application rates were examined, approximately 11% of the fields that were rated as "low" priorities for P-based management had planned organic P application rates of greater than 60 lbs phosphate (P_2O_5) $acre^{-1}$ (68 kg P_2O_5 ha^{-1}), while P removal in the harvested portion of crops grown in this region is typically 45-50 lbs P_2O_5 $acre^{-1}$ (51-57 kg P_2O_5 ha^{-1}) (Sims and Campagnini, 2002). This decision to apply additional P is thus a planned increase in soil test P level. Finally, 87% of the fields in the "low" category had no organic P application planned for the current year, which seems inconsistent with the amount of manure that is generated within the state.

Related to this last point, all of the results we have presented thus far have been based on the single, most recent year for which information was available about each field. However, it is also important to recognize that P site index values for a field are not static, but will vary from year to year as a function of changes in crop, tillage, and P source

Table 7. Distribution of actual values for soil test phosphorus (P), soil erosion, and planned fertilizer and organic P application rate for Delaware fields in the "low" category of the phosphorus site index (PSI < 50; n = 212 fields).

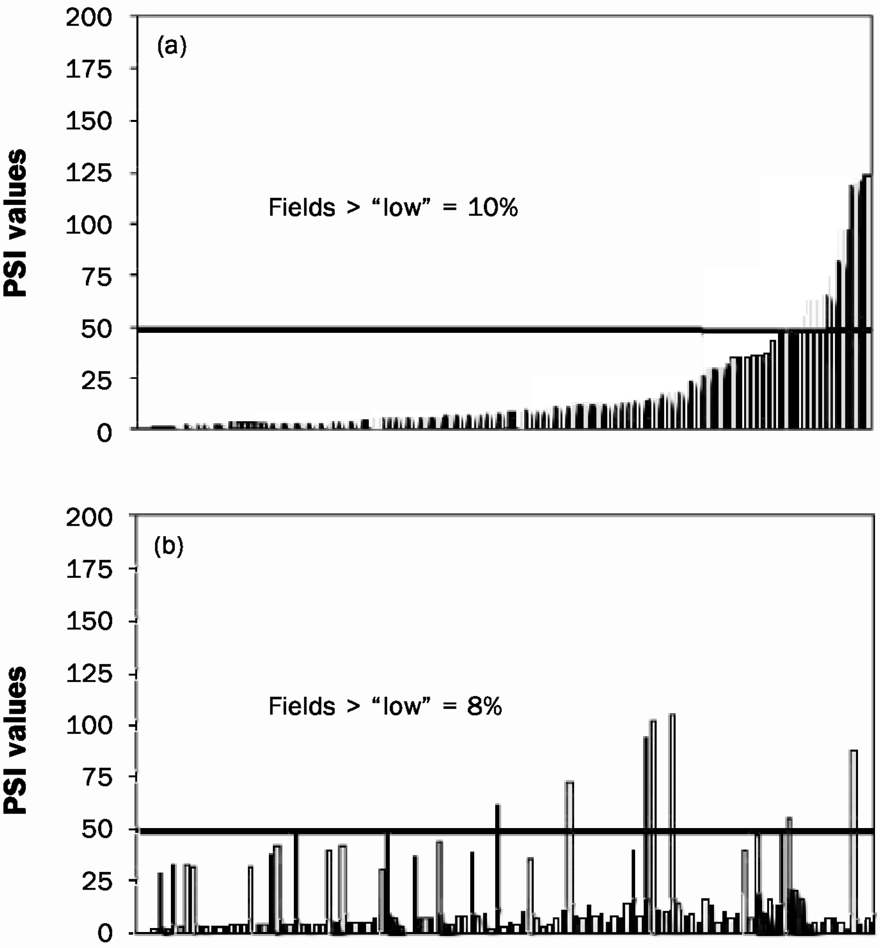
Parameter	Units	Number (percentage) of fields in each range				
		< 1	> 1-2	> 2-5	> 5-10	> 10
Soil erosion	tons/acre/yr	99 (46%)	42 (20%)	42 (20%)	27 (13%)	2 (1%)
		Low	Medium	Optimum	Excessive	Excessive
		< 25	> 25-50	> 50-100	> 100-200	> 200
Soil test P	FIV† units	2 (1%)	19 (9%)	75 (35%)	79 (37%)	37 (18%)
		0	0-15	> 15-30	> 30-60	> 60-120
Planned fertilizer P application rate‡	lbs P_2O_5/acre	111 (52%)	2 (1%)	47 (22%)	44 (21%)	8 (4%)
		0	0-15	> 15-30	> 30-60	> 60-120
Planned organic P application rate‡	lbs P_2O_5/acre	185 (87%)	0 (0%)	4 (2%)	0 (0%)	23 (11%)

† **Fertility index value.**

‡ ***Note:*** **The planned rates of fertilizer P and organic P do not directly correspond to the soil test P categories presented in this table.**

Figure 3

Illustration of the changes in phosphorus site index (PSI) values from year to year for one of the seven Delaware farms evaluated, using actual P application rates, methods, and timing planned for a) 1999 and b) 1998 for these fields. All data sorted in the same ascending order based on phosphorus site index (PSI) values for 1999.



management practices. For example, many of the fields in the "low" category will very likely plan to add manure P in subsequent years. Consider, for instance, the changes in P site index values for one of the Delaware farms based on actual P application rates and methods used in 1998 and 1999 (Figure 3). While the number of fields on this farm that were in the "medium" or higher categories remained about the same, they were clearly not the same fields. Thus, to be most effective, P site index evaluations should be conducted annually for each field and P management practices adjusted accordingly. Another option would be to calculate P site index evaluations based on average manure applications and methods over an entire crop rotation.

Summary and Conclusion

The Delaware phosphorus site index: Current status and future directions. The P site index worked well for identifying fields with differing relative potential risks of P loss. Because of this the Delaware nutrient management commission and USDA-NRCS have now officially incorporated the P site index into guidelines and/or regulations related to P-based management. In Delaware, the Delaware Nutrient Management Commission formally defined "high P soils" in May 2002 as those with a soil test P value greater than 150 fertility index value and provided farmers with fields in this soil test P range with two options: (i) limit P applications to "three-year crop removal"; (ii) limit P applications to the amount recommended by a University of Delaware P Site Index. Three-year crop removal limits the total amount of P that can be applied as fertilizer or organic P during a three-year period to a rate that cannot exceed the amount removed from the field in the harvested portion of the crops grown. This approach does not require the use of a P site index but provides it as an option for farmers.

We believe that widespread implementation of the P site index approach will enable land managers to focus resources on those areas having the greatest potential to contribute to water quality problems due to off-site movement of P. However, our results also suggest that the P site index as presently structured has some limitations that need to be evaluated during the implementation phase. There are two specific needs.

First, the goal of the P site index is to identify agricultural fields with the greatest potential for off-site transport of P. In Delaware, and elsewhere in the United States, this has been done based on the best professional judgment of the individuals with the greatest expertise in this area. Risk categories for P loss have been assigned based on consensus interpretations of the results of years of research, usually conducted at rather small scales, on the factors known to influence and control P loss from soil to water. To date, very little field-scale validation of the accuracy of P site index risk categories has occurred. Given the enormous investments in time and monitoring costs required to conduct comprehensive validation studies it seems unlikely that extensive large-scale validation will occur in the near future. This raises the question as to whether or not the risk categories, which guide the implementation of P-based nutrient management plans, are sufficiently protective of water quality. For example, in Delaware we know that agriculture contributes to nonpoint source P pollution, that statewide P surpluses exists, that many soils are now considered to be excessive in P relative to crop requirements, and that substantial reductions of P loading are needed to meet water quality goals stated in the TMDLs. Yet our P site index assessments indicate P-based management is required for only 28% of the fields we evaluated, primarily because of the low P transport factors associated with most of the cropland on these farms. We also note the year-to-year variability in P site index ratings, which can markedly influence watershed scale assessments of P loss. Given this, we believe the most important need at this time is a concerted effort to validate, perhaps through the use of watershed-scale nonpoint source pollution models, the accuracy of the P site index risk categories. The data needed to conduct these modeling efforts should become available in the future as P site index assessments are conducted on more farms in accordance with the requirements of the Delaware and Maryland nutrient management regulations.

Second, a clear consensus is needed on the need for a soil test P level where the use of P-based nutrient management planning should be required, even if these fields fall into "low" P site index categories. We question if is it acceptable to recommend the continual buildup of soil P even when a field is designated as a low risk for P movement to surface water. Phosphorus is a natural resource with a finite global supply, therefore as good natural resource managers should we advocate practices that promote the over-application of manures and fertilizers just because, based on our current understanding of P transport processes, the potential impacts of P on water quality seem minimal? Clearly, more beneficial uses of this natural resource could be obtained by re-distributing it to areas that need P to attain economically optimum crop yields rather than over-applying P to cropland in areas with low risks for erosion, runoff, and leaching.

In conclusion, we believe that implementing the P site index will assist in the reduction of nonpoint P pollution of surface and shallow groundwaters. However, it is essential to monitor, critically analyze, and continually improve the P site index to validate the best professional judgment that went into its development and to improve it as new research on P loss from soil to water becomes available.

Endnotes

[1]FIV=Fertility index value. A unitless term that categorizes the probability of crop response to applications of P using a scale of 0-100, where 0-25 FIV = low, 26-50 FIV = medium, 50-100 FIV = optimum, and > 100 FIV = excessive. For Delaware, FIV units are numerically equivalent to Mehlich 3 soil test P values expressed in units of mg P kg^{-1} (ppm) (Sims and Gartley, 1996).

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