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A Critical Evaluation of the Kentucky Phosphorus Index

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ABSTRACT

The U.S. Department of Agriculture's Natural Resource Conservation Service (USDA-NRCS) is currently revising its 590 Nutrient Management Conservation Standard. As part of this revision, USDA-NRCS is considering requiring states to test the accuracy of their phosphorus (P) indices using either measured P loss data or simulated P loss data generated from process-based models. The objective of this study was to critically evaluate the KY P index by comparing index output with simulated P loss data obtained from a validated P loss model. Furthermore, the general formulation of the index was evaluated against current research on the processes controlling P transport in the environment. Results suggested that in some areas the index does a good job in assigning P loss risk; however, this analysis also showed some important deficiencies in the index, primarily the neglect of important factors known to affect P loss (e.g., soil erosion and P application rates) and how the different factors in the index are weighted. To reduce the amount of P that is exported from agricultural fields to waterways within Kentucky, resources should be devoted to revising the KY P index to address these limitations as well as developing long-term monitoring sites where the P index and more process-based models can be evaluated against measured P loss data.

KEY WORDS: Phosphorus, P Index, 590 Standard, phosphorus loss, phosphorus modeling

INTRODUCTION

Accelerated eutrophication due to excess P loading is widespread among freshwater bodies of the U.S. (National Research Council 2008) with a sizeable portion of the P originating from agricultural fields (U.S. Environmental Protection Agency 2010). In response to water-quality concerns over P export from agricultural fields to surface waters, the USDA's Natural Resource Conservation Service (USDA-NRCS) revised its 590 Nutrient Management Conservation Standard to include P-based planning strategies to restrict P application to fields where the risk of P loss is high (USDA and USEPA 1999). The resulting 590 Standard prescribed three different strategies which states could adopt to rate a field's vulnerability to P loss: agronomic soil test P, environmental threshold soil test P, and the P index. Kentucky has adopted both the environmental P threshold and P index for P-based planning strategies. In general, the P index is considered to be less restrictive than an environmental P threshold (Sharpley et al. 2001).

The P index is an assessment tool developed to identify fields which are most vulnerable to P loss by accounting for the major source and transport factors controlling P movement in the environment (Lemunyon and Gilbert 1993). Each factor included in the index is weighted in such a way as to reflect that factor's perceived importance on P loss. Since its inception, the P index has been revised several times and has been adopted in many different forms throughout the U.S. (Sharpley et al. 2003). Revisions include multiplying source and transport factors rather than summing them, including a contributing distance factor in the index, use of continuous values for some input variables, inclusion of factors to account for best management practices, and calculating an actual P load rather than a relative risk.

The flexibility of the P index allows states to tailor their indices to reflect the dominant factors governing P transport in their region. In developing a P index, a state must determine which field characteristics to include and how to weight each of them. Ideally, a P index should be developed by correlating measured edge-of-field P losses to field-specific characteristics. Given the dearth of available P loss data, however, many P indices have been developed based on professional judgment. This includes the factors within the index, how each factor is weighted, how the final P index value is calculated, and what the final values mean in relation to P planning.

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The Kentucky P index includes 10 field characteristics and 4 ratings (NRCS 2001). The index is used to assign risk of P loss based on a field's runoff potential, soil erosion potential, soil test P (STP) concentration, distance to receiving water body, location, P application method, impairment status of receiving water body, and width of vegetative buffer (Table 1). Each field characteristic is weighted by a factor of 1, 2, or 3 to reflect that factor's perceived importance on P loss. Each site characteristic is assigned a value rating of 1, 2, 4, or 8 points representing low, medium, high, and very high risk of P loss, respectively. The weighted value ratings for each characteristic are summed to obtain a final P index value. The value of the P index is then used to determine whether P application needs to be restricted (Table 2). The weighted factors included in the index were based on the professional judgment of the technical specialists who developed the 590 Standard for KY (NRCS 2001).

To this author's knowledge, the KY P index has not been modified since its initial formulation, nor has it been critically evaluated. Given the large amount of research that has been conducted since the KY P index was first developed, it seems reasonable that the index should be critically evaluated in light of this recent research. Ideally, a P index should be evaluated against observed P loss data. However, due to the lack of edge-of-field P loss data, only a handful of studies exist that compare observed edge-of-field P loss data with a P index (Sharpley et al. 2001; Eghball and Gilley 2002; DeLaune et al. 2004a, 2004b; Harmel et al. 2005; Sonmez et al. 2009). While several of these studies do show a good correlation between the P index and observed P loss, the P index is still far from being considered a validated model. When observed P loss data are not available to test P indices, simulated P loss data generated from process-based models may be a suitable alternative provided the model has been validated for the region of interest (Veith et al. 2005). Indeed, as part of the 590 Standard revision process a Working Group of scientists within the Southern Extension-Research Activity Group 17 (SERA-17) recently recommended that states be required to evaluate their P index against simulated P loss data when measured P loss data are unavailable (Sharpley et al. 2011). Therefore, the objective of this study was to critically evaluate the KY P index by comparing the output with simulated P loss data obtained from a validated P loss model to identify areas where the index may need revising. Moreover, the general formulation of the KY P index was evaluated against current understandings of the processes controlling P transport in the environment.

MATERIALS AND METHODS

The potential for P loss from an agricultural field will depend on the amount of P available in the soil, applied fertilizers, and applied manures as well as the transport potential from runoff, leaching, and erosion. In this study the KY P index was evaluated by assessing how well the index accounts for these different source and transport factors. Where appropriate, the KY P index was evaluated against output from a process-based model. This involved comparing KY P index values with P loss data generated using a process-based P loss model for hypothetical fields with varying runoff rates, erosion rates, STP values, and field slopes. When output from the index could not be directly compared with output from the model, the index was evaluated against current understandings of the processes controlling P movement through the landscape. This included P application method, timing, and amount; distance from P application to surface water; potential for P leaching through the subsurface; and formulation of the index.

In this study the Annualized Phosphorus Loss Equation (APLE) model of Vadas et al. (2009) was used to evaluate the KY P index. The APLE model is a spreadsheet model comprised of a suite of empirical and process-based equations that estimate annual P loss from the landscape when surface runoff is the dominant pathway of P loss. These equations have been calibrated and validated from multiple experiments ranging from soil boxes to field plots and have proven to be robust in their prediction of P runoff under a variety of conditions.

Output from the KY P index and the APLE model were compared under field conditions in which soil P is the only available P source and surface runoff is the dominant loss

Table 1. Kentucky P index (NRCS 2001).

Field feature	Weighting factor	Value ratings			
		Low (1 point)	Medium (2 points)	High (4 points)	Very high (8 points)
Hydrologic soil group	1	A	B	C	D
Residual soil test P level (mg/kg)	3	200–250	251–400	401–533	>533
Field slope (%)	1	<2	2–5	6–12	>12
Land cover (%)	3	60–90	30–60	15–30	0–15
Vegetative buffer width (ft)	3	>29	20–29	10–19	<10
Impaired watershed?	1	NO			YES
Application timing	3	June–September	April, May, October; March or November w/winter cover	March or November w/o winter cover; Febuary w/winter cover	December, January, February
Application method	3	Injected	Surface applied and incorporated within 48 hr.	Surface applied and incorporated within 1 month	Surface applied and unincorporated for greater than 1 month
Downstream distance from application area to spring or waterbody	2	Over 150 ft	50–100	0–50	Adjacent
County location	1	Bluegrass region	All other		

pathway. Under these conditions P can be transported off site in surface runoff either as dissolved P or P attached to eroding soil particles. The KY P index accounts for risk of P loss from soil with soil test P (STP), hydrologic soil group (HSG), field slope, and percent land cover where STP represents the P source contribution and hydrologic soil group, field slope, and percent land cover are used to rate the risk of runoff and erosion. To account for the risk of P loss due to STP, the index rating for STP increases from 1 for Mehlich-3 soil test P (STP) values ranging from 400 to 500 lbs/acre to 4 for STP values ranging from 800 to 1066 lbs/acre (Table 1). For soils with STP values below 400 lbs/acre the P index is not required. And while a value of 8 is given for STP concentrations exceeding 1066 lbs/acre, this is the STP value at which no further P can be applied. To account for the role of runoff in P loss risk, the index rating increases with decreasing soil infiltration capacity as classified by hydrologic soil group (HSG). NRCS classifies soils into four HSGs (A, B, C, and D) based on a soil's infiltration capacity. Soils in group A have low runoff potential and are given a rating of 1 whereas soils in group D have high runoff potential and thus are given a rating of 8 in the index. The index also increases in value with increasing field slope and decreasing land cover (Table 1), presumably due to increased erosion potential, though the KY 590 Standard is not clear on this point (NRCS 2001).

The APLE model calculates annual dissolved P loss as increasing linearly with soil labile P and runoff:

$$DP_{soil} = C \cdot LP \cdot Q \cdot 0.1 \qquad (1)$$

where DP_{soil} is annual dissolved P loss from soil (kg/ha), C is an extraction coefficient equal to the slope of a line relating labile P to runoff P (assumed here to be 5×10^{-4}; Vadas et al. 2009), LP is labile P (mg/kg) and was assumed to equal 50% of Mehlich-3 STP (Vadas et al. 2009), Q is annual runoff in mm, and 0.1 is a unit conversion factor to obtain units of kg/ha.

The APLE model calculates annual particulate P loss using the sediment loading function of McElroy et al. (1976) and Williams

Table 2. Risk of P loss based on P index and corresponding nutrient application rate.

Final P index value	Risk of P loss	Nutrient application rate
<30	Low	Nitrogen based
30–60	Medium	Nitrogen based
61–112	High	P based (crop removal)
>112	Very High	No P application

and Hann (1978):

$$P_{sed} = SL \cdot SP \cdot PER \cdot 10^6 \quad (2)$$

where P_{sed} is annual sediment-bound P lost in runoff (kg/ha); SL is annual soil lost through erosion (kg/ha); SP is total soil P (mg/kg) determined as the sum of active, stable, and organic P pools and is generally correlated with LP; 10^6 is a unit conversion factor to obtain units of kg/ha; and PER is the P enrichment ratio representing the ratio of P in eroded sediment to that in the soil calculated as (Vadas et al. 2009):

$$PER = EXP(2.2 - 0.25 \cdot \ln(SL)) \quad (3)$$

Annual runoff required for Eq. [1] was calculated with the SCS curve number method (U.S. Department of Agriculture, Soil Conservation Service 1972):

$$Q_d = \frac{(P_d - I_a)^2}{(P_d - I_a + S)} \text{ for } P_d > 0.2 \cdot S \quad \text{otherwise } Q = 0 \quad (4)$$

where Q_d is daily runoff (mm), P_d is daily precipitation in (mm), and I_a is initial abstraction (mm) of water assumed to equal 20% of the maximum potential water retention by the soil (S; mm). The maximum potential water retention parameter is calculated from the curve number (CN) by:

$$S = 25.4 \cdot \left(\frac{1000}{CN} - 10 \right) \quad (5)$$

where CN is a function of hydrologic soil group, cover type, treatment, hydrologic condition, and antecedent moisture condition. To evaluate whether the KY P index adequately accounts for the effect of field slope on P loss, S values were modified for slopes of 1.5, 3.5, 9, and 13% following the method used in the Annualized Policy/Environmental Extender (APEX) model (Gassman et al. 2009):

$$S_\beta = S \left(1.1 - \frac{\beta}{\beta + \exp(3.7 + 0.021 * \beta)} \right) \quad (6)$$

where S_β is the slope-adjusted retention parameter and β is field slope.

Annual soil loss needed for the APLE model was calculated using the Revised Universal Soil Loss Equation Version 2 (RUSLE2) (USDA-ARS 2006). Erosion rates were calculated for field slopes of 1.5, 3.5, 9, and 13% representing low, medium, high, and very high index risk values, respectively. Curve numbers required for equation 5 were also obtained from RUSLE2.

The KY P index was evaluated by determining whether risk values generated by the index were positively correlated with output generated from the APLE model for varying STP, runoff potential, and field slope. Specifically, simulated P loss data were generated using erosion and runoff data calculated for four soil series found in Grayson County, KY representing three hydrologic soil groups (B, C, and D) and a range in soil erodibility factors (Table 3). Simulations were performed for three standard 1-yr crop rotations available for Crop Management Zone 63 in RUSLE2. These included tall fescue forage hay, no-till winter wheat, and no-till corn grain with fall weeds. Runoff data were generated using a 30-yr daily precipitation record for Leitchfield, KY (average annual precipitation is approximately 1200 mm). Average daily runoff values were summed over the entire year for each year to obtain annual runoff values. The average of these annual runoff values was then used in the simulations.

Index values for the simulated fields were calculated by assigning a high risk rating (8 points) to vegetative buffer width and downstream distance because the APLE model generates edge-of-field P loss data and does not account for vegetative buffers or distance to receiving water body. Thus, the

comparisons in this study ignore any setback requirements to focus solely on how well the index represents edge-of-field P loss. Application method was also assigned a high risk rating whereas impaired watershed, application timing, and county location were all assigned a risk rating of low (1 point). Land cover rating was assigned a medium risk value (2 points) for the forage hay simulations whereas a low risk rating was assigned to the wheat and corn simulations based on the RUSLE2-calculated vegetative surface coverage at time of P application.

Rainfall and soil data used for comparing the KY P index and the APLE model were chosen from Grayson County strictly for convenience and not intended to be representative of the entire Commonwealth. Instead, the objective of this study was to assess the general trend of the KY P index against output from a process-based model to identify potential limitations with the index. Comparisons between the index and simulated data for a few hypothetical fields are sufficient for such an analysis, although a more exhaustive comparison may be warranted in future studies.

RESULTS

The KY P index was first evaluated against simulated P loss data generated with the APLE model for a range of STP values. Increasing STP values resulted in increases in both the P index and the APLE simulated P loss data for each soil series (Figure 1). For the simulated data, P loss increased asymptotically with increasing STP due to how APLE treats particulate P loss as increasing nonlinearly with soil P. On the other hand, due to the exponential weighting used in the KY P index, the increase in index value with increasing STP is greatest at the highest STP value. The KY P index, as with many other state P indices, treats STP as a discrete rather than continuous variable; thus the index may underestimate the risk of P loss from soil for a given range in STP values. For instance, the index calculated the risk of P loss from soils with STP values ranging from 501 to 800 lbs/acre as being equivalent whereas simulated P loss values increased by 25 to 40% over this range of STP values depending on soil type, field slope, and crop type.

Table 3. Soil series used in for generating simulated P loss data using the APLE model.

Soil series	HSG[1]	K[2]	T[3]
Johnsburg silt loam (Jo)	D	0.48	3.0
Ramsey loam (RaD)	D	0.22	1.0
Shelocta gravelly silt loam (ShB)	B	0.35	4.0
Zanesville silt loam (ZaB)	C	0.48	3.0

[1] Hydrologic soil group.
[2] RUSLE2 soil erodibility factor.
[3] Soil loss tolerance (tons/acre/yr).

Increasing field slope increased both runoff and erosion as predicted by the SCS curve number method and RUSLE2, respectively. For each crop type and soil series, erosion rates as predicted by RUSLE2 increased linearly with increasing field slope from 1.5 to 9% but a greater increase in erosion rates when field slope increased from 9 to 13% was observed (Figure 2). For runoff, increasing field slope resulted in linear increases in runoff as calculated by the SCS curve number method using the slope modification method employed by the APEX model (Figure 2). Increasing field slope resulted in a near linear increase in simulated P loss data for all four soils simulated with tall fescue and winter wheat (Figure 3). With soils simulated with corn grain, however, increasing field slope from 9 to 13% resulted in a greater increase in simulated P loss than at lower slopes. For all soils and crop types, increasing field slope from 9 to 13% resulted in a greater increase in the P index than did increases at lower slopes.

Comparing the Shelocta (HSG B), Zanesville (HSG C), and Johnsburg (HSG D) soils showed that soils with greater runoff potential resulted in greater simulated P loss and P index values (Figures 1, 3), although differences between soils with different runoff potentials varied depending on STP and field slope for the simulated data whereas for the KY P index differences were independent of STP and field slope. For instance, the difference in simulated P loss between the Shelocta (HSG B) and Johnsburg (HSG D) soils when planted with winter wheat was 0.70 kg/ha for STP of 400 and 1.6 kg/ha for STP of 1000 lbs/acre (Figure 1C), yet the KY P index is weighted in such a way that the difference in index values between HSG B and D is 6 for any given STP value (Figure 1D). Similarly, for the corn simula-

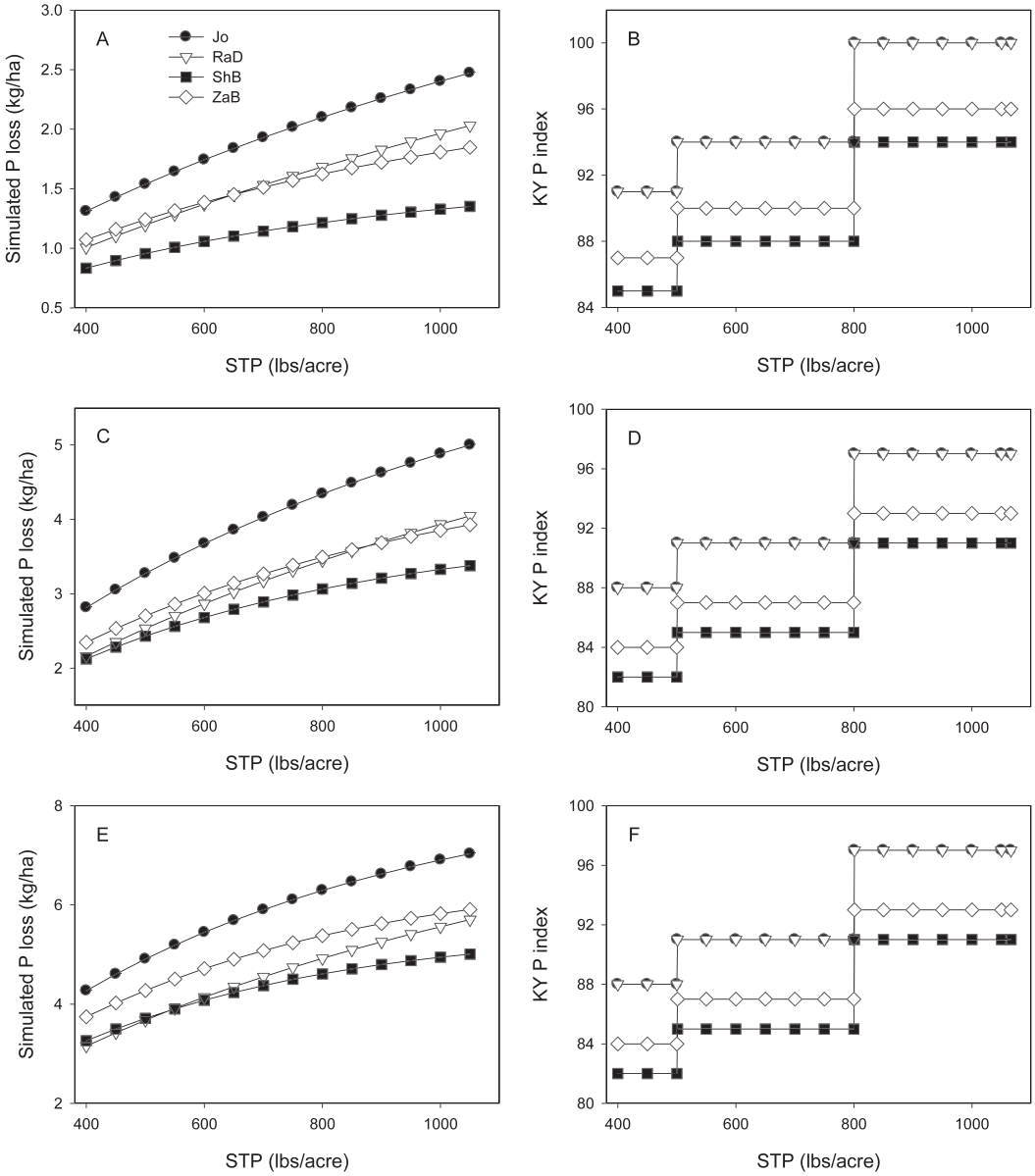

Figure 1. Effect of increasing soil test P (STP) on simulated P loss data (left panels) and the KY P index (right panels) for each soil series (Johnsburg (Jo), Ramsey (RaD), Shelocta (ShB), and Zanesville (ZaB) for the (A, B) forage hay, (C, D) winter wheat, and (E, F) corn grain simulations for a field slope of 3.5%. For these simulations vegetative buffer width, application method, and downstream distance were all assigned a risk rating of very high (8 points) whereas impaired watershed, application timing, and county location were all assigned a risk rating of low (1 point). Land cover rating was assigned a medium risk value (2 points) for the forage hay simulations whereas a low risk rating was assigned to the winter wheat and corn simulations.

tions the difference in simulated P loss between the Shelocta (HSG B) and Johnsburg (HSG D) soils was 1.1 kg/ha for a field slope of 1.5% and 3.7 kg/ha for a field slope of 13% (Figure 3E) while the difference in index values remained constant (Figure 3F).

While runoff from both the Johnsburg and Ramsey soils was the same due to both soils

being classified as HSG D, RUSLE2 calculated erosion rates for the Ramsey soil 40 to 50% lower than the Johnsburg soil for each crop type (Figure 2). The reduced erosion rate for the Ramsey soil was due to the lower erodibility factor for this soil (0.22 compared with 0.48 for Johnsburg soil, Table 3). Soil erodibility is a function of soil texture, soil organic matter content, subsoil structure, and soil permeability and is an important factor controlling soil loss. This decrease in erosion explains why simulated P loss for the Ramsey soil was noticeably lower than the Johnsburg soil (Figures 1, 3). The KY P index, however, rated risk of P loss from these two soils as being equal because the KY P index does not account for soil erodibility (Figures 1, 3) and thus does not adequately capture the differences in risk between these two soils. To better represent risk of P loss by eroding soil will require incorporation of erosion rates into the KY P index; most state P indices currently use RUSLE or RUSLE2 to calculate erosion rates (Sharpley et al. 2003).

Analyzing data from all the simulations combined, a mild but significant correlation ($r = 0.29$, $P < 0.001$) was observed between the simulated data and index values (Figure 4). The correlation between simulated data and index values increased dramatically when data for each crop type were analyzed separately with r values of 0.78, 0.74 and 0.62 for the forage hay, wheat, and corn simulations, respectively. This further highlights the inability of the KY P index to account for differences in P loss risk among different crop rotations. Inclusion of erosion rates into the KY P index will likely increase its correlation with output from the APLE model.

DISCUSSION

The objective of any P index is to simply and accurately estimate the risk of P loss from the landscape. Although the P index is used in the majority of states to assess risk of P loss from agricultural fields, most state P indices have not been rigorously evaluated against measured P loss data to determine how well the index assigns risk—a major reason being the lack of field data available for such an analysis. Recognizing this, a Working Group of scientists within the Southern Extension-Research Activity Group 17 (SERA-17) recently recommended that P indices be evaluated against simulated P loss data using accepted P transport models when measured P loss data are unavailable (Sharpley et al. 2011). Veith et al. (2005) used this approach to evaluate the Pennsylvania P index by comparing index values with P loss values calculated with the SWAT model and observed good correlations between the P index and output from SWAT and concluded that the Pennsylvania P index was generally accurate. Comparing KY P index values with simulated P data generated with the APLE model for a handful of hypothetical fields with ranges in STP values, runoff potential, erosion rates, and field slopes, showed that index values were generally correlated with the simulated data. This analysis, however, also showed some important limitations with the index including how the different factors in the index are weighted and how erosion is accounted for in the index.

In addition to comparing the KY P index against output from a process-based model, the index can be further evaluated by assessing whether the formulation of the index is consistent with published research and whether the index accounts for all the importance source and transport factors expected to control P movement through the landscape in Kentucky. This includes P application method, timing, and amount; distance from P application to surface water; potential for P leaching through the subsurface; and formulation of the index.

The application of mineral fertilizer or animal manure to agricultural fields can result in significant increases in dissolved runoff P concentrations. Loss of P from applied fertilizers and manures will depend on application method, rate, and timing. While the KY P index accounts for both P application method and timing it does not include P application rate. Application method is accounted for in the KY P index by assigning the lowest value rating when P is injected into the soil and the highest value rating when P is surface applied and left unincorporated for more than 1 month. This approach is consistent with studies which have shown that incorporation of manure into the subsurface results in reduced dissolved runoff P concen-

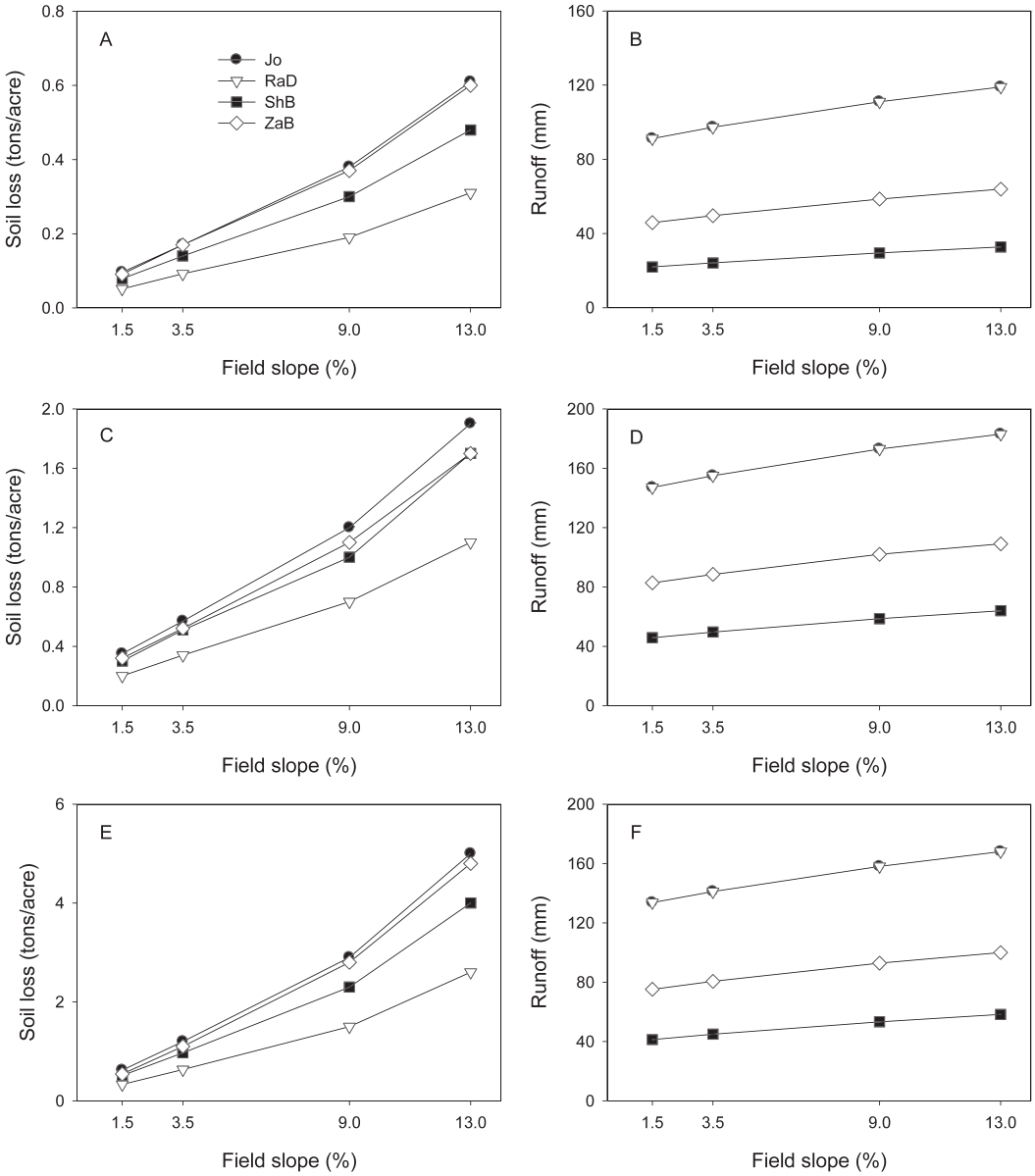

Figure 2. Relationship between field slope and RUSLE2-predicted erosion rates (left panels) and runoff predicted using the SCS curve number method modified for slope (right panels) for each soil for the (A, B) forage hay, (C, D) winter wheat, and (E, F) corn grain simulations.

trations compared with surface applications (Kleinman et al. 2002; Pote et al. 2003; Daverede et al. 2004; Torbert et al. 2005; Sistani et al. 2009; Sistani et al. 2010). A potential limitation with the index is that it does not allow for partial incorporation of P. That is, P is assumed to be either fully incorporated or remain completely on the surface. In developing the APLE model Vadas et al. (2009) assumed an inverse linear relationship between fraction of P incorporated and runoff P concentrations in their model. Further studies are needed, however, to determine the relationship between P loss and fraction of P incorporated into the soil. Another potential limitation with the index is

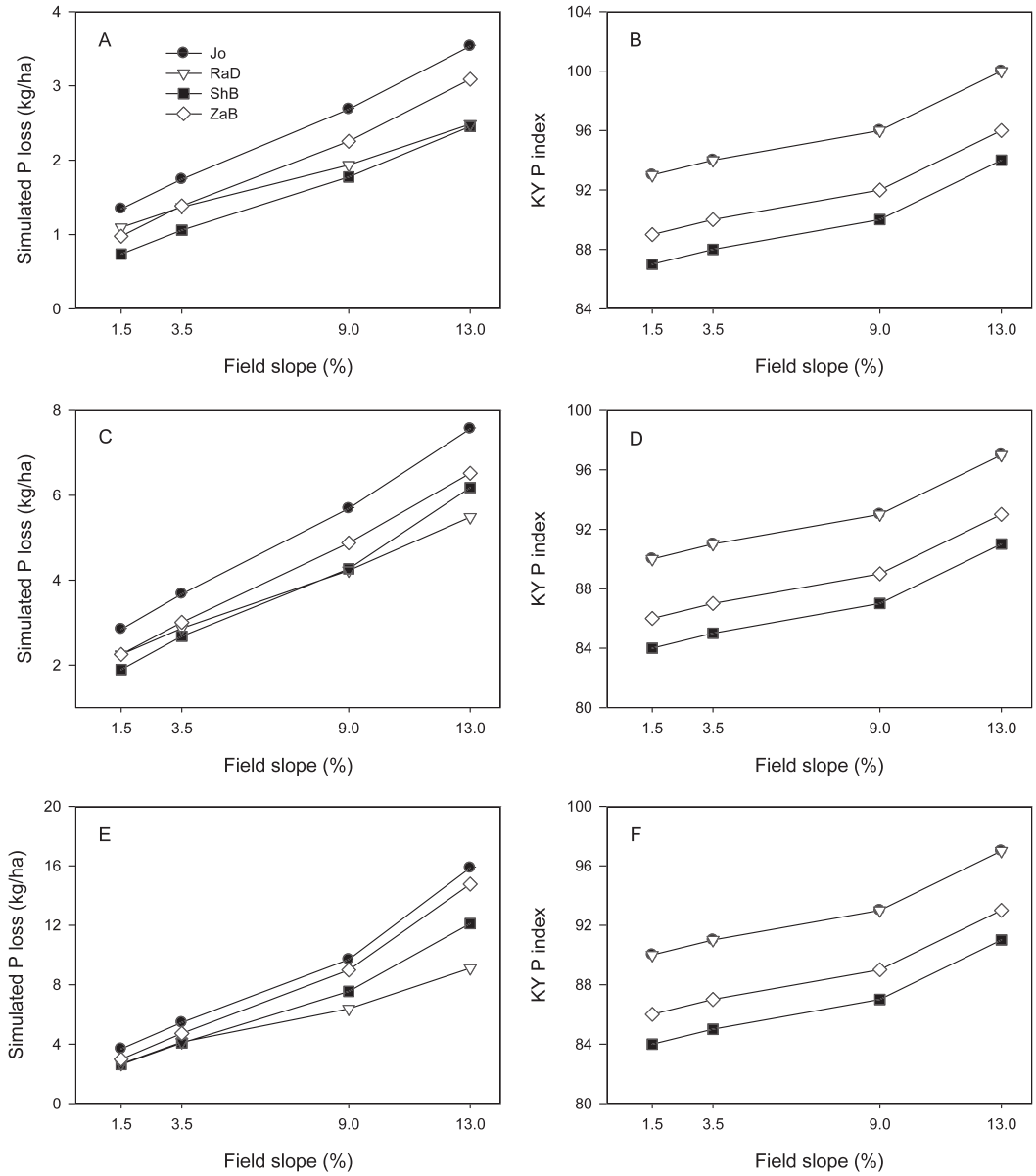

Figure 3. Effect of field slope on simulated P loss data (left panels) and the KY P index (right panels) for each soil series soil for the (A, B) forage hay, (C, D) winter wheat, and (E, F) corn grain simulations for STP value of 600 lbs/acre. For these simulations vegetative buffer width, application method, and downstream distance were all assigned a risk rating of very high (8 points) whereas impaired watershed, application timing, and county location were all assigned a risk rating of low (1 point). Land cover rating was assigned a medium risk value (2 points) for the forage hay whereas a low risk rating was assigned to the winter wheat and corn simulations.

that it does not account for the possible increase in particulate P loss that may occur when P is incorporated into the soil due to increased soil erosion (Andraski et al. 1985; Cox and Hendricks 2000). Incorporation of erosion rates into the index would help address this limitation.

Application timing is another important factor to include when assessing risk of P loss from applied P sources. When P applications

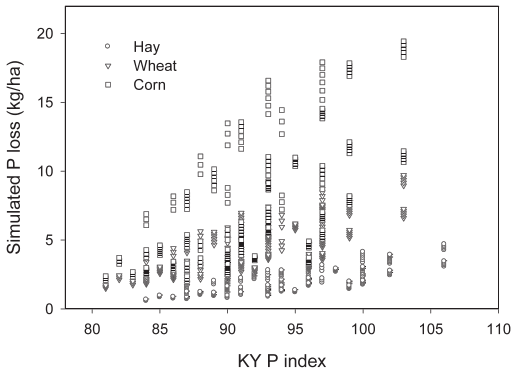

Figure 4. Relationship between simulated P loss data and the KY P index. Results show that the KY P index is in general directionally consistent with the simulated P loss data with a correlation coefficient of 0.29 ($P < 0.001$). However, a large amount of scatter exists highlighting potential limitations with the index.

are made during periods when runoff-generating precipitation events are common, risk of P loss will be greater. The KY P index accounts for application timing by assigning risk based on the month of planned P application. Low values are assigned to summer months when runoff is generally low due to reduced precipitation and increased evapotranspiration and high values are assigned to winter months when precipitation is greater and evapotranspiration is low. Furthermore, plant nutrient uptake will be lowest during the winter season thereby also increasing risk of P loss.

In addition to runoff volume, the time interval between P application and the next runoff event has been shown to greatly affect P loss for surface applied P, with P loss decreasing with increasing time between application and runoff event (Schroeder et al. 2004; Sharpley 1997; Sistani et al. 2009); for incorporated P sources, however, timing between P application and runoff may not be as important (Sistani et al. 2009). Because the time interval between P application and a runoff event is impossible to account for in a P index, it is important that best management practices are followed that prevent P application on fields during or immediately prior to expected precipitation events. One approach would be to develop a Web-based program in which a producer enters the geographic location and the program calculates whether P application can occur on a given day based on recent and forecasted weather conditions.

Phosphorus application rate is another important factor controlling risk of P loss with increasing fertilizer or manure application rates resulting in increased P in runoff, as well as elevated runoff P concentrations for extended periods of time following application (Schroeder et al. 2004). Indeed, recently applied P can override soil P as the dominant factor controlling runoff P concentrations (Kleinman et al. 2002; DeLaune et al. 2004a), yet the KY P index is one of only a few P indices that does not include P application rate in its calculations (Sharpley et al. 2003). Therefore, consideration should be given to including P application rate in the KY P index. Because runoff P loss from applied fertilizers and manures varies depending on the solubility of the P source (Kleinman et al. 2002; Shigaki et al. 2006), a weighting factor should be included to account for the relative solubility of the applied P source (Leytem et al. 2004; Elliot et al. 2006; Vadas et al. 2009). Inclusion of such a factor also can be used to evaluate the impact that manure management strategies such as addition of P-sorbing amendments (Moore et al. 2000; DeLaune et al. 2004a) or manipulation of animal diets (Wu et al. 2000; DeLaune et al. 2004a) has on P loss risk assessment and thus allowable manure application rates.

Another important factor controlling the potential of applied P to adversely affect a water body is the distance between the water body and location where nutrient application occurred. The KY P index ranks fields adjacent to water bodies as very high risk, those within 0 to 50 ft as high risk, 50 to 150 ft as medium risk, and those 150 feet or greater as low risk of P loss. Because the impact of distance between field and receiving water body on P transport will depend on numerous factors including field slope and land cover, it is difficult to determine what distance represents a reasonable estimate of high risk of P loss and what distance represents a low risk of P loss. Based on observations from a small watershed in Pennsylvania, Gburek et al. (2000) assigned a risk of very high to fields within 150 ft of a receiving water body and low risk to fields greater than 500 ft from a receiving water body in the Pennsylvania P

index. These distances are much greater than the distances used for calculating risk in the KY P index. Research must be conducted on agricultural fields in KY to obtain a better understanding of how transport distance affects risk of P loss to receiving water bodies.

The KY P index, along with the majority of state P indices, does not consider the risk of P loss through leaching. This is primarily due to the long-held assumption that P is so strongly sorbed to sediments that its translocation through the subsurface is minimal and therefore poses minimal risk to surface waters. This assumption, however, may not be true in soils with low P sorption capacities, soils with high infiltration rates, and/or shallow soils. For instance, in tile-drained fields where leaching distance is short and drainage water is diverted directly to nearby surface waters, P loads from leaching can be substantial (Sims et al. 1998). Moreover, in well-developed karst areas where soils are thin and groundwater moves primarily through large underground conduits, the retention of P may be minimal. Given the presence of both tile-drained fields and shallow soils in well developed karst areas in Kentucky, consideration should be given to including risk of P loss by subsurface leaching in the KY P index. Pennsylvania (Weld et al. 2002) and North Carolina (N.C. PLAT Committee 2005) are two of several states that have included risk of leaching loss in their P index, and these indices can serve as examples.

Another important factor to consider when evaluating a P index is how the final index value is calculated. The KY P index follows the formulation of the original P index in that the final index value is calculated as the sum of the rated transport and source factors, with each weighted factor treated separately (Lemunyon and Gilbert 1993). Gburek et al. (1998) demonstrated that a multiplicative formulation, where a P index is calculated as the product of the summed transport and source factors, better captures the role that transport plays on P loss. Incorporating this multiplicative approach into the Pennsylvania P index, the authors found improvements in the index's ability to predict P loss (Gburek et al. 2000), and as a result, many states have adopted the multiplicative formulation for calculating their index (Sharpley et al. 2003). A third formulation used in a handful of states sums P loss from each individual component contributing to P loss. In this formulation, each component is calculated as the product of both transport and source factors and best reflects the processes governing P transport in the environment and is consistent with how P loss is calculated in process-based P loss models.

CONCLUSIONS

The objective of this paper was to critically evaluate the KY P index to identify where the index may need revising and to encourage discussion and research for updating it. Given the lack of available P loss data, this evaluation relied on comparing results from the KY P index with P loss data generated using established models such as APLE, RUSLE2, and the SCS curve number method. While this analysis was limited to a few hypothetical fields and field and management conditions, this analysis did provide valuable insight into some potential limitations with the index – primarily the neglect of important factors known to affect P loss (i.e., soil erosion and P application rates) and in how the different factors in the index are weighted. To reduce the amount of P that is exported from agricultural fields to waterways within Kentucky, effort and resources should be devoted to updating the KY P index as well as developing long-term monitoring sites where the index and process-based models can be evaluated against measured P loss data. When considering modifications to the KY P index, however, it is important that environmental concerns be balanced with considerations regarding the potential economic impact to landowners and producers.

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LITERATURE CITED

Andraski, B. J., D. H. Mueller, and T. C. Daniel. 1985. Phosphorus losses in runoff as affected by tillage. Soil Science Society of America Journal 49:1523–1527.

Cox, F. R., and S. Hendricks. 2000. Soil test phosphorus and clay contents effects on runoff water quality. Journal of Environmental Quality 29:1582–1586.

Daverede, I. C., A. N. Kravchenko, R. G. Hoeft, E. D. Nafziger, D. G. Bullock, J. J. Warren, and L. C. Gonzini. 2004. Phosphorus runoff from incorporated and surface-applied liquid swine manure and phosphorus fertilizer. Journal of Environmental Quality 33:1535–1544.

DeLaune, P. B., P. A. Moore, Jr., D. K. Carmen, A. N. Sharpley, B. E. Haggard, and T. C. Daniel. 2004a. Development of a phosphorus index for pastures fertilized with poultry litter—factors affecting phosphorus runoff. Journal of Environmental Quality 33:1947–1953.

DeLaune, P. B., P. A. Moore, Jr., D. K. Carmen, A. N. Sharpley, B. E. Haggard, and T. C. Daniel. 2004b. Evaluation of the phosphorus source component in the phosphorus index for pastures. Journal of Environmental Quality 33:2192–2200.

Eghball, B., and J. E. Gilley. 2002. Phosphorus risk assessment index evaluation using runoff measurements. Journal of Soil and Water Conservation 56:202–206.

Elliot, H. A., R. C. Brandt, P. J. A. Kleinman, A. N. Sharpley, and D. B. Beegle. 2006. Estimating source coefficients for phosphorus site indices. Journal of Environmental Quality 35:2195–2201.

Gassman, P. W., J. R. Williams, X. Wang, A. Saleh, E. Osei, L. M. Hauck, R. C. Izaurralde, and J. D. Flowers. 2009. The Agricultural Policy Environmental EXtender (APEX) Model: an emerging tool for landscape and watershed environmental analyses. Technical Report 09-TR 49. Center for Agricultural and Rural Development, Iowa State University, Ames, IA.

Gburek, W. J., and A. N. Sharpley. 1998. Hydrologic controls on phosphorus loss from upland agricultural watersheds. Journal of Environmental Quality 27:267–277.

Gburek, W. J., A. N. Sharpley, L. Heathwaite, and G. J. Folman. 2000. Phosphorus management at the watershed scale: a modification of the phosphorus index. Journal of Environmental Quality 29:130–144.

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

Kleinman, P. J. A., A. N. Sharpley, B. G. Moyer, and G. F. Elwinger. 2002. Effect of mineral and manure phosphorus sources on runoff phosphorus. Journal of Environmental Quality 31:2026–2033.

Lemunyon, J. L., and R. G. Gilbert. 1993. The concept and need for a phosphorus assessment tool. Journal of Production Agriculture 6:483–496.

Leytem, A. B., J. T. Sims, and F. J. Coale. 2004. Determination of phosphorus source coefficients for organic phosphorus sources: laboratory studies. Journal of Environmental Quality 33:380–388.

McElroy, A. D., S. Y. Chiu, and J. W. Nebgen, et al. 1976. Loading function for assessment of water pollution from nonpoint sources. Environmental Protection Agency, EPA 600/2-76-151, Washington, DC.

Moore, Jr., P. A., T. C. Daniel, and D. R. Edwards. 2000. Reducing phosphorus runoff and inhibiting ammonia loss from poultry manure with aluminum sulfate. Journal of Environmental Quality 29:37–49.

National Research Council. 2008. Nutrient control actions for improving water quality in the Mississippi River Basin and Northern Gulf of Mexico. Committee on the Mississippi River and the Clean Water Act: Scientific, Modeling and Technical Aspects of Nutrient Pollutant Load Allocation and Implementation. National Research Council, Washington, DC.

Natural Resources Conservation Service (NRCS). 2001. Kentucky phosphorus (P) matrix. U.S. Department of Agriculture, Conservation practice standard: nutrient management code 590, Lexington, KY.

North Carolina PLAT Committee. 2005. North Carolina Phosphorus Loss Assessment: I. Model description and II. Scientific basis and supporting literature. North Carolina Agricultural Research Service Technical Bulletin 323, North Carolina State University, Raleigh, NC.

Pote, D. H., W. L. Kingery, G. E. Aiken, F. X. Han, P. A. Moore, Jr, and K. Buddington. 2003. Water-quality effects of incorporating poultry litter into perennial grassland soils. Journal of Environmental Quality 32:2392–2398.

Schroeder, P. D., D. E. Radcliffe, and M. L. Cabrera. 2004. Rainfall timing and poultry litter application rate effects phosphorus loss in surface runoff. Journal of Environmental Quality 33:2201–2209.

Sharpley, A. N. 1997. Rainfall frequency and nitrogen and phosphorus in runoff from soil amended with poultry litter. Journal of Environmental Quality 26:1127–1132.

Sharpley, A. N., R. W. McDowell, J. L. Weld, and P. J. A. Kleinman. 2001. Assessing site vulnerability to phosphorus loss in an agricultural watershed. Journal of Environmental Quality 30:2026–2036.

Sharpley, A. N., J. L. Weld, D. B. Beegle, P. J. A. Kleinman, W. J. Gburek, P. A. Moore, Jr., and G. Mullins. 2003. Development of phosphorus indices for nutrient management planning strategies in the United States. Journal of Soil and Water Conservation 58: 137–152.

Sharpley, A. N., D. Beegle, C. Bolster, L. Good, B. Joern, Q. Ketterings, J. Lory, R. Mikkelsen, D. Osmond, and P. Vadas. 2011. Revision of the 590 Nutrient Management Standard: SERA-17 Recommendations. Southern Cooperative Series Bulletin No. 412. Published by SERA-IEG-17, Virginia Tech. University, Blacksburg, VA. Available at http://www.sera17.ext.vt.edu/Documents/590Recommends2011.pdf. Accessed 05/11/2011.

Shigaki, F., A. Sharpley, and L. I. Prochnow. 2006. Source-related transport of phosphorus in surface runoff. Journal of Environmental Quality 35:2229–2235.

Sims, J. T., R. R. Simard, and B. C. Joern. 1998. Phosphorus loss in agricultural drainage: historical perspective and current research. Journal of Environmental Quality 27:277–293.

Sistani, K. R., C. H. Bolster, T. R. Way, H. A. Torbert, D. H. Pote, and D. B. Watts. 2010. Influence of poultry litter application methods on the longevity of nutrient and *E. coli* in runoff from tall fescue pasture. Water Air Soil Pollution 206:3–12.

Sistani, K. R., H. A. Torbert, T. R. Way, C. H. Bolster, D. H. Pote, and J. G. Warren. 2009. Broiler litter application method and runoff timing effects on nutrient and *Escherichia coli* losses from tall fescue pasture. Journal of Environmental Quality 38:1216–1223.

Sonmez, O., G. M. Pierzynski, L. Frees, B. Davis, D. Leikam, D. W. Sweeney, and K. A. Janssen. 2009. A field-based assessment tool for phosphorus losses in runoff in Kansas. Journal of Soil and Water Conservation 64:212–222.

Torbert, H. A., R. D. Harmel, K. N. Potter, and M. Dozier. 2005. Evaluation of some P index criteria in cultivated agriculture in clay soils. Journal of Soil and Water Conservation 60:21–29.

U.S. Department of Agriculture, Agricultural Research Service. 2006. RUSLE2. Available at http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm. Accessed 05/05/2011.

U.S. Department of Agriculture, Soil Conservation Service. 1972, National Engineering Handbook, Hydrology Section 4, Chapters 4–10.

U.S. Department of Agriculture and U.S. Environmental Protection Agency. 1999. Unified national strategy for animal feeding operations. U.S. Government Printing Office, Washington, DC. Available at http://cfpub.epa.gov/npdes/afo/ustrategy.cfm?program_id=7. Accessed 05/05/2011.

U.S. Environmental Protection Agency. 2010. Chapter 2: Agriculture. In Guidance for Federal land management in the Chesapeake Bay Watershed. EPA841-R-10-002., 247 pp. Office of Wetlands, Oceans and Watersheds, Washington, DC. Available at http://www.epa.gov/nps/chesbay502/pdf/chesbay_chap02.pdf. Accessed 05/05/2011.

Vadas, P. A., L. W. Good, P. A. Moore, Jr, and N. Widman. 2009. Estimating phosphorus loss in runoff from manure and fertilizer for a phosphorus loss quantification tool. Journal of Environmental Quality 38:1645–1653.

Veith, T. L., A. N. Sharpley, J. L. Weld, and W. J. Gburek. 2005. Comparison of measured and simulated phosphorus losses with indexed site vulnerability. Transactions of the American Society of Agricultural Engineers 48:557–565.

Weld, J. L., R. L. Parsons, D. B. Beegle, A. N. Sharpley, W. J. Gburek, and W. R. Clouser. 2002. Evaluation of phosphorus management strategies in Pennsylvania. Journal of Soil and Water Conservation 57:448–454.

Williams, J. R., and R. W. Hann. 1978. Optimal operations of large agricultural watersheds with water quality constraints. Texas Water Resources Institute, Texas A&M University, Tech. Report No. 96.

Wu, Z., L. D. Satter, and R. Soja. 2000. Milk production, reproductive performance, and fecal excretion of phosphorus by dairy cows fed three amounts of phosphorus. Journal of Dairy Science 83:1028–1041.