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Identifying Sites Vulnerable to Phosphorus Loss in Agricultural Runoff

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ABSTRACT

The continual application of more phosphorus (P) in fertilizer and manure to agricultural systems than removed in harvested crops can lead to surface soil accumulation of P. As a result, soil P has become of environmental rather than agronomic concern in areas of intensive crop and livestock production where P enrichment of runoff can promote eutrophication. To target cost-effective remedial measures, sites vulnerable to P loss in runoff must be identified. Site identification by traditional field trials and computer simulations can be time consuming, costly, and data intensive. The Lemunyon and Gilbert field index was used to rank the vulnerability for P loss from 30 unfertilized and P-fertilized, grassed, and cropped watersheds in the Southern Plains. Watershed vulnerability to P loss in runoff was closely related (r^2 = 0.70) to actual losses measured over the last 16 yr (0.1–5 kg P ha^{-1} yr^{-1}). Vulnerability to P loss decreased in the order: conventionally tilled wheat (*Triticum aestivum* L.); no-till wheat; native grass; and set-aside grass. Also, erosive gully remediation by shaping, sprigging with Midland bermudagrass [*Cynodon dactylon* (L.) Pers.] reduced vulnerability from medium to low. The P index is a valuable tool to identify P sources within a watershed that will require more intensive management to minimize P loss in runoff while maintaining crop productivity.**

In areas of intensive crop and livestock production, annual inputs of phosphorus (P) to agricultural systems can often exceed P outputs. In many cases, this has increased P loss in runoff, which often promotes freshwater eutrophication (Sharpley et al., 1994). The loss of P in runoff is controlled to a large extent by transport (runoff and erosion) and source factors (soil P content and rate, timing, method, and type of P applied). Thus, efforts to minimize P loss in runoff involve reducing runoff and erosion by conservation tillage, buffer strips, cover crops, and contour plowing. Source controls include minimizing the build-up of surface soil P through the use of soil test P recommendations to guide fertilizer and manure applications and subsurface placement where possible.

These control measures reduce P losses to a greater extent if they are implemented on targeted critical source areas in a watershed that are vulnerable to P loss in runoff (Heatwole et al., 1987; Prato and Wu, 1991). Thus, sites vulnerable to P loss in runoff must be identified to implement cost-effective remedial strategies. Site vulnerability may be assessed by field studies, computer simulation, or both. However, site assessment by field studies are time consuming, costly, and labor intensive, while simulation models require detailed soil and management information. Thus, Lemunyon and Gilbert (1993) developed a simple P index as a field tool to quantify the relative importance of transport and source factors controlling P loss in runoff. However, the index has received limited field testing and validation. Stevens et al. (1993) applied the index to soils in the Dairy–McKay and Granger Drain Hydrologic Unit areas of western Oregon and eastern Washington to rank their potential for P loss between sites. Even so, the authors concluded that further validation studies were needed to determine if runoff from high-vulnerability sites actually contains more P than from sites ranked as having a low vulnerability.

This article presents an application of the index to 30 unfertilized and P-fertilized, grassed, and cropped watersheds in the Southern Plains, and compares index values with measured losses of P in runoff from these watersheds during the last 16 yr, which have been previously reported by Chichester and Richardson (1992), Sharpley et al. (1985, 1991, 1992), and Smith et al. (1991a).

MATERIALS AND METHODS

Watersheds

Management of the 30 watersheds is summarized in Table 1 and represents agricultural land use in the Southern Plains area of Oklahoma and Texas. The major soil types at the Bushland, El Reno, Ft. Cobb, Little Washita, Riesel, and Woodward locations are Pullman clay loam (fine, mixed, thermic Torrertic Paleustolls), Kirkland silt loam (fine, mixed, thermic Udertic Paleustolls), Cobb fine sandy loam (fine-loamy, mixed, thermic Udic Haplustalfs), Lucian–Nash complex (loamy, mixed, thermic shallow Udic Haplustolls), Houston Black clay (fine montmorillonitic, thermic Udic Pellusterts), and Woodward loam (coarse-silty, mixed, thermic Typic Ustochrepts), respectively. Surface soil samples (0–15 cm) were collected from each watershed to determine soil test P by the Mehlich-3 method (Mehlich, 1984), which was used to recommend fertilizer P applications rates. Fertilizer P was broadcast at fall planting of both conventional and no-till wheat at El Reno and Woodward, and during harrowing in March at Ft. Cobb. At Riesel, fertilizer P was applied in March before planting and disked to incorporate the P. Weed control on the no-till watersheds at El Reno and Woodward was accomplished primarily with phenoxy and glyphosate herbicides. At Bushland, chlorsulfuron was also used.

Two paired watersheds in the Little Washita River Basin, south central Oklahoma (L1 and L2; Table 1), had extensive gully formation and erosion. In the fall of 1985, one of these watersheds was shaped to remove the gullies, fertilized, sprigged to Midland bermudagrass, and a small pond (<0.2 ha) was constructed in the upper half of the watershed. Additional information on these watersheds may be obtained from Chichester and Richardson (1992), Sharpley et al. (1985, 1992), and Smith et al. (1991a,b).

Runoff Collection and Analysis

Watershed runoff was measured using precalibrated flumes equipped with water-level recorders, with 5 to 15 samples collected automatically during each runoff event. The samples were composited in proportion to flow rate to provide a single representative sample. All runoff samples were refrigerated at 4°C from collection until analysis. Total P was determined

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Table 1. Site characteristics for 1976 to 1992.

Site	Study period	Land use	Tillage	Area	Slope	Soil P†	Fertilizer P added
				ha	%	mg kg^{-1}	kg ha^{-1} yr^{-1}
Bushland, TX							
B10A	1984–1992	Wheat–sorghum–fallow	No-till	3.0	1.0	25	0
B11A	1984–1992	rotation	No-till	3.0	1.0	31	0
B12A	1984–1992		No-till	3.0	1.0	24	0
B10B	1984–1992	Wheat–sorghum–fallow	Sweeps, mulch tread	2.6	1.0	27	0
B11B	1984–1992	rotation	Sweeps, mulch tread	2.6	1.0	29	0
B12B	1984–1992		Sweeps, mulch tread	2.6	1.0	23	0
El Reno, OK							
E1	1977–1992	Native grass	None	1.6	2.6	13	0
E2	1977–1992	Native grass	None	1.6	2.9	15	0
E3	1977–1992	Native grass	None	1.6	3.2	14	0
E4	1977–1992	Native grass	None	1.6	3.6	15	0
E5	1984–1992	Wheat–sorghum	Moldboard, disk	1.6	3.5	22	12
E6	1979–1992	Wheat	Moldboard, disk	1.6	2.9	32	12
E7	1984–1992	Wheat	No-till	1.6	2.9	38	13
E8	1979–1992	Wheat	Sweeps, disk	1.6	2.7	21	13
Ft. Cobb, OK							
C1	1982–1992	Peanuts–grain–sorghum rotation	Moldboard, disk	2.6	2.0	26	19
C2	1982–1992		Moldboard, disk	2.1	2.0	23	18
Little Washita, OK							
L1	1980–1992	Native grass	None	3.8	5.0	7	0
L2	1980–1983	Native grass	None	5.7	5.3	8	0
L2	1985–1992	Midld. bermudagrass	Gully treatment			15	24
Riesel, TX							
Y	1976–1982	Mixed grass, cotton, oat, sorghum	Disk	125.0	3.0	16	28
Y2	1976–1982		Disk	52.8	3.0	15	24
Y6	1976–1982	Cotton, oat, sorghum rotation	Disk	6.1	3.0	22	20
Y8	1976–1982		Disk	7.8	2.0	18	15
Y10	1976–1982		Disk	7.0	2.0	20	22
Y14	1976–1982	Klein grass	None	2.2	1.0	8	0
W10	1976–1982	Ctl. bermudagrass	None	8.5	2.0	7	0
SW11	1976–1982	Wtgrn. hardinggrass	None	1.1	1.0	4	0
Woodward, OK							
W1	1977–1992	Native grass	None	4.8	7.0	14	0
W2	1977–1992	Native grass	None	5.6	8.2	15	0
W3	1979–1986	Wheat	Sweeps, disk	2.7	8.6	29	23
	1987–1992	Native grass	None			22	23‡
W4	1982–1986	Wheat	No-till	2.9	7.4	41	23
	1987–1992	Native grass	None			30	23‡

† Average soil P content during the study is represented by Mehlich-3-extractable P.
‡ Native grasses received P fertilizer the year of establishment only.

by perchloric acid digestion of unfiltered samples (O'Connor and Syers, 1975). Suspended sediment concentration of runoff was determined in duplicate, as the difference in weight of 250-mL aliquots of unfiltered and filtered (0.45 μm) runoff after evaporation (105°C) to dryness. Sediment and total P discharge of each runoff event was calculated as the product of concentration and runoff volume and was summed to calculate annual discharge.

Phosphorus Indexing System

The P index is outlined in Tables 2 and 3. Each site characteristic affecting P loss is assigned a weight, assuming that certain characteristics have a relatively lesser or greater effect on potential P loss than others. An assessment of watershed vulnerability to P loss in runoff is made by selecting the rating value for each characteristic from the index (Table 2). Each rating is multiplied by the appropriate weighting factor. Weighted values of all site characteristics are summed and watershed vulnerability obtained from Table 3. No manure was added to the watersheds during the study; thus, organic P rate and application method characteristics had values of 0 (Table 2). If manure is applied, a higher vulnerability and P loss would be expected.

In the original index, soil test P was not quantified, but was categorized as low, medium, high, and very high (Lemunyon and Gilbert, 1993). It was intended that the range in soil test P values be established regionally, dependent on area conditions, proximity of P-sensitive waters, and agroeconomic priorities. For the present study, soil test P ranges were based on potential crop response and fertilizer recommendations (Johnson and Tucker, 1980). The very high category (>65 mg kg^{-1} Mehlich-3 P) represents the level at which no yield response to fertilizer P will be expected in the study area.

For each watershed, a P rating value was obtained using annual sediment discharge and runoff (Table 2), soil test P measured in August (Table 1), and amount and method of fertilizer application (Table 1). For conventional-till wheat (E8) in 1982, for example, sediment discharge was 3558 kg ha^{-1} yr^{-1}, runoff was 13.9 cm, soil test P was 33 mg kg^{-1}, and 13 kg P ha^{-1} were broadcast at fall planting of wheat (Table 4). Using these site characteristics and Table 2, the index value for erosion is 6 (4 × 1.5), runoff 4 (8 × 0.5), soil test P 2 (2 × 1), P application rate 1.5 (2 × 0.75), and method 2 (4 × 0.5). The sum of these values is 15.5, which categorizes this watershed as having a medium vulnerability to P loss in 1992 (Table 3).

RESULTS

A wide range in mean annual sediment (4–87451 kg ha^{-1} yr^{-1}) and total P discharged (27–16622 g ha^{-1} yr^{-1})

Table 2. The P indexing system to rate the potential P loss in runoff from site characteristics (adapted from Lemunyon and Gilbert, 1993).

Site characteristic (weight)	Phosphorus loss potential (value)				
	None (0)	Low (1)	Medium (2)	High (4)	Very high (8)
Transport factors					
Soil erosion (1.5)†	<10	10–100	100–500	500–5000	>5000
Runoff (0.5)‡	<0.1	0.1–1.0	1–5	5–10	>10
Source factors					
Soil test P (1.0)§	<10	10–20	20–40	40–65	>65
Fertilizer P application rate (0.75)¶	None applied	<10	10–20	20–40	>40
Fertilizer P application method (0.5)	None applied	Placed with planter deeper than 5 cm	Incorporated immediately before crop	Incorporated >3 mo before crop or surface applied <3 mo before crop	Surface applied >3 mo before crop
Organic P source application rate (0.5)¶	None applied	1–15	16–30	30–45	>45
Organic P source application method (1.0)	None	Injected deeper than 5 cm	Incorporated immediately before crop	Incorporated >3 mo before crop or surface applied <3 mo before crop	Surface applied >3 mo before crop

† Units for soil erosion are kg ha^{-1}.
‡ Units for runoff are cm.
§ Soil test P is Mehlich-3-extractable P and units are mg P kg^{-1}.
¶ Units for P application are kg P ha^{-1}.

from the 30 watersheds was observed over the last 16 yr (Tables 4 and 5). Phosphorus index ratings for each watershed ranged from 1 to 25, exhibiting a general increase with degree of land cultivation (Table 4). For example, at El Reno the rating increased in the order: grass (5.2); no-till wheat (11.3); double crop (12.6); conventional-till wheat (14.9); and conventional-till wheat with residue removed (16.9). Overall, the conventionally tilled wheat and peanut–(*Arachis hypogena* L.) sorghum [*Sorghum bicolor* (L.) Moench] watersheds were of significantly ($P < 0.05$) greater vulnerability to P loss than the grassed watersheds. In terms of site vulnerability to P loss, the grassed watersheds were of low vulnerability and the cropped watersheds of medium vulnerability (Table 3).

Although less sediment and total P were lost from the no-till than conventionally tilled wheat watersheds (Table 4), their vulnerability to P loss did not differ ($P > 0.05$). This may be attributed to the build-up of surface soil test P under no-till wheat (Table 1). For example, at El Reno in 1992, the surface 0 to 5 cm of no-till wheat (E7) had a Mehlich-3 soil test P content of 43 mg kg^{-1} compared with 23 mg kg^{-1} for conventional-till wheat (E8). Clearly, the index is flexible enough to reliably account for both source and transport factors.

A considerable portion of low productivity and erodible croplands in the Southern Plains is being set aside as part of the Conservation Reserve Program, planted to perennial grasses, and maintained in an idle state. Conversion of conventionally tilled (W3) and no-till wheat watersheds (W4) at Woodward to native grasses in 1986 reduced sediment and total P loss 102 and 10-fold for conventional-till and 38 and 13-fold for no-till wheat (Table 4). Consistent with this decrease were lower vulnerabilities to P loss from set-aside grass (4.3 and 4.6) than wheat (16.4 and 12.9).

Table 3. Site vulnerability to P loss as a function of total index values.

Site vulnerability	Total index rating value
Low	<10
Medium	10–18
High	19–36
Very high	>36

Treatment of one of the two gullied watersheds at Little Washita reduced erosion, total P loss, and P index values (Table 5). Before gully treatment, L2 had a significantly ($P < 0.05$) greater sediment and total P loss than L1, whereas P index ratings were similar. After gully shaping and grass introduction on L2, sediment loss was 5.6-fold and total P loss 3.9-fold lower than from the untreated L1 watershed (Table 5). Also, L2 had a low vulnerability (8.5) compared with a medium vulnerability for L1 (14.8).

The order of vulnerability to P loss is related to measured total P loss (Fig. 1). From Fig. 1, it can be seen that watersheds classified as having a high vulnerability to P loss in runoff had total P losses in excess of 2 kg ha^{-1} yr^{-1}. The close relationship between P index rating and total P loss shown in Fig. 1 [P index $= -5.7 + 6.3\log(\text{total P loss})$; $r^2 = 0.70$], indicates the indexing procedure can give reliable estimates of vulnerability to P loss in runoff from watersheds of widely differing management.

DISCUSSION

In areas where surface waters have been determined to be biologically sensitive to P inputs, vulnerability to P loss may be used to assess farm management options in terms of soil testing, soil conservation, and P management (Sims, 1993). As vulnerability increases from low to very high, the frequency of soil P testing should increase from every 3 yr to every year, and estimates of the time required to deplete soil P to optimum levels should be made. Soil conservation measures should also be encouraged, but as site vulnerability becomes medium or greater, reduced tillage, buffer strips, grassed waterways, and the use of high P demand crops should be considered. Any changes in P management that may

Table 4. Mean annual sediment, runoff, total P loss, and P index rating value as a function of watershed management.†

Management	Sediment	Runoff	Total P Mean	Total P Min.	Total P Max.	P index rating Mean	P index rating Min.	P index rating Max.
	kg ha^{-1} yr^{-1}	cm	g ha^{-1} yr^{-1}					
Grass								
E1	39	11.6	210	71	580	5.3	3.0	6.5
E2	27	9.5	210	42	581	5.1	1.0	8.0
E3	35	10.0	195	52	363	5.0	3.0	6.5
E4	40	9.0	283	29	568	5.5	3.0	7.5
W1	33	0.6	27	1	114	2.5	1.5	4.5
W2	465	1.3	202	3	752	4.1	1.0	8.0
W3	115	1.4	122	47	294	4.3	3.0	6.0
W4	153	1.6	99	21	192	4.6	2.5	8.0
Y14	603	15.2	345	25	957	4.6	2.5	5.0
W10	74	11.2	217	70	600	4.3	2.5	7.0
SW11	870	13.1	516	49	848	4.6	2.0	7.0
Avg.	223a	7.7ab	221a			4.5a		
No till								
B10A	213	2.6	224	54	408	5.8	4.0	9.0
B11A	440	3.2	382	59	699	7.5	4.0	10.0
B112A	911	5.5	634	38	1 544	8.5	6.0	12.0
E7	375	10.3	1128	79	3 421	11.3	7.5	15.5
W4	883	6.5	1262	50	3 508	12.9	7.5	17.0
Avg.	564b	5.6ab	726b			9.2ab		
Reduced till								
B10B	617	1.7	423	15	1 338	5.6	3.5	9.0
B11B	790	2.3	438	87	731	7.6	5.5	9.0
B12B	2 418	2.0	541	21	1 523	8.0	3.5	14.0
Avg.	1 275b	2.0a	467b			7.1a		
Conventional till								
E5	2 250	10.5	1534	26	4 562	12.6	8.0	17.5
E6	5 341	9.8	2967	190	11 414	16.9	8.0	23.5
E8	2 876	8.6	1945	117	12 534	14.9	9.5	23.5
W3	11 738	4.3	4617	213	15 572	16.4	11.0	25.0
Y	1 599	11.4	671	132	1 376	13.9	11.5	16.0
Y2	901	12.6	860	113	1 505	13.4	9.5	16.0
Y6	2 083	8.3	1105	79	2 608	14.9	11.0	25.0
Y8	1 363	9.6	883	278	1 667	13.7	12.5	15.5
Y10	4 015	14.4	2458	39	4 876	16.5	10.0	23.0
Avg.	3 574c	9.9ab	1893c			14.8bc		
Peanut-sorghum								
C1	14 351	12.2	4309	267	8 866	21.4	14.5	23.5
C2	19 016	10.3	5961	282	10 809	20.9	14.0	24.5
Avg.	16 684d	11.3b	5135d			21.2c		

† Means followed by different letters are significantly different ($P < 0.05$) between specific management types as determined by analysis of variance.

affect P loss in runoff should be considered before implementation. Also, development of a long-term P management plan should be encouraged for sites of high vulnerability to P loss and be required to be implemented on sites of very high vulnerability (Sims, 1993).

Normally, the P index would be applied in field situations with estimated runoff and sediment yield. As for any model, reliability of output or index values will be dependent on the accuracy of inputs such as runoff or sediment yield. In the present study, observed runoff and sediment yield were used to facilitate a better test of the P index by eliminating any shortcomings in runoff or sediment yield estimation. Also, the present study

Table 5. Mean annual runoff (cm), sediment (kg ha^{-1} yr^{-1}), total P loss (kg ha^{-1} yr^{-1}), and P index rating value (unitless) for untreated (L1) and treated gully (L2) watersheds.†

Parameter	1980–1983 L1 gullied	1980–1983 L2 gullied	1985–1992 L1 gullied	1985–1992 L2 treated‡
Runoff	4.6 a	6.5 b	10.3 a	13.2 b
Sediment	15 876 a	56 211 b	27 461 a	4 890 b
Total P	2 742 a	5 657 b	6 385 a	1 637 b
P index	14.3 a	14.5 a	14.8 a	8.5 b

† L1 and L2 values or each period followed by different letters are significantly different ($P < 0.05$) as determined by analysis of variance.
‡ On watershed L2, the gullies were treated by shaping and 'Midland' bermudagrass planting.

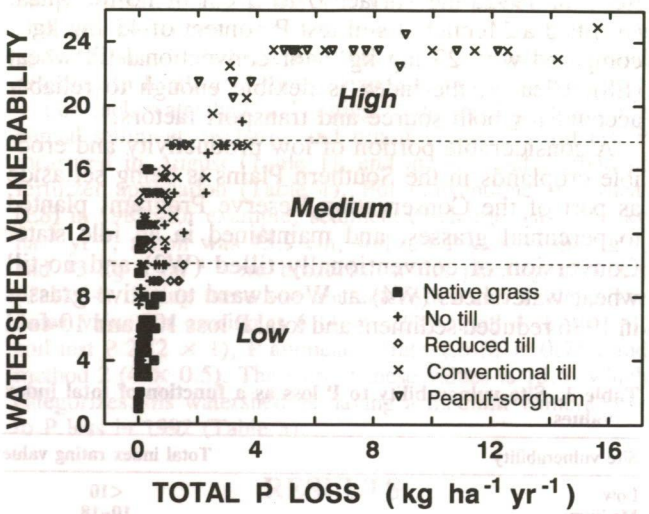

Fig. 1. Relationship between P index rating of watershed vulnerability to P loss in runoff and measured total P loss in runoff.

based the range of soil test P categories on crop yield response in the area. The magnitude of site vulnerability will depend on the range of soil test P values used. Thus, it is critical that reliable soil test P values for each category be established for specific areas based on regional agronomic, economic, and environmental concerns. Clearly, soil test P values must be categorized at regional levels to ensure index flexibility in accounting, because P-related water quality problems occur in specific areas rather than being nation wide.

Currently, the index assesses site vulnerability to P loss on an annual basis using annual erosional and runoff losses and average soil test P values. This may not be an accurate representation of site vulnerability in some cases. For example, up to 90% of annual soil, runoff, and P loss can occur in only one or two intensive storms during a year (Edwards and Owens, 1991; Smith et al., 1991b). However, if climatic, topographic, and agricultural management factors are such that these losses occur during 15 to 20 runoff events spread over a year, site vulnerability to P loss would not be as great as similar losses from only one storm.

In addition, modification of the index to include dissolved P may be warranted in situations with high soil P. For example, even if erosion is minimal, elevated surface soil P can maintain total P losses in runoff in excess of 5 kg ha^{-1}, of which >95% is dissolved P (Edwards and Daniel, 1993). Further, as dissolved P is immediately available for algal uptake, the loss of total P predominantly as dissolved P will have a greater impact on the biological productivity of P-sensitive surface waters than particulate or sediment-bound P. Thus, the index should describe the primary form of P transported in runoff as well as the total amount.

The results show that the P index is a valuable tool to identify sites within a watershed or basin that are sources of P, vulnerable to loss in runoff. The Natural Resource Conservation Service plans to use the index for field personnel to easily identify agricultural areas or practices that have the greatest potential to accelerate eutrophication. It is intended that the index will identify and reliably assess management options available to land users that will allow them flexibility in targeting control strategies that minimize P loss, while maintaining crop productivity.

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REFERENCES

Chichester, F.W., and C.W. Richardson. 1992. Sediment and nutrient loss from clay soils as affected by tillage. J. Environ. Qual. 21: 587–590.

Edwards, D.R., and T.C. Daniel. 1993. Effects of poultry litter application rate and rainfall intentsity on quality of runoff from fescuegrass plots. J. Environ. Qual. 22:361–365.

Edwards, W.M., and L.B. Owens. 1991. Large storm effects on total soil erosion. J. Soil Water Conserv. 46:75–77.

Heatwole, C.D., A.B. Bottcher, and L.B. Baldwin. 1987. Modeling cost-effectiveness of agricultural nonpoint pollution abatement programs in two Florida basins. Water Res. Bull. 23:127–131.

Johnson G., and B. Tucker. 1980. Oklahoma State University soil test calibrations. Oklahoma State Univ. Ext. Serv. Fact Sheet 2225. Oklahoma State Univ., Stillwater, OK.

Lemunyon, J.L., and R.G. Gilbert. 1993. The concept and need for a phosphorus assessment tool. J. Prod. Agric. 6:483–496.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409–1416.

O'Connor, P.W., and J.K. Syers. 1975. Comparison of methods for the determination of total phosphorus in waters containing particulate material. J. Environ. Qual. 4:347–350.

Prato, T., and S. Wu. 1991. Erosion, sediment, and economic effects of conservation compliance in an agricultural watershed. J. Soil Water Conserv. 46:211–214.

Sharpley, A.N., S.J. Smith, W.A. Berg, and J.R. Williams. 1985. Nutrient runoff losses predicted by annual and monthly soil sampling. J. Environ. Qual. 14:354–360.

Sharpley, A.N., S.J. Smith, O.R. Jones, W.A. Berg, and G.A. Coleman. 1992. The transport of bioavailable phosphorus in agricultural runoff. J. Environ. Qual. 21:30–35.

Sharpley, A.N., S.J. Smith, J.R. Williams, O.R. Jones, and G.A. Coleman. 1991. Water quality impacts associated with sorghum culture in the Southern Plains. J. Environ. Qual. 20:239–244.

Sharpley, A.N., S.C. Chapra, R. Wedepohl, J.T. Sims, T.C. Daniel, and K.R. Reddy. 1994. Managing agricultural phosphorus for the protection of surface waters: Issues and options. J. Environ. Qual. 23:437–451.

Sims, J.T. 1993. The phosphorus index: A phosphorus management strategy for Delaware's agricultural soils. Dep. of Plant and Soil Science, Univ. of Delaware, Newark, DE.

Smith, S.J., A.N. Sharpley, J.W. Naney, W.A. Berg, and O.R. Jones. 1991a. Water quality impacts associated with wheat culture in the Southern Plains. J. Environ. Qual. 20:244–249.

Smith, S.J., A.N. Sharpley, J.R. Williams, W.A. Berg, and G.A. Coleman. 1991b. Sediment-nutrient transport during severe storms. p. 48–55. *In* S.S. Fan and Y.H. Kuo (ed.) Fifth Interagency Sedimentation Conf., Las Vegas, NV. March 1991. Federal Energy Regulatory Commission, Washington, DC.

Stevens, R.G., T.M. Sobecki, and T.L. Spofford. 1993. Using the phosphorus assessment tool in the field. J. Prod. Agric. 6:487–492.