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Phosphorus Risk Assessment Index Evaluation Using Runoff Measurements

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ABSTRACT: An index to evaluate the phosphorus (P) pollution potential of agricultural fields was proposed by Lemunyon and Gilbert in 1993. Data from three rainfall simulation studies were used to evaluate the relative importance of the variables in the P index. These studies included plots containing sorghum (Sorghum bicolor L.), winter wheat (Triticum aestivum L), and corn (Zea mays L) residues on which chemical fertilizer and composted or noncomposted beef cattle feedlot manure were applied under no-till and disked conditions. The factors of erosion, runoff, soil P level, P application source, and method, and rate of P addition were weighted and considered in the index calculation. Measured soil erosion accounted for 78% and 88% of the variability in total and particulate P losses, respectively, indicating the importance of erosion in the loss of sediment bound P. Bioavailable and dissolved P losses were unrelated to measured soil erosion but were influenced by tillage, runoff amount, and P source. The P index of Lemunyon and Gilbert was modified based on the results of these experiments. The correlation coefficient value (r) between total P loss and the modified P index values, was 0.74 as compared to 0.52 for the Lemunyon and Gilbert's P index. Additive index values were more closely correlated with total P loss than the index values calculated by multiplying the weight of each factor. If erosion and runoff are accurately predicted, the P index can serve as a useful tool for identifying sites where transport of P to surface water can be a potential concern.

Keywords: Animal waste, erosion, eutrophication, fertilizer, P loss, runoff, water quality

Manure and composted manure are valuable and renewable resources that can be effectively utilized for crop production and soil improvement. However, runoff from cropland areas receiving manure or compost may contribute to increased phosphorus (P) in streams and lakes. The main factors controlling P movement in surface runoff are transport (runoff and erosion) and such source factors as manure or fertilizer application method and rate and soil P test level (Sharpley et al. 1993). Elevated soil P levels may result from application of manure at rates in excess of crop nutrient requirements (Sims 1993; Sharpley et al. 1998). Eghball and Power (1999) showed a significant accumulation of plant available P in the top 15 cm of soil following N-based beef cattle manure or compost application, but no accumulation occurred with P-based applications. Elevated soil test P levels have been shown to increase dissolved P concentrations in runoff (Daniel et al. 1994; Pote et al. 1996, 1999).

In many agricultural watersheds, total annual P transport occurs mainly from a few relatively large storms (Edwards and Owens 1991; Pionke et al. 1997). In studying a small upland agricultural watershed, Gburek and Sharpley (1998) found that the areas of runoff production, and consequently the areas controlling most P transport, are often a limited and identifiable portion of the landscape.

Lemunyon and Gilbert (1993) developed a P risk assessment index that included both transport and source factors. The factors of erosion, runoff, soil test P level, P fertilizer application rate, P fertilizer application method, organic P source application rate, and organic P source application method were assigned weighted values of 1.5, 0.5, 1.0, 0.75, 0.5, 1.0, and 1.0, respectively. Each factor included several risk levels classified as none, low, medium, high, and very high, to which weight values of 0, 1, 2, 4, and 8 were assigned, respectively. By multiplying the weight value of each factor by its level weight, a score is determined (i.e., for a soil with medium erosion, the erosion score is 1.5 X 2 = 3). By adding the scores for all factors, a site vulnerability index can be calculated. A low index value (< 8) indicates low P loss vulnerability while a very high value (> 32) indicates great vulnerability to P loss.

Sharpley (1995) evaluated the P index for several watersheds where erosion and total P loss were measured and found a good relationship between the index value and the total P loss. Stevens et al. (1993) calculated the P index for several sites and found different values for various sites depending on erosion potential, soil P test level, and manure and fertilizer applications. Gburek et al. (2000) proposed two modifications to the original P index. These included multiplicative determination of the P index to account for lack of runoff potential for some areas and considering the proximity and potential for contributing to the stream via surface runoff.

The factors that influence P loss from a field need to be tested so that the usefulness of the P risk assessment index can be evaluated. The weight values for the variables used in the P index should also be examined.

The objectives of this study were to examine the effects of source and transport factors on P loss from three sites that had received beef cattle manure, composted manure, or inorganic fertilizer, and to evaluate and modify the P index with measurements obtained from three rainfall simulation studies.

Methods and Materials

Data from three field rainfall simulation experiments (Eghball and Gilley 1999; Eghball et al. 2000) were used in this study. Two experiments, one with sorghum residue and the other with winter wheat residue were conducted on a Sharpsburg silty clay loam (fine, smectitic, mesic, Typic Argiudoll) soil located near Lincoln, Nebraska. Experimental treatments in the sorghum residue study included the application of composted and noncomposted beef cattle feedlot manure to meet N or P requirements of the succeeding corn crop, chemical fertilizer, and an untreated check under no-till and disked conditions. On the plots containing wheat residue, treatments included the application of composted and noncomposted beef cattle feedlot manure (N-based), chemical fertilizer, and an untreated check under no-till and disked conditions.

On the no-till plots, the manure, compost, and fertilizer were left undisturbed on the soil surface. A single disking operation, to approximately 8 cm deep, was performed up and down the slope on the tilled treatments to incorporate the manure, compost, and fertilizer. Average slope gradients were 7% and 6% on the sorghum and wheat residue plots, respectively.

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The third experiment was conducted on a Monona soil (fine-silty, mixed, mesic, Typic Hapludoll) containing corn residue located near Treynor, Iowa. Within the study area, which had an average slope of 12%, narrow (~ 75 cm) switchgrass (*Panicum virgatum* L.) hedges, separated by 16 corn rows (97 cm row spacing), had been established perpendicular to the slope. Experimental treatments included the application of beef cattle feedlot manure, inorganic fertilizer, and untreated checks in no-till and disked systems, with or without a switchgrass hedge. Manure and fertilizer were left undisturbed on the soil surface of the no-till plots or were incorporated to a soil depth of 8 cm by disking up and down the slope on the tilled plots (plots were located within two hedges). The narrow grass hedges significantly reduced erosion, runoff, and P losses (Eghball et al. 2000; Gilley et al. 2000).

A split plot in a randomized complete block design with three replications was used for the three experiments. Tillage systems were the main plots and the subplots included check, fertilizer, compost or manure treatments. A portable rainfall simulator, based on a design by Swanson (1965), was used in all three experiments. Each 3.7 by 10.7 m plot was established using sheet metal borders. Runoff measurements were made soon after manure, compost, and fertilizer were applied. This represented an optimum situation for P loss in runoff. An initial 1 hr rainfall was applied at an intensity of 64 mm hr^{-1} over the entire plot area at existing soil-water conditions. A second 1 hr application (wet run) at the same intensity was conducted approximately 24 hr later. Runoff was collected during both runs and sampled for total P, particulate P, bioavailable P, and dissolved P.[1] Bioavailable P is the fraction of the P in runoff that is available to algae (Sharpley 1993).

Table 1. Phosphorus risk assessment index and site vulnerability ratings based on Lemunyon and Gilbert (1993).

Site characteristics	Unit	None (0)	Low (1)	Medium (2)	High (4)	Very High (8)
Erosion (1.5)	Mg ha^{-1}	Not Applicable	< 10	10–20	20–30	> 30
Runoff (0.5)	-	Negligible	Very Low or Low	Medium	High	Very High
Soil test (1.0)	mg kg^{-1}	Not applicable	Very Low or Low	Medium	High	Very High
P Fertilizer Rate (0.75)	kg P ha^{-1}	None	1–15	16–45	46–75	> 76
P Fertilizer Method (0.5)	-	None Applied	Placed with Planter at 5 cm Depth	Incorporated immediately before crop	Incorporated > 3 Months before Crop or Surface Applied < 3 Months before Crop	Surface Applied > 3 Months before Crop
P Organic Rate (1)	kg P ha^{-1}	None	1–15	16–30	31–45	> 46
P Organic Method (1)	-	None Applied	Injected Deeper than 5 cm	Incorporated Immediately before Crop	Incorporated > 3 Months before Crop or Surface Applied < 3 Months before Crop	Surface Applied to Pasture or > 3 Months before Crop

Total of Weighted Rating Value (Σ Site Characteristic X Weight)	↓ Site Vulnerability to P Loss
< 8	Low
8–14	Medium
15–32	High
> 32	Very High

Table 1 shows the P index developed by Lemunyon and Gilbert (1993). The soil erosion, soil test P level, P application method, P source, and application rate used in the index calculation were based on the measurements from the three field experiments (Table 2). The runoff class for all sites was medium based on soil classification information. Average soil Bray and Kurtz No. 1 P tests in the 0–5 cm depth were 31.3, 76.1, and 82.9 mg kg^{-1} on the sites containing sorghum, wheat, and corn residue experiments, respectively. Corresponding values for the 0–15 cm soil depth were 19.1, 36.2 and 55.3 mg kg^{-1}, respectively. These soil P levels are considered high to excessive for corn production in Nebraska and P fertilizer application would not be recommended (Hergert et al. 1995). Total P concentrations in the top 5 cm soil for the sorghum, wheat, and corn residue sites were 541, 643, and 847 mg kg^{-1}, respectively.

For index determination, the weight of each factor was multiplied by its risk level weight to determine the score for each factor, and then the scores for all factors were added to identify an overall value.

Table 2. Phosphorus application rate, erosion, runoff, loss of dissolved, bioavailable, particulate, and total P and P index values for various treatments.

Crop residue	Tillage	Treatment†	P Application Rate	Erosion	Runoff	Dissolved P	Bioavailable P	Particulate P	Total P	L & G‡ Additive	Modified Additive	Modified Multiplicative
			kg ha^{-1}	Mg ha^{-1}	mm	kg ha^{-1}				P index values		
Sorghum	No-till	Manure N	221	2.5	51	1.023	1.705	2.913	3.936	20.5	6	1
Sorghum	No-till	Manure P	51	2.7	43	0.343	0.748	2.021	2.364	20.5	7.5	1
Sorghum	No-till	Compost N	359	4.1	41	0.948	1.862	6.693	7.639	22	8	2
Sorghum	No-till	Compost P	51	4.1	51	0.423	0.830	2.850	3.273	22	7.5	1
Sorghum	No-till	Fertilizer	26	1.1	35	1.836	1.855	1.239	3.075	10	5.5	0.5
Sorghum	No-till	Check	0	2	31	0.090	0.145	1.107	1.197	4.5	3	0.125
Sorghum	Disked	Manure N	221	16.5	50	0.304	1.099	6.646	6.951	25	11	2
Sorghum	Disked	Manure P	51	7	27	0.036	0.201	2.192	2.228	19	9.5	0.75
Sorghum	Disked	Compost N	359	10.7	43	0.291	0.950	5.104	5.396	25	11	2
Sorghum	Disked	Compost P	51	11.7	46	0.049	0.444	3.491	3.539	25	10.5	1
Sorghum	Disked	Fertilizer	26	14	48	0.040	0.313	5.302	5.343	17.5	10.5	1
Sorghum	Disked	Check	0	7	28	0.015	0.150	2.364	2.379	9	7	0.375
Wheat	No-till	Manure N	208	0.6	27	0.657	0.762	0.214	0.872	22.5	6.25	1.5
Wheat	No-till	Compost N	428	1.1	37	0.952	1.101	0.517	1.463	22.5	6.25	1.5
Wheat	No-till	Fertilizer	26	1.1	35	1.098	1.167	0.651	1.293	12	5.75	0.75
Wheat	No-till	Check	0	0.9	36	0.045	0.085	1.612	1.657	6.5	3.25	0.188
Wheat	Disked	Manure N	208	9.8	48	0.120	0.308	3.367	3.487	27	9.25	2.25
Wheat	Disked	Compost N	428	8.4	50	0.155	0.369	3.048	3.203	21	9.25	2.25
Wheat	Disked	Fertilizer	26	7.1	48	0.034	0.106	3.590	3.624	13.5	8.75	1.125
Wheat	Disked	Check	0	10.2	54	0.027	0.110	3.486	3.513	17	9.25	0.75
Corn	No-till	Manure WOH	256	0.58	10	0.341	0.462	0.483	0.824	22.5	6.25	1.5
Corn	No-till	Manure WH	256	0.27	5	0.095	0.122	0.134	0.225	22.5	6.25	1.5
Corn	No-till	Fertilizer WOH	26	0.77	14	0.166	2.251	0.452	0.637	12	5.75	0.75
Corn	No-till	Fertilizer WH	26	0.31	8	0.069	0.114	0.184	0.239	12	5.75	0.75
Corn	No-till	Check WHO	0	0.73	16	0.033	0.112	0.462	0.494	6.5	3.25	0.188
Corn	No-till	Check WH	0	0.4	7	0.028	0.053	0.175	0.202	6.5	3.25	0.188
Corn	Disked	Manure WOH	256	1.66	20	0.294	0.479	0.782	1.076	16.5	5.25	0.75
Corn	Disked	Manure WH	256	0.99	17	0.186	0.261	0.391	0.566	16.5	5.25	0.75
Corn	Disked	Fertilizer WOH	26	2.78	26	0.073	0.227	1.265	1.554	9	6.75	0.75
Corn	Disked	Fertilizer WH	26	2.03	24	0.068	0.192	0.722	1.010	9	4.75	0.375
Corn	Disked	Check WOH	0	2.15	27	0.050	0.169	1.137	1.187	6.5	3.25	0.188
Corn	Disked	Check WH	0	0.69	16	0.056	0.112	0.298	0.354	6.5	3.25	0.188

† N and P indicate N and P-based manure or compost application; WH is with hedge and WOH is without hedge.
‡ L & G is Lemunyon and Gilbert (1993).

Multiplying the scores of each factor, instead of adding, may prevent domination of a certain factor or account for lack of, or reduced, runoff potential when a P index value is determined. We also calculated the index values in a "multiplicative" manner in which the score for each factor was determined as in the additive method, but the scores for the factors were multiplied (instead of added) to determine an overall value.

Correlation analysis was performed to determine the relationship between P index values and total, particulate, dissolved, and bioavailable P loss using SAS (1985). Stepwise regression analysis was used to evaluate the relationship between runoff P loss and the source and transport factors. In the regression analysis, discrete variables of P sources (0 for no treatment, 1 for fertilizer, and 2 for organic P sources) and tillage systems (0 for no-till and 1 for tillage) were converted to numeric values and used as dummy variables (Draper and Smith 1966).

Results and Discussion

Total and particulate P losses were significantly related to measured erosion while tillage, runoff amount, and the P source were the most important factors affecting the transport of dissolved and bioavailable P (Table 3). Erosion accounted for 78% and 88% of the variability in total and particulate P losses, respectively. Runoff amount, soil P test, and tillage factors minimally affected total and particulate P losses (Table 3). In this study, P application rates of manure, compost, and chemical P fertilizer did not significantly influence loss of particulate and bioavailable P even though the rates of applied manure or compost P were several times greater than the recommended chemical P fertilizer rate (Table 2). This indicates that a greater portion of the fertilizer P was carried in runoff as compared to manure or compost P.

Total and particulate P losses were highly related to measured erosion in the three experiments (Table 3 and Figure 1). Sharpley (1995) also showed significant correlation (r = 0.76) between total P loss and soil erosion on several grasslands in Oklahoma and Texas. On the other hand, bioavailable and dissolved P losses were unaffected by the erosion amount (Table 3 and Figure 1). Bioavailable P concentration in runoff was found to be highly correlated with runoff dissolved P concentration (Eghball and Gilley 1999). Controlling erosion seems to be a major

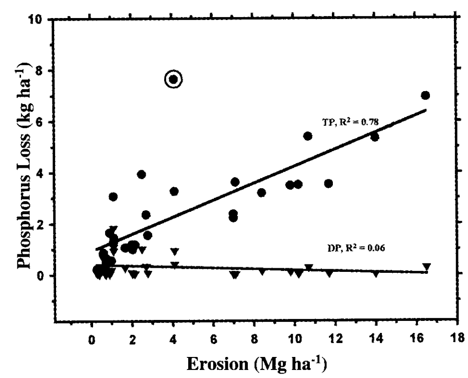

Figure 1. Total (circles) and dissolved P (triangles) losses in runoff as related to soil erosion in rainfall simulation runoff studies conducted in Nebraska and Iowa. The circled value was not used in the regression analysis for total P.

factor in reducing total and particulate P losses from fields receiving manure, compost, and chemical P fertilizer. Soil test P accounted for 1% of the variability in the total and dissolved P losses (Table 3). It should be emphasized that the soil P in these experiments ranged from 31–83 mg kg^{-1} in the top 5 cm of soil. Even though these values are considered excessive for crop production in Nebraska (Hergert et al. 1995), they are smaller than those reported by Pote et al. (1996, 1999) who showed a significant linear relationship between soil P level and dissolved P loss in runoff. The proportion of variability in dissolved P loss explained by the soil test P might have increased if the soil test P levels were higher.

Controlling bioavailable and dissolved P losses would require a significant reduction in runoff and incorporation of the applied P source within the soil. Strategies that can be used to reduce runoff include increased residue on the soil surface, greater infiltration by increasing soil organic matter and improved soil structure. Chemical amendments, including alum, can also be used to reduce dissolved P loss from fields receiving animal manure (Shreve et al. 1995).

The P index may be modified to correspond with the management and environmental conditions to which it is applied. For example, while erosion is an important factor on cropland areas, runoff and soil test P may be more important on pasture or grassland sites. Thus, erosion would have a high weight on the cropland and a low weight on grasslands. Based on the results of our experiments, the Lemunyon and Gilbert (1993) index was modified to reflect the greater effects of erosion on runoff P loss and the less important influence of P application rate and soil test P. The following weight changes were made in the modified index: erosion from 1.5 to 4.0, soil test P from 1 to 0.5, P fertilizer rate from 0.75 to 0.5, P fertilizer method from 0.5 to 1.0, and P organic rate from 1 to 0.5. The erosion weight of 4 in the modified index was based on the linear-plateau model of correlation coefficients between total P loss and various erosion weights (Figure 2). The weight of each factor and values for the modified index are shown in Tables 2 and 4. The additive P index values calculated using the weights given by Lemunyon and Gilbert (1993) (Table 1) were compared with the modified index.

Total and particulate P losses were significantly correlated with the index values (Table 5). The correlation coefficient for total P loss was higher (r = 0.74; P = 0.0001) when the additive modified index was used as compared to the Lemunyon and Gilbert index (r = 0.52; P = 0.002). The r values between total P loss and the modified index values with various erosion weights are given in Figure 2.

The additive method of index calculation resulted in higher r-values for total

Table 3. Stepwise regression indicating the effects of selected factors on total, particulate, bioavailable, and dissolved P losses (all in kg ha^{-1}) in runoff from rainfall simulation experiments conducted in Nebraska and Iowa.

Variable	Total P	Particulate P	Bioavailable P	Dissolved P
	--------	-------- Partial R^2	--------	--------
Erosion	0.78	0.88	–‡	0.06
Runoff	0.10	0.04	0.07	0.12
B & K P (0-5 cm)†	0.01	–	–	0.01
Applied P rate	0.01	–	–	0.01
Tillage¶	0.01	–	0.14	0.20
P source¶	–	–	0.13	0.06
Total	0.91	0.92	0.34	0.46

† B & K is Bray and Kurtz No. 1 soil P test.
‡ Slashes indicate that the variable had a probability level > 0.50.
¶ Discrete variables of tillage systems (0 for no-till and 1 for tillage) and P source (0 for no treatment, 1 for fertilizer and 2 for organic P sources) were converted to numeric.

Table 4. Modified P risk assessment index and site vulnerability ratings using the modified index.

Site characteristics	Unit	None(0)	Low (0.5)	Medium (1)	High (1.5)	Very High (2)
Erosion (4.0)	Mg ha^{-1}	Not Applicable	0–2.5	2.6–5.0	5.1–10.0	> 10.0
Runoff (0.5)	–	Negligible	low	Medium	High	Very High
Soil test (0.5)†	mg kg^{-1}	Not Applicable	< 30	30–75	76–125	> 125
P fertilizer rate (0.5)	kg P ha^{-1}	None	< 15	15–40	41–65	> 65
P fertilizer method (1.0)	–	None Applied	Placed with Planter at 5 cm Depth	Incorporated Immediately before Crop	Incorporated > 3 Months before Crop or Surface Applied < 3 Months before Crop	Surface Applied > 3 Months before Crop
P organic rate (0.5)	kg P ha^{-1}	None	< 30	30–55	56–80	> 80
P organic method (1)	–	None Applied	Injected Deeper than 5 cm	Incorporated Immediately before Crop	Incorporated > 3 Months before Crop or Surface Applied < 3 Months before Crop	Surface Applied to Pasture or > 3 Months before Crop

↓

Total of weighted rating value for additive (Σ site characteristic X weight)	Total of weighted rating value‡ for multiplicative ($\prod$ site characteristic X weight)	Site Vulnerability to P Loss
< 3	< 0.5	Low
3–6.5	0.5– 1.0	Medium
6.6–10	1.1– 2.0	High
> 10	> 2.0	Very High

†Bray and Kurtz No. 1 P (0 –5 cm soil depth).
‡The risk factor of none was not used.

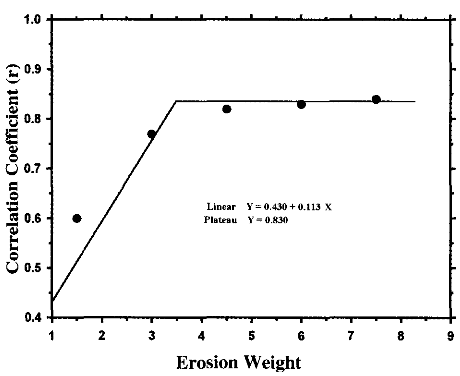

Figure 2. Correlation coefficients of the modified P index values versus runoff total P loss as the erosion weight increased. Standard error of estimates are 0.430 ± 0.022, 0.113 ± 0.027, and 0.83 ± 0.079.

Table 5. Correlation between total, particulate, bioavailable, and dissolved P losses and additive or multiplicative index values.

Index Calculation Method	Total P	Particulate P	Bioavailable P	Dissolved P
	r			
Lemunyon & Gilbert iIndex, Additive	0.52**	0.50**	0.29	0.18
Modified Index, Additive	0.74**	0.77**	0.15	– 0.04
Modified Index, Multiplicative	0.58**	0.55**	0.31	0.18

** and * indicate 0.01 and 0.05 probability levels, respectively.

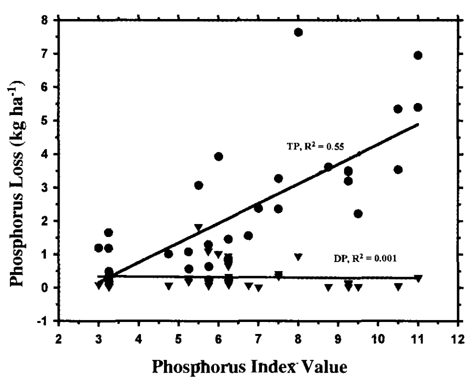

Figure 3. Total (circles) and dissolved P (triangles) losses in runoff as related to the modified P index values in rainfall simulation runoff studies conducted in Nebraska and Iowa.

and particulate P losses than did the multiplicative method (Table 5). The P index values were not significantly correlated with dissolved or bioavailable P loss (Table 5) indicating that the P indexes were much better predictors of the vulnerability of the site to the loss of sediment-bound P.

Total P loss in runoff was significantly correlated with the modified P index values when measured erosion was used to determine the erosion weight factor (Figure 3). Dissolved P loss was unrelated to the index value (Figure 3). Perhaps another index needs to be developed for dissolved or bioavailable P loss in which runoff amount, P source, and tillage factors would have greater weights. Site vulnerability needs to be considered when management systems are implemented. As site vulnerability increases from low to very high, conservation practices and a long term P management system needs to be implemented to reduce or eliminate P loss in runoff. Our field experiments were conducted to represent the worst case scenario for runoff P losses as rainfall occurred just after manure, compost, and fertilizer applications. It was also assumed that the sediments were carried directly into concentrated flow or stream. Some sediment may settle before reaching the concentrated flow or stream, and hence, reduce the sediment-bound P loss on a watershed scale (Gburek et al. 2000).

Summary and Conclusion

Erosion was the primary factor influencing total and particulate phosphorus (P) losses in runoff from fields receiving manure, compost, chemical P fertilizer, and no treatment under no-till and disked conditions. Runoff amount, P source, and tillage were the main factors influencing loss of dissolved and bioavailable P in fields that had recently received organic and inorganic P. In the long-term, organic or inorganic P applications should increase soil P level and may make this factor more important in the loss of dissolved and bioavailable P. Control of runoff and erosion is important in areas that are subject to P loss in runoff. Conservation practices that reduce runoff and erosion should be employed in vulnerable areas receiving animal manure and chemical P fertilizer. The P risk assessment index was significantly correlated with total and particulate P loss but not with the loss of bioavailable or dissolved P, indicating the usefulness of the index in assessing site vulnerability to runoff P loss. The P risk assessment index may be modified for the varying situations under which it is applied.

For cropland conditions, erosion is a dominant factor, while on pasture or grassland areas, runoff amount or soil P test might be the important factors influencing runoff loss of P. The P index can serve as a useful tool for identifying sites where transport of P to surface water can be a potential concern if erosion and runoff are accurately predicted.

ENDNOTE

[1] For chemical analysis methods, see Eghball and Gilley (1999, 2000).

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