Evaluation of the Phosphorus Source Component in the Phosphorus Index for Pastures

P. B. DeLaune,* P. A. Moore, Jr., D. K. Carman, A. N. Sharpley, B. E. Haggard, and T. C. Daniel

ABSTRACT

A phosphorus (P) index for pastures was developed to write nutrient management plans that determine how much P can be applied to a given field. The objectives of this study were to (i) evaluate and compare the P index for pastures, particularly the P source component, and an environmental threshold soil test P level by conducting rainfall simulations on contrasting soils under various management scenarios; and (ii) evaluate the P index for pastures on field-scale watersheds. Poultry litter was applied to 12 small plots on each of six farms based on either an environmental threshold soil test P level or on the P index for pastures, and P runoff was evaluated using rainfall simulators. The P index was also evaluated from two small (0.405 ha) watersheds that had been fertilized annually with poultry litter since 1995. Results from the small plot study showed that soil test P alone was a poor predictor of P concentrations in runoff water following poultry litter applications. The relationship between P in runoff and the amount of soluble P applied was highly significant. Furthermore, P concentrations in runoff from plots with and without litter applications were significantly correlated to P index values. Studies on pastures receiving natural rainfall and annual poultry litter applications indicated that the P index for pastures predicted P loss accurately without calibration ($y = 1.16x - 0.23$, $r^2 = 0.83$). These data indicate that the P index for pastures can accurately assess the risk of P loss from fields receiving poultry litter applications in Arkansas and provide a more realistic risk assessment than threshold soil test P levels.

Management of P from nonpoint sources, such as pastures fertilized with animal manures, has received increasing attention in recent years due to P runoff from pastures contributing to accelerated eutrophication of receiving water bodies (Carpenter et al., 1998). Between 1982 and 1997, the number of livestock operations in the United States has decreased by 24%; however, the total number of animal units has remained fairly constant (Kellogg et al., 2000). In 1997, 40% of the total animal units were confined. As a result, management of agricultural P has become a priority in preventing further water quality impairment. Regulations of the USEPA Concentrated Animal Feeding Operations (CAFO) state that manure application rates for P may be determined using soil test P levels, threshold soil test P levels, or a P index (USDA and USEPA, 1999).

P.B. DeLaune, Department of Biological and Agricultural Engineering, and T.C. Daniel, Department of Crop, Soil, and Environmental Sciences, University of Arkansas, Fayetteville, AR 72701. P.A. Moore, Jr. and B.E. Haggard, USDA-ARS, Poultry Production and Product Safety Research Unit, Fayetteville, AR 72701. D.K. Carman, USDA-NRCS, National Water Management Center, Little Rock, AR 72203. A.N. Sharpley, USDA-ARS, Pasture Systems and Watershed Management Research Unit, University Park, PA 16802. Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee by the USDA and does not imply its approval to the exclusion of other products that may be suitable. Received 24 Oct. 2003. *Corresponding author (pdelaun@uark.edu).

Published in J. Environ. Qual. 33:2192–2200 (2004).

677 S. Segoe Rd., Madison, WI 53711 USA

Several researchers have indicated that there are potential problems with using cutoff levels or threshold soil test P levels to manage P applications (Sharpley et al., 1999; Pierson et al., 2001; Sharpley and Rekolainen, 1997). Establishing threshold soil test P levels is often a highly controversial process because the database relating soil test P to P runoff is limited and, when available, site specific (Pote et al., 1996, 1999; Sharpley, 1995; Sharpley et al., 1999). The relationship between soil test P and P runoff, especially for grasslands fertilized with broiler litter, clearly requires further investigation if the relationship is used to regulate P management (Sharpley et al., 1999). Pierson et al. (2001) concluded that it would be difficult to use soil test P as an indicator of potential P loss from grasslands fertilized with broiler litter. The National P Project is being conducted across the country to better assess the relationship between soil test P and P runoff. The general objective of the National P Project is to develop P management recommendations that sustain agriculture and protect water quality. The field objectives of the National P Project are to characterize soil test P–P runoff relationships for a representative cross-section of benchmark soils across the United States. Benchmark soils are those that are important agricultural soils across all Major Land Resource Areas (MLRAs) in the United States.

An alternative approach to managing P is the P index. The original P index was developed as a risk assessment tool for P runoff potential from individual fields within a watershed (Lemunyon and Gilbert, 1993). The original P index consisted of an additive matrix that combined P source and P transport factors to estimate the risk of P runoff. The authors of the original P index considered modification and adaptation of the P index to be critical to accurately reflect local landscape characteristics and management practices (USDA Soil Conservation Service, 1994).

Gburek et al. (2000) recommended the separation and multiplication of source and transport factors to better assess the risk of P runoff. Preliminary testing of the original P index has shown it to adequately reflect P loss potential for watersheds of about 2 ha (Sharpley, 1995). However, Gburek et al. (1996) found that the original P index inadequately represented and assessed surface runoff from larger watersheds with variable source areas of surface runoff. Several states have adopted a multiplicative matrix and are making modifications to the original P index to more accurately reflect local landscape characteristics and management practices. As with the original P index, most P indices are being developed through many discussions with area scientists and representatives of state and federal technical, advisory, and regulatory agencies.

Abbreviations: SRP, soluble reactive phosphorus.

Table 1. The Arkansas phosphorus index† for pastures, site characteristics, and calculation methodology.

Characteristic	P loss category	Loss rating value
	P source characteristics	
Soil test P	continuous variable	0.000666 × STP‡ (lb acre^{-1})
Soluble manure P rate	continuous variable	0.404 × SRP§ applied (lb acre^{-1})
	P transport characteristics	
Soil erosion	<1	0
	1 to 2	0.1
	2 to 3	0.2
	3 to 5	0.4
	>5	1.0
Soil runoff class	negligible	0.1
	low	0.2
	moderate	0.3
	high	0.5
	very high	1.0
Flooding frequency	none	0
	occasional	0.1
	frequently	2.0
Application method	incorporated	0.1
	surface-applied	0.2
	surface-applied on frozen ground or snow	0.5
Application timing	June to October	0.1
	March to May	0.2
	November to February	0.5
Harvest management	hayed only	0.1
	hayed and grazed	0.2
	grazed only	0.3
	Other site characteristics	
Annual precipitation, mm	0–254	0.2
	254–508	0.4
	508–762	0.6
	762–1016	0.8
	1016–1270	1.0
	1270–1524	1.2
	1524–1778	1.4
Best management practices (BMPs)	buffer strips, terracing or contour strips, or denying cattle access to streams	0.9

† P index = P source × P transport × precipitation × BMPs.
‡ Soil test phosphorus.
§ Soluble reactive phosphorus.

The P index for pastures was developed with the cooperation of several state and federal agencies in Arkansas. Unlike most P indices that are used for all agricultural settings, this P index was developed specifically for pastures. Experiments were designed to observe how P runoff was affected by soil test P, soluble P in the litter, poultry litter application rate, modified diets (phytase and high available P corn), and fertilizer type (commercial versus manure) (DeLaune et al., 2004). The P index for pastures is multiplicative, with four terms: P index = P source × P transport × precipitation × best management practices (BMPs). Weighting factors for P sources were derived using regression analysis from rainfall simulation studies (DeLaune et al., 2004). The source term is comprised of soil test P and soluble P application rate (Table 1). The P transport terms includes soil erosion, soil runoff class, application method, application timing, flooding frequency, and harvest management (Table 1). Credit for BMPs is given only once. For example, only BMPs not affecting the source or transport calculation are included, such as buffer strips (Table 1). A precipitation factor is included because wet regions generate more runoff than arid regions (Table 1). In Arkansas, the precipitation factor is one for the entire state. However, the precipitation factor would vary if the P index for pastures was used in adjacent states or other states that may use this P index as a framework for the development of a management-specific P index. Fields are assigned a P index of low, medium, high, or very high if the calculated P index is <0.6, 0.6 to 1.2, 1.2 to 1.8, or >1.8, respectively (Table 2). When the value is low or medium, manure application can be based on nitrogen (Table 2). Litter applications are based on P when the value is high and no P application is recommended when the value is very high (Table 2). The Natural Resources Conservation Service (NRCS) of Arkansas currently uses this index to write nutrient management plans.

Research was warranted to evaluate the ability of the P index for pastures to accurately assess the risk of P losses before implementation as a nutrient management tool. It was also important to determine and compare assessment capabilities between the P index for pastures and an environmental threshold soil test P level. The objectives of this research were to (i) evaluate and compare the P index for pastures, particularly the P source component, and an environmental threshold soil test P level by conducting rainfall simulations on six poultry or beef farms located in Arkansas and Oklahoma with contrasting soils under various management scenarios; and (ii) evaluate the P index for pastures on field-scale watersheds receiving annual poultry litter applications and natural rainfall.

Table 2. Phosphorus index for pastures interpretations and recommendations.

P index rating	Site interpretations and recommendations
<0.6†	Low potential for P movement from site. Apply nutrients based on crop needs, normally N. Caution against long-term buildup.
0.6 to 1.2	Medium potential for P movement from site. Evaluate the index and determine any areas that could cause long-term concerns. Consider adding conservation practices or reduced P application to maintain the risk at 1.2 or less. Apply nutrients based on crop needs, normally N.
1.2 to 1.8	High potential for P movement from site. Evaluate the index and determine elevation cause. Add appropriate conservation practices and/or reduce P application. The immediate planning target is a P index value of 1.2 or less. If this cannot be achieved with realistic conservation practices and/or reduced P rates in the short term, then a management plan needs to be developed with the long-term goal of a P index less than 1.2. Apply nutrients to meet crop P needs according to NRCS Nutrient Management Standard 590.
>1.8	Very high potential for P movement from site. No litter application. Add conservation practices to decrease this value below 1.8 in the short-term and develop a progressive conservation plan that would reduce the P index to a lower risk category, with a long-term goal of a P index value less than 1.2.

† Estimated annual P loss from a field in lb P acre^{-1} yr^{-1}.

MATERIALS AND METHODS

Site Locations

To conduct this research, plots needed to be established on benchmark soils with a preexisting range of soil test P levels. A wide range of soil test P levels was a prerequisite to develop relationships between soil test P and P runoff and to evaluate the P index for pastures. Along with a gradient of low to high soil test P levels, a variety of management practices and soil series were also sought.

Six farms within the Eucha–Spavinaw watershed (three in Benton County, AR, and three in Delaware County, OK) were identified with poultry or beef cattle operations that were characteristic of operations in the Ozark Highlands. Each site consisted of a poultry or beef cattle operation with a history of annual poultry litter applications to pastures for at least the past 10 years. Poultry litter had not been applied since the previous spring on each farm. Once the six farms were selected, a USDA-NRCS soil classifier from the Washington County, AR, office examined and confirmed the soil series for the field used at each farm. The soils used for this study were Captina silt loam (fine-silty, siliceous, active, mesic Typic Fragiudult), Jay silt loam (fine-silty, mixed, active, thermic Oxyaquic Fragiudalf), Newtonia silt loam (fine-silty, mixed, superactive, thermic Typic Paleudoll), Nixa silt loam (loamy-skeletal, siliceous, active, mesic Glossic Fragiudult), and Taloka silt loam (fine, mixed, active, thermic Mollic Albaqualf).

Plot Installation

After verification of the soil series on each farm, soil samples were collected in a grid pattern to locate areas of low, medium, high, and very high soil test P levels. One soil series was isolated at each farm representing a benchmark soil in that area. Initially, a grid was laid out over an area ranging from approximately 1.6 to 4.1 ha, depending on the farm. Approximately 100 points were flagged within each grid (distance between grid points ranged from 12 to 23 m, depending on the farm). Three soil cores (0–15 cm) were taken at each point and composited and marked using a real-time differential global positioning system (DGPS). The DGPS had a horizontal accuracy of 2 to 3 m (Trimble Navigation Limited, 1996). Soil samples were dried at 60°C and ground to pass a 2-mm screen. Mehlich-III P was determined using an inductively coupled argon plasma spectrometer (ICP) after extracting 2 g of soil with 14 mL of Mehlich-III extracting solution (Mehlich, 1984). After analysis, a real-time DGPS was used to navigate back to grid locations lying within close proximity containing low and high soil test P levels. Another grid (27.4 × 21.3 m) was then laid out between the flagged points. This second grid was more intensively sampled than the initial grid with points being flagged every 1.52 by 4.05 m. Three soil cores were collected and composited for Mehlich-III P analysis. Each point flagged within the smaller sampling grid was mapped using DGPS.

Plot construction began after six locations having a wide range of soil test P on the same soil series at each farm were located (Table 3). Once a suitable area was found, a wooden frame having the same dimension as the field plots (2 × 1.5 m) was placed on the ground to determine the proper placement of the plot. A Brunton (Riverton, WY) compass was used to determine the slope along the length of the plot. After the outline of the frame was drawn, a concrete saw was used to cut a continuous groove in the soil around the perimeter of the plot area. Metal strips 15 cm in height were inserted into the continuous groove so that approximately 5 cm of the metal strips were exposed to hydrologically isolate the plot area from surrounding land. The metal strips were inserted on three sides as well as down the center of the plot to divide the plot in half. A 15-cm-tall strip, termed the "silt plate," was placed into the ground at the downslope edge until the top of the strip was just below the soil surface. An aluminum collection trough was then placed at the downslope edge. A flange of the collection trough was placed between the soil in the plot and silt plate to prevent runoff from flowing under the collection trough. Two collection troughs were used for each plot, one for each side of the divider. An auger was used to dig holes at each end of the collection trough and a plastic bucket was inserted into the hole for runoff collection. Six small plots (1.5 × 2 m) were constructed on each farm in the spring of 2000. Each of these plots was divided in half resulting in six paired plots (12 plots total) at each farm.

Runoff Collection

Portable rainfall simulators as described by Humphry et al. (2002) were used for this portion of the study. Rainfall simulators provided a 70 mm h^{-1} storm event sufficient in duration to provide 30 min of continuous runoff. Runoff water was collected continuously for 30 min and pumped into collection barrels. Runoff water pumped into collection barrels was mixed and aliquots were taken for analysis. Aliquots were filtered through a 0.45-μm filter and acidified to pH 2 with HCl. Soluble reactive P was determined colorimetrically on filtered, acidified samples using the automated ascorbic acid reduction method (American Public Health Association, 1998).

Treatments

Three rainfall simulations were conducted on each plot before the addition of any fertilizer treatment to observe the relationship between soil test P and soluble reactive phosphorus (SRP) concentrations in runoff water. Thereafter, various scenarios were tested on each farm. Five soil cores (0–15 cm)

Table 3. Soil test P, poultry litter application rate, soluble phosphorus application rate, litter type, basis of litter application, and P index for each plot used in runoff studies within the Eucha–Spavinaw watershed.

Plot	Soil test P	Poultry litter application rate	Soluble P application rate	Litter type†	Basis of litter application	P index
	kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}			
			Farm A			
1	94	4.48	0.43	A	P index	0.19
2	72	4.48	4.55	N	soil test P	1.21
3	144	11.0	1.03	A	P index	0.39
4	132	4.48	4.55	N	soil test P	1.27
5	97	6.72	6.82	N	P index	1.81
6	114	4.48	4.55	N	soil test P	1.25
7	102	3.36	3.42	N	P index	0.96
8	117	4.48	4.55	N	soil test P	1.26
9	198	3.36	0.32	A	P index	0.26
10	162	0	0	NA	soil test P	0.15
11	152	6.72	6.82	N	P index	1.86
12	124	4.48	4.55	N	soil test P	1.26
			Farm B			
1	52	4.48	0.43	A	P index	0.15
2	47	6.72	5.21	N	soil test P	1.36
3	77	6.72	5.21	N	P index	1.39
4	105	4.48	3.47	N	soil test P	0.97
5	178	2.24	0.21	A	P index	0.28
6	131	4.48	3.47	N	soil test P	1.28
7	140	11.0	1.03	A	P index	0.39
8	89	4.48	3.47	N	soil test P	0.96
9	158	3.36	2.61	N	P index	0.80
10	175	0	0	NA	soil test P	0.16
11	163	4.48	3.47	N	P index	1.32
12	102	4.48	3.47	N	soil test P	1.25
			Farm C			
1	268	3.36	2.21	N	P index	0.81
2	280	0	0	NA	soil test P	0.26
3	274	6.72	4.40	N	P index	1.76
4	226	0	0	NA	soil test P	0.27
5	139	4.48	2.93	N	P index	1.12
6	84	4.48	2.93	N	soil test P	1.05
7	110	2.24	0.21	A	P index	0.20
8	81	4.48	2.93	N	soil test P	1.05
9	234	8.96	0.84	A	P index	0.43
10	181	0	0	NA	soil test P	0.17
11	307	2.24	0.43	A	P index	0.34
12	284	0	0	NA	soil test P	0.26
			Farm D			
1	272	2.24	0.21	A	P index	0.39
2	380	0	0	NA	soil test P	0.45
3	512	4.48	4.55	N	P index	2.09
4	454	0	0	NA	soil test P	0.54
5	311	1.57	0.15	A	P index	0.42
6	385	0	0	NA	soil test P	0.46
7	369	4.48	0.43	A	P index	0.58
8	375	0	0	NA	soil test P	0.45
9	394	3.36	3.41	N	P index	1.58
10	523	0	0	NA	soil test P	0.63
11	328	7.39	0.69	A	P index	0.48
12	379	0	0	NA	soil test P	0.35
			Farm E			
1	148	6.72	4.40	N	P index	1.25
2	155	0	0	NA	soil test P	0.14
3	218	5.60	3.67	N	P index	1.13
4	221	0	0	NA	soil test P	0.21
5	222	3.14	0.29	A	P index	0.28
6	189	0	0	NA	soil test P	0.18
7	141	3.14	0.29	A	P index	0.21
8	142	4.48	2.93	N	soil test P	0.87
9	201	11.0	1.03	A	P index	0.45
10	172	0	0	NA	soil test P	0.16
11	171	3.36	2.21	N	P index	0.72
12	188	0	0	NA	soil test P	0.17
			Farm F			
1	178	5.60	3.67	N	P index	1.25
2	167	0	0	NA	soil test P	0.18
3	118	4.48	2.93	N	P index	1.09
4	126	6.72	4.40	N	soil test P	1.58
5	203	8.96	0.84	A	P index	0.46
6	171	0	0	NA	soil test P	0.18
7	91	3.14	0.29	A	P index	0.20
8	99	6.72	4.40	N	soil test P	1.55
9	229	2.24	0.21	A	P index	0.30
10	215	0	0	NA	soil test P	0.23
11	200	3.36	2.21	N	P index	0.74
12	198	0	0	NA	soil test P	0.18

† A, alum; N, normal; NA, none applied.

Table 4. Maximum application rates by soil runoff potential for environmental threshold soil test P recommendations (Oklahoma NRCS Conservation Practice Standard Code 633 at time of study).

Soil test P	Slight runoff potential†	Moderate runoff potential	Severe runoff potential
mg kg^{-1}			
0–60	crop needs for N	crop needs for N	crop needs for N, split applications
60–150	101 kg P ha^{-1}	67 kg P ha^{-1}	not to exceed 67 kg P ha^{-1} in two years
>150	no application	no application	no application

† Runoff potential based on hydrologic soil group and slope (USDA Soil Conservation Service, 1975).

were taken from each plot after the third rainfall event and analyzed for Mehlich-III P. Soil was collected immediately adjacent to each plot to replace the soil within each plot removed via sampling. Soil test P data were needed from each plot to determine the appropriate poultry litter application rates (Table 3).

Because each farm had six paired plots, litter applications were applied to one-half of the plot based on a 150 mg kg^{-1} environmental threshold soil test P level and applied to the other one-half based on the P index for pastures (Table 3). The basis of litter application from the environmental threshold is listed in Table 4. The P index scenarios were calculated at each farm using varying litter application rates and soluble P application rates. Calculated scenarios were selected resulting in two P index values each in the low, medium, and high or very P index category. This was done to provide a wide range of values to evaluate the relationship between the P index and P loss from each plot. Both alum-treated and untreated litter was used in the study. This provided two litter sources with different soluble P concentrations, which resulted in a wide range of values for the P source component. Soluble reactive P in the litter was determined colorimetrically using the automated ascorbic reduction method (American Public Health Association, 1998) after extracting 20 g of litter with 200 mL of double deionized water for 2 h on a mechanical shaker (Self-Davis and Moore, 2000). After litter application, three rainfall simulations were conducted on each plot. Therefore, a total of six rainfall simulations were conducted on each plot at each farm. Rainfall simulations were conducted immediately after litter application on each farm and thereafter at Days 5 and 10 on Farms A and C, 5 and 7 on Farm B, 5 and 8 on Farm D, and 3 and 8 on Farms E and F.

Field-Scale Validation of the Phosphorus Index

Annual P loss was also measured from two 0.405-ha watersheds receiving poultry litter and natural rainfall since 1995 (Moore et al., 2000). Untreated poultry litter had been applied annually to one watershed, whereas alum-treated poultry litter had been applied to the adjacent watershed. Poultry litter applications began in 1995. Runoff data were also collected in 1994 before litter application. Application rates were 5.6 Mg ha^{-1} for each year, except in 1995 and 1996 when the application rate was 8.96 Mg ha^{-1}. The litter was surface-applied in April or May of each year to the fescue (*Festuca arundinacea* Schreb.)-cropped watersheds. The forage was cut and removed each year.

Complete details of field management and a description of the soil are given in Moore et al. (2000). Each watershed was equipped with automatic water samplers (American Sigma Corp., Medina, NY). After each rainfall event, water samplers were checked to determine if runoff had occurred. Runoff volumes and P concentrations in runoff were recorded each year. The P source potential of the watersheds was calculated for each year since the amount of soluble P applied was known as well as the soil test P concentration. The transport factors of the P index for pastures were also known (transport = 0.8); therefore, the P index of the two watersheds was calculated. Furthermore, annual P loss was easily calculated since the runoff volume and runoff concentration from every runoff event in the past seven years had been measured. Results from these field-scale studies were used to evaluate the P index for pastures.

Statistical Analysis

Analysis of variance was used to determine significant treatment effects on P loss (SAS Institute, 1990). When significance was indicated, means were separated using Fisher's protected least significant difference (LSD, $P < 0.10$). An alpha of 0.10 was used to minimize the likelihood of a Type II error. Linear regression analyses were also performed using JMPIN to test if the slope was significantly positive (SAS Institute, 1996).

RESULTS AND DISCUSSION

Rainfall Simulation Studies

Soil Test Phosphorus versus Phosphorus Runoff

No litter was applied to plots during the first three rainfall simulation events on each farm. Before litter application, average SRP concentrations in runoff water were significantly correlated to Mehlich-III soil P concentrations (Fig. 1a). This relationship has been shown in previous studies (DeLaune et al., 2004; Pote et al., 1996, 1999; Sharpley, 1995). The highest SRP concentrations in runoff water were observed from Farm D, which also had the highest soil test P levels (Fig. 1a). Average concentrations of SRP in runoff water from three runoff events were as high as 5.8 mg P L^{-1}. This value is higher than typically observed from runoff plots with no recent P additions. One possible explanation for these high values is the fact that the plots on this farm may have received a "dusting" of poultry litter before rainfall simulation studies as poultry litter was applied to the surrounding area after the plots had been constructed. The last three rainfall simulation events (Events 4–6) occurred after poultry litter was applied based on either the P index or the environmental threshold soil test P level. All of the plots did not receive poultry litter applications (Table 3). Once treatments were applied to the plots, SRP concentrations in runoff water were poorly correlated with Mehlich-III soil P (Fig. 1b). However, a significant linear relationship was observed between SRP concentrations in runoff water and the amount of soluble P applied (Fig. 1c). Previous reports have also shown good relationships between soil test P and P concentrations in runoff before litter application, but poor relationships after litter application due to soluble P application rates (DeLaune et al., 2004; Sauer et al., 2000). A significant linear relationship ($P < 0.0001$), which accounted for more variability ($r^2 = 0.66$), was

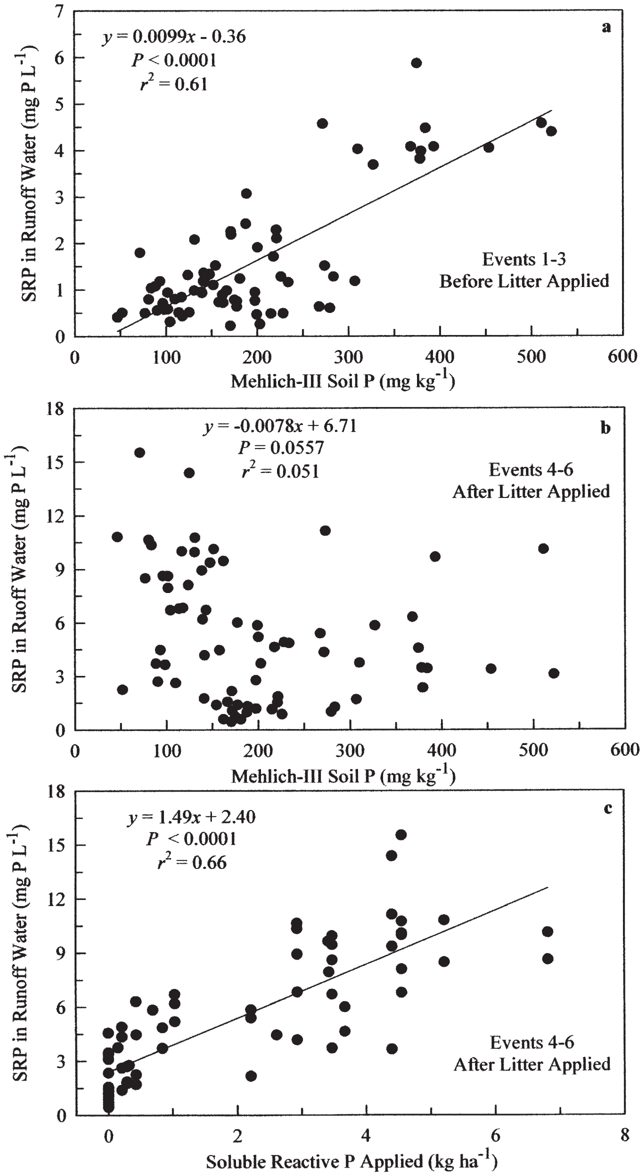

Fig. 1. Relationship between (a) average soluble reactive phosphorus (SRP) in runoff from three runoff events before litter application and Mehlich-III P; (b) average SRP in runoff from three runoff events after litter application and Mehlich-III P; and (c) average SRP in runoff from three runoff events after litter application and the amount of soluble P applied. Soil test P (Mehlich-III) was measured after Events 1–3, before litter application. (Small plot, simulated runoff events.)

found between SRP concentrations in runoff and the P index (Fig. 1c). This provides evidence that a management tool that accounts for multiple factors may give a better assessment than a sole factor.

Threshold Soil Test Phosphorus versus Phosphorus Index

The P index for pastures provides an annual P loss assessment (Table 2). Runoff volumes often varied greatly for some of the paired plots in the rainfall simulation study. Likewise, large differences in runoff volumes were observed on the same plots for different runoff

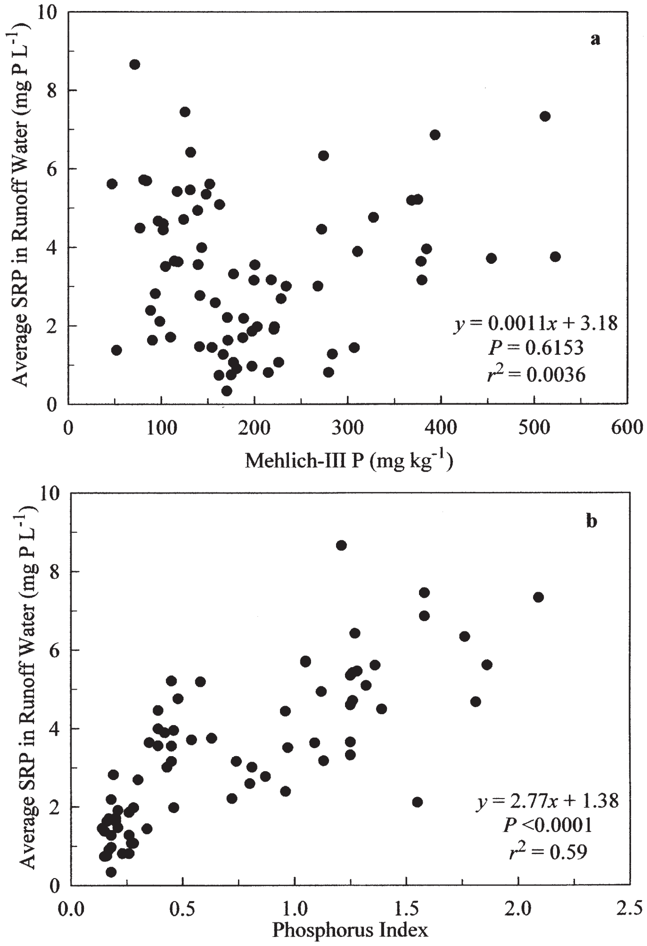

Fig. 2. Relationship between average soluble reactive phosphorus (SRP) in runoff water from six runoff events (three events before litter application, three events after litter application) and (a) Mehlich-III P and (b) the P index. (Small plot, simulated runoff events.)

events. As previously mentioned, this study was part of the National Soil Test P Project. The protocol for this project calls for the use of small plots (0.75 × 2.0 m). The small size of these plots resulted in high amounts of variability in hydrology. Humphry et al. (2002) noted that the use of these small plots may not be appropriate for all research applications and is not intended to represent edge of field values from a large watershed, but this approach does allow for relative comparisons and is sufficient in runoff studies relating soil P and runoff P.

Although hydrologic parameters were affected by the small plot size, the relationship between soil test P and P runoff and the relationship between the P index and P runoff was compared. Because management tools (threshold soil test phosphorus [STP] and P index) provide an annual assessment, P concentrations in runoff water were averaged for the six runoff events from all farms. The average SRP concentration in runoff from the six runoff events was poorly correlated to soil test P ($r^2 = 0.0036$, $P > 0.05$; Fig. 2a). However, a highly significant correlation was found between SRP concentrations in runoff water and the P index ($r^2 = 0.59$, $P < 0.0001$; Fig. 2b). Because the P index accounts for soluble P in applied fertilizer or manure (Table 1), and

Table 5. Relationship between soluble reactive P concentrations in runoff water and soil test phosphorus (STP) or the P index for pastures.

Farm	Soil series (hydrologic soil group†)	Variable	Equation	$P > F$
A	Captina (C)	STP	$y = -0.0179x + 8.89$	0.0433
		P index	$y = 2.34x + 2.10$	0.0158
B	Jay (C)	STP	$y = -0.0059x + 4.77$	0.3191
		P index	$y = 3.14x + 0.68$	<0.0001
C	Nixa (C)	STP	$y = -0.0058x + 5.38$	0.1359
		P index	$y = 3.93x + 0.47$	<0.0001
D	Nixa (C)	STP	$y = 0.002x + 3.13$	0.4828
		P index	$y = 2.08x + 3.20$	0.0002
E	Newtonia (B)	STP	$y = -0.0016x + 3.01$	0.7954
		P index	$y = 2.29x + 1.35$	0.0011
F	Taloka (D)	STP	$y = -0.0058x + 4.37$	0.3660
		P index	$y = 2.55x + 0.76$	0.0048

† Minimum annual steady ponded infiltration rate for a bare ground surface determines hydrologic soil groups (USDA Soil Conservation Service, 1993).

soluble P application rate was strongly correlated to SRP in runoff (Fig. 1c), P concentrations in runoff water were more closely related to the P index.

The relationship between the P index and P runoff was evaluated for each of six farms with different management scenarios and soil types. Phosphorus concentrations in runoff water were more closely correlated to the P index than soil test P for each farm used in this study (Table 5). A significant positive relationship was found between the average SRP concentration in runoff for six runoff events and the P index on each farm (Table 5). In contrast, poor relationships were observed between soil test P and SRP concentrations in runoff on each farm (Table 5). This can be attributed to the overwhelming influence of soluble P applied to the plots. Pierson et al. (2001) noted that to use soil test P as a risk assessment for P loss, a separate relationship would have to be developed for fields with and without recent litter applications. The P index was significantly correlated to average SRP concentrations in runoff for both plots receiving and not receiving poultry litter (Fig. 3).

Mean litter application rates on the six farms were 5.00 Mg ha^{-1} and 2.05 Mg ha^{-1} based on the P index

Table 6. Mean litter application rate, soluble P application rate, and soluble reactive phosphorus (SRP) in runoff water as a result of litter applications based on the P index or the environmental threshold soil test P level.

Management option	n	Litter application rate	Soluble P application rate	SRP in runoff
		Mg ha^{-1}	kg ha^{-1}	mg P L^{-1}
P index	36	5.0a†	2.06a	3.57a
Threshold soil test P	36	2.05b	1.65a	3.21a

† Within column means followed by the same letter are not significantly different ($P < 0.05$).

and threshold soil test, respectively (Table 6). Half of the plots receiving litter applications based on threshold soil test P recommendations had Mehlich-III P concentrations greater than 150 mg P kg^{-1}; therefore, no litter was applied to these plots (Table 3). Sharpley et al. (2001) noted that a P index assessment tool is generally less restrictive than an environmental threshold soil test P level as far as P applications to fields are concerned. However, a P index assessment tool does not necessarily lead to greater surface losses of P. For example, although poultry litter application rates were significantly higher based on the P index, average SRP concentrations in runoff water from these plots were not significantly different than plots receiving poultry litter applications based on threshold soil test P levels (Table 6). The mean concentrations of SRP in runoff water from six runoff events were 3.57 and 3.21 mg P L^{-1} for plots receiving poultry litter application based on the P index and threshold soil test P level, respectively (Table 6). Although the litter application rates were significantly different, soluble P application rates did not differ significantly due to the use of alum-treated litter on plots receiving applications based on the P index, thus demonstrating the importance of P solubility in poultry litter. In this study, alum additions to poultry litter decreased soluble P levels in the litter.

Mean application rates were 4.90 and 5.12 Mg ha^{-1} for normal litter and alum-treated litter, respectively (Table 7). As alum-treated litter and untreated litter had similar total P concentrations (data not shown), it may have been expected that plots receiving alum-treated litter would result in higher P concentrations in runoff. However, mean SRP concentrations in runoff water from six runoff events were 2.76 and 4.70 mg P L^{-1} from plots fertilized with alum-treated litter and untreated litter, respectively (Table 7). DeLaune et al. (2004) showed that P concentrations in runoff were not highest from litter containing the highest total P concen-

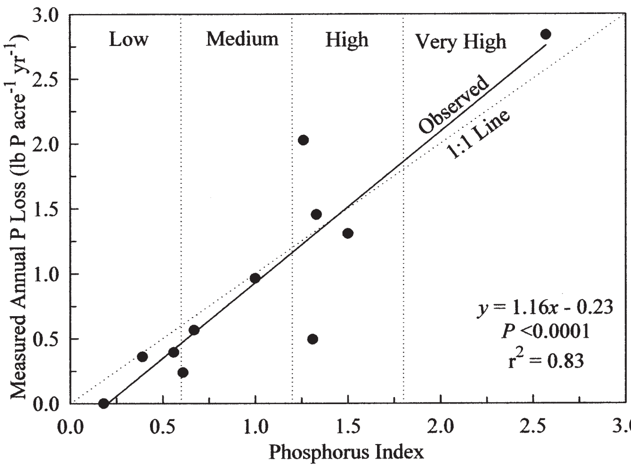

Fig. 4. Relationship between the P index and measured annual P loss from two 0.405-ha watersheds receiving natural rainfall and annual poultry litter applications. The P index was calculated annually based on annual litter application rate and soluble P concentration, soil test P concentration, and transport potential (0.8).

trations, but from litter having the highest soluble P concentrations. Concentrations of SRP in runoff water were significantly lower from alum-treated litter than untreated litter, with no significant difference between plots receiving alum-treated litter and no litter (Table 7).

Field-Scale Study

The best evaluation data for the P index for pastures came from two 0.405-ha watersheds where annual P loss had been measured from 1994 to 2000. Varying litter rates and P contents resulted in a wide range of P index values from 0.18 to 2.57. Soluble P levels in the untreated poultry litter ranged from 0.41 to 1.48 kg P Mg^{-1}, whereas soluble P levels in the alum-treated poultry litter ranged from 0.12 to 0.70 kg P Mg^{-1}. In 1995, concentrations of soluble P in the litter were 0.70 and 1.48 kg P Mg^{-1} for the alum-treated litter and untreated litter, respectively. These levels were 178% higher for alum-treated litter and 112% higher for untreated litter than any other year. After 1995, soluble P levels averaged 0.19 P Mg^{-1} for alum-treated litter and 0.51 kg P Mg^{-1} for untreated litter. Average P concentrations in runoff were 6.49 and 1.54 mg P L^{-1} for untreated poultry litter and alum-treated poultry litter, respectively.

The P index value is an estimate of annual P loss (lb $acre^{-1}$ yr^{-1}) by application year. The relationship between measured annual P loss and the P index is shown in Fig. 4. Results show that the P index predicted annual P losses from pastures receiving natural rainfall and annual poultry litter applications reasonably well ($y = 1.16x - 0.23$, $r^2 = 0.83$). Results from this study probably give a more realistic indication of P loss in actual watersheds than that of rainfall simulation studies. This is due to the fact that the watersheds in this study received annual litter applications and, most importantly, natural rainfall and natural runoff events.

Data from these watersheds were not used in the development of the P index, but for evaluation only. The P index not only gave an accurate assessment, but also accurately predicted annual P loss. Most mechanistic models require extensive calibration to adequately predict P losses. However, the P index closely predicted P losses without any calibration. As designed to accomplish, the P index for pastures provides a simple assessment tool with readily available input parameters that can easily be used by nutrient management planners. The P index for pastures performed well in predicting P losses from two small watersheds located in Arkansas receiving poultry litter applications. More studies and further evaluation are needed to examine the effect of various sources of P on P losses. Although initial evaluation studies have been conducted in Texas (Harmel et al., 2002), the use of the P index for pastures outside of Arkansas has yet to be fully evaluated. An accurate assessment may be best ensured when factors affecting the transport of P reflect local conditions.

CONCLUSIONS

Rainfall simulation studies conducted on six farms in the Eucha–Spavinaw watershed showed that P concentrations in runoff water were closely related to soil test P when no litter was applied. Once litter was applied, P concentrations were significantly correlated to the amount of soluble P applied as well as the P index, whereas soil test P and P concentrations in runoff were not correlated at five of six sites. Average P concentrations in runoff water from six simulated runoff events were more closely correlated to the P index for pastures than soil test P. Application rates based on the P index were significantly higher than those based on a threshold soil test P, but P concentrations in runoff water were not significantly different due to similar soluble P application rates. Alum-treated litter significantly reduced P concentrations in runoff water compared with untreated litter, and P concentrations in runoff water from small plots fertilized with alum-treated litter were not significantly different than unfertilized plots. Measured annual P losses from two watersheds with natural rainfall and annual litter applications were accurately predicted using the P index. Unlike mechanistic models, the P index for pastures provided an accurate assessment without extensive calibration. The transport component was similar for all conditions tested, whereas the P source component varied greatly. Because the P index accurately estimated annual P losses from two watersheds that received annual litter applications and natural rainfall, it is justifiable to conclude that weighting factors and variables in the P source component are appropriate for poultry litter applications. Research is underway to better understand the effects of various hydrologic factors on P losses. Future studies are also warranted on the effect of different P sources on P losses. Application of litter based on the P index allows more management options than applications based on a soil test P threshold. These studies have provided evidence that the P index provides a better assessment of P runoff than Mehlich-III soil test P, especially when litter P is added.

REFERENCES

American Public Health Association. 1998. Standard methods for the examination of water and wastewater. 19th ed. APHA, Washington, DC.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Appl. 8:559–568.

DeLaune, P.B., P.A. Moore, Jr., D.K. Carman, A.N. Sharpley, B.E. Haggard, and T.C. Daniel. 2004. Development of a phosphorus index for pastures fertilized with poultry litter—Factors affecting phosphorus runoff. J. Environ. Qual. 33:2183–2191 (this issue).

Gburek, W.J., A.N. Sharpley, L. Heathwaite, and G.J. Folmar. 2000. Phosphorus management at the watershed scale: A modification of the phosphorus index. J. Environ. Qual. 29:130–144.

Gburek, W.L., A.N. Sharpley, and H.B. Pionke. 1996. Identification of critical sources for phosphorus export from agricultural catchments. p. 263–282. *In* M.G. Anderson and S.M. Brooks (ed.) Advances in hillslope processes. John Wiley & Sons, Chichester, UK.

Harmel, R.D., P.B. DeLaune, B.E. Haggard, K.W. King, C.W. Richardson, P.A. Moore, and H.A. Torbert. 2002. Initial evaluation of a phosphorus index on pasture and cropland watersheds in Texas. ASAE Paper 02-2075. *In* Am. Soc. of Agric. Eng. Annual Int. Meeting, Chicago, IL. 28–31 July 2002. ASAE, St. Joseph, MI.

Humphry, J.B., T.C. Daniel, D.R. Edwards, and A.N. Sharpley. 2002. A portable rainfall simulator for plot-scale runoff studies. Appl. Eng. Agric. 18(2):199–204.

Kellogg, R.L., C.H. Lander, D.C. Moffitt, and N. Goellehon. 2000. Manure nutrients relative to the capacity of cropland and pastureland to assimilate nutrients: Spatial and temporal trends for the United States. USDA-NRCS Publ. nps00-0579 [Online]. Available at www.nrcs.usda.gov/technical/land/pubs/manntr.pdf (verified 19 July 2004). USDA, Washington, DC.

Lemunyon, J.L., and R.G. Gilbert. 1993. Concept and need for a phosphorus assessment tool. J. Prod. Agric. 6:483–486.

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

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

Pierson, S.T., M.L. Cabrera, G.K. Evanylo, H.A. Kuykendall, C.S. Hoveland, M.A. McCann, and L.T. West. 2001. Phosphorus and ammonium concentrations in surface runoff from grasslands fertilized with broiler litter. J. Environ. Qual. 30:1784–1789.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, Jr., D.R. Edwards, and D.J. Nichols. 1996. Relating extractable soil phosphorus to phosphorus losses in runoff. Soil Sci. Soc. Am. J. 60:855–859.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, Jr., D.M. Miller, and D.R. Edwards. 1999. Relationship between phosphorus levels in three Ultisols and phosphorus concentrations in runoff. J. Environ. Qual. 28:170–175.

SAS Institute. 1990. SAS/STAT user's guide. Version 6. 4th ed. SAS Inst., Cary, NC.

SAS Institute. 1996. JMPIN user's guide. Version 3. Student ed. SAS Inst., Cary, NC.

Sauer, T.J., T.C. Daniel, D.J. Nichols, C.P. West, P.A. Moore, Jr., and G.L. Wheeler. 2000. Runoff water quality from poultry litter-treated pasture and forest sites. J. Environ. Qual. 29:515–521.

Self-Davis, M.L., and P.A. Moore, Jr. 2000. Determining water-soluble phosphorus in animal manure. p. 74–76. *In* G.M. Pierzynski (ed.) Methods of phosphorus analysis for soils, sediments, residuals, and waters. Southern Coop. Ser. Bull. 396 [Online]. Available at www.soil.ncsu.edu/sera17/publications/sera17-2/pm_cover.htm (verified 15 July 2004). North Carolina State Univ., Raleigh.

Sharpley, A.N. 1995. Dependence of runoff phosphorus on extractable soil phosphorus. J. Environ. Qual. 24:920–926.

Sharpley, A., T. Daniel, B. Wright, P. Kleinman, T. Sobecki, R. Parry, and B. Joern. 1999. National research project to identify sources of agricultural phosphorus loss. Better Crops 83:12–15.

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. J. Environ. Qual. 30:2026–2036.

Sharpley, A.N., and S. Rekolainen. 1997. Phosphorus in agriculture and its environmental implications. p. 1–54. *In* H. Tunney, O.T. Carton, P.C. Brookes, and A.E. Johnston (ed.) Phosphorus loss from soil to water. CABI Publ., Cambridge.

Trimble Navigation Limited. 1996. GPS mapping systems. General reference. Surveying & Mapping Division, Sunnyvale, CA.

USDA and USEPA. 1999. Unified national strategy for animal feeding operations [Online]. Available at www.epa.gov/npdes/pubs/finafost.pdf (verified 19 July 2004). USDA and USEPA, Washington, DC.

USDA Soil Conservation Service. 1975. Engineering field manual. U.S. Gov. Print. Office, Washington, DC.

USDA Soil Conservation Service. 1993. Soil survey manual. USDA Handb. 18. U.S. Gov. Print. Office, Washington, DC.

USDA Soil Conservation Service. 1994. A phosphorus assessment tool. Eng. Tech. Note 1901. Southern Natl. Tech. Center, USDA-SCS, Ft. Worth, TX.