Field evaluation of three phosphorus indices on new application sites in Texas[1]

R.D. Harmel, H.A. Torbert, P.B. DeLaune, B.E. Haggard, and R.L. Haney

ABSTRACT: Phosphorus (P) indices were developed to address nonpoint source P losses from agricultural fields; however, only limited information on P index performance at the field- and watershed-scale is available. Evaluation of P indices is necessary to provide the basis of modification and improvement of their usefulness as P management tools. In this study, the ability of the Texas P index to estimate P loss potential was evaluated by comparison with measured annual P loads over three years on four new pasture and six new cultivated litter application sites in the Texas Blackland Prairie. The Arkansas and Iowa P indices were also evaluated. The Texas and Iowa versions were able to provide reasonable estimates of P loss potential as illustrated with significant linear relationships ($p < 0.01$) between P index values and measured annual P loads. In general, the P index values, Mehlich 3 soil test P, and poultry litter application rate were better correlated with dissolved P concentrations and loads (r^2 ranged from 0.12 to 0.91) than with total P and particulate P loads (r^2 ranged from 0.00-0.31). A major source of error in P index load estimations was their inability to capture variability in annual soil erosion. This source of error was dramatically reduced by using measured erosion instead of estimated annual average erosion (average r^2 values increased from 0.24 to 0.58). While these results illustrate a potential for the P indices to make relative P loss assessments, research on incentives to prevent buildup of soil P levels, linkages between P levels in soils and receiving waters, and other important issues related to the use of P indices is warranted.

Keywords: Phosphorus, fertilizer management, nonpoint source pollution, agricultural runoff, water quality

Recently, phosphorus (P) has become a highly scrutinized urban and agricultural nonpoint source (NPS) pollutant because of the role P plays as the limiting nutrient in many freshwater aquatic ecosystems. Agricultural P sources include commercial fertilizer application, manure and litter application, and animal production operations. The shift to larger confined animal operations has magnified the impact of P inputs associated with disposal and utilization of animal manures (Ribaudo et al., 2003; USDA, USEPA, 1999). In an effort to assess the potential risk of P leaving agricultural sites and reaching adjacent water bodies, Lemunyon and Gilbert (1993) developed a site assessment tool called the P index. The P index focuses on agricultural settings, but comprehensive watershed management programs should also address sources, such as home lawns, golf courses, wastewater treatment plants, and industrial discharges, which can also contribute substantial P loading.

In Texas, with a growing animal production industry, management of animal manures and litters has become an important environmental and economic issue. Most manure is applied to pasture land near production facilities; however, application to alternative

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Table 1. Summary of current phosphorus (P) index components for selected state methods (adapted from Sharpley et al., 2003).

State method	Texas	Arkansas	Iowa
Factors			
Soil test P	Mehlich 3, TAMU, Bray 1, Bray 2, Olsen	Mehlich 3	Mehlich 3, Bray 1, Olsen
Application rate	lb P_2O_5 per acre per year	lb soluble P per acre per year	lb P_2O_5 per acre per year
Application method	Incorporation, injection, surface applied	Incorporation, surface applied	Incorporation, injection, surface applied
Application timing	Season applied, time to incorporation	Season applied	Season applied, time to incorporation
Management	—	Organic P source, grazing intensity	Soil conservation practices, tillage
Erosion	Water (RUSLE), wind (WEQ)	Water (RUSLE)	Water (RUSLE), classic and ephemeral gulley
Surface runoff class	Curve number field slope	Curve number, field slope, annual precipitation	Curve number, annual precipitation
Subsurface drainage / flooding	—	Flooding frequency	Field slope, tile drainage, soil texture, annual precipitation
Contributing distance	Proximity of nearest field edge to named stream or lake	—	Distance to stream
Connectivity	—	Conservation practice presence	Buffer presence and width
Receiving water priority	—	—	—
Index value determination	Risk assessment (additive)	Loss assessment (multiplicative)	Erosion, surface runoff, and subsurface drainage loss assessment (multiplicative)

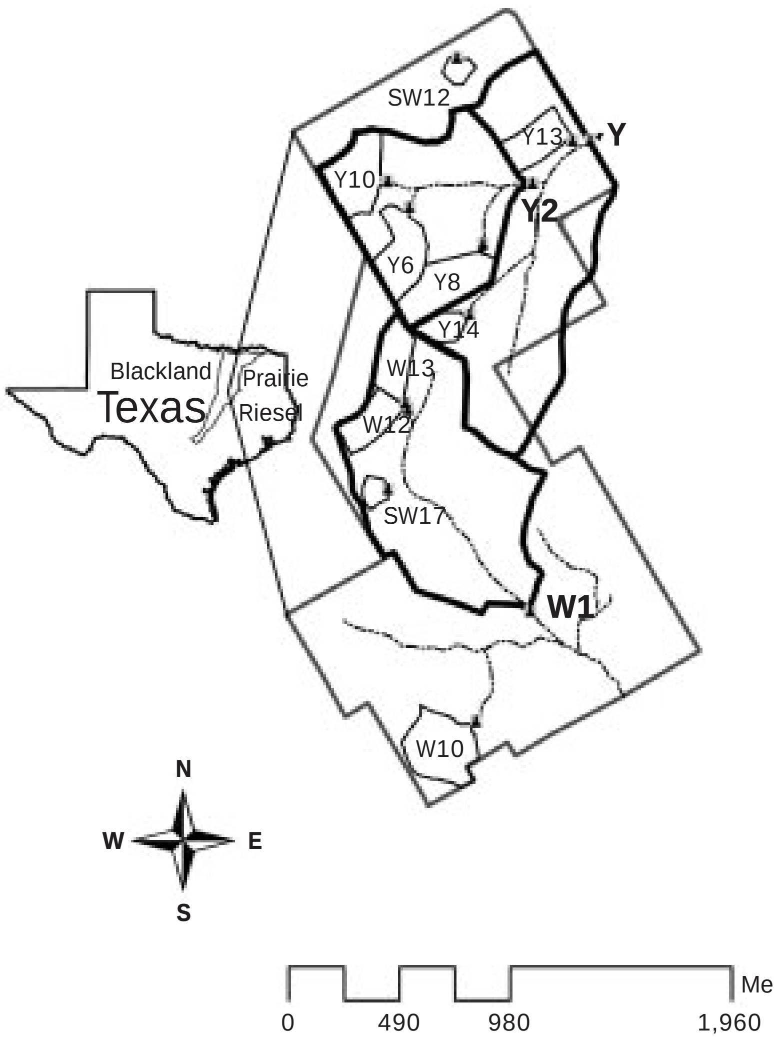
additional land use areas is expanding. With this expansion of land application, management tools, such as the P index, are needed to mitigate potential negative impacts of P loss to aquatic ecosystems.

The original P index designed by Lemunyon and Gilbert (1993) and described in U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) (1994) has formed the basis of a majority of current P indices, which were developed by states for their specific needs and conditions. These P indices are similar to some degree. For example, they were designed to factor in field characteristics and management practices, to assess risk of P loss from individual agricultural fields receiving animal manure and other P fertilizers, to allow flexibility in developing field-specific remedial strategies, and to allow continual refinement as research knowledge on P loss mechanisms expands. While some similarity exists, states generally developed versions based on state-specific topography, hydrology, and management. Consequently, the individual P indices are more likely to capture the risk associated with nutrient management in that state (Sharpley et al., 2003). Nevertheless, research is needed to assure that the P indices are capturing the risk associated with differing nutrient management practices.

The various P indices were developed based on source and transport factor research (Sharpley et al., 2003) and in many cases were refined by professional judgment and/or small plot rainfall simulation studies (DeLaune et al., 2004). Sharpley et al. (2001) reported significant relationships between P index values and P concentrations in a small plot rainfall simulation study conducted in an agricultural watershed in Pennsylvania. In a series of three rainfall simulation studies conducted in Nebraska and Iowa, Eghball and Gilley (2001) examined correlation between P index components and measured P loads. They determined that erosion was strongly correlated with total and particulate P loads and that runoff, tillage, and P source were weakly correlated to dissolved and bioavailable P loads. Few studies have been conducted on the performance of P indices at the watershed-scale, but these studies have generally concluded that P loss vulnerability was related to measured P losses. Sharpley (1995) reached this conclusion by comparing values from the original P index (Lemunyon and Gilbert, 1993) to previous measured annual P loads from small watersheds in Texas and Oklahoma. DeLaune et al. (2004b) reached the same conclusion by comparing Arkansas P index values to measured P loads from two, one acre fields that have received poultry litter annual poultry litter application since 1995. In a regional evaluation, Birr and Mulla (2001) also reported strong correlations between P index values and P concentration data from lakes and streams in Minnesota. These studies provide valuable comparisons between P indices and P runoff data, but the need for additional watershed-scale evaluations of the indices is urgent (Sharpley et al.,

Figure 1

Study watersheds at the U.S. Department of Agriculture-Agricultural Research Service Grassland, Soil and Water Research Laboratory, Riesel, Texas.



2003; Leytem et al., 2003; DeLaune et al., 2004a). These additional evaluations should focus on the evaluation of P-based nutrient management impacts on farm or watershed-scale P export.

With this need in mind, the present three year field study explored P index performance in terms of annual P loads for cultivated and pasture watersheds over a range of litter application rates on new application fields located in the Texas Blackland Prairie. The major focus of this paper is the evaluation of the Texas P index (TX-PI) because of its regional importance for animal waste management in the dairy and poultry industry in Texas (Table 1). For comparison, the Arkansas (AR-PI) and Iowa (IA-PI) P indices were also evaluated. These two P indices were selected because of differences in design structure and because they seemingly met the topography, hydrology, and management characteristics of the Blackland Prairie. The AR-PI was selected because of its use for poultry litter application in pasture settings and its geographical proximity to Texas. The IA-PI was selected for its application to both cultivated and pasture settings. The AR-PI and the IA-PI were also selected because they have the potential to predict actual P loads, which indicated that the design criteria was modeled to be proportional to actual P loads and not only a relative risk of P loss. By examining predicted P loss, insight can be gained into how these and other similar P indices capture the actual measured losses and translate those predictions into risk assessment.

The specific objectives of this study were 1) to evaluate the ability of the Texas P index to estimate P loss risk potential, 2) to evaluate the ability of two additional P indices with differing designs to estimate P loss potential for Texas Blackland Prairie conditions, and 3) to provide measured field-scale data for further evaluation of other P index versions.

Methods and Materials

A study was initiated to evaluate the ability of P indices to estimate P loss potential by comparison with measured P losses. The study watersheds are located at the USDA Agricultural Research Service's Grassland, Soil and Water Research Laboratory in Riesel, Texas (Figure 1). The six cultivated watersheds and four pasture watersheds used in this study represent new application sites, since no organic fertilizer was previously applied. The results of this study represent a fallow year and two years in the transition from a traditional inorganic fertilization strategy to an annual poultry litter application with supplemental nitrogen. Measured P loss data from these watersheds were used to evaluate three different P indices: the Texas P index, the Arkansas P index, and the Iowa P index.

Texas P index. The TX-PI (USDA-NRCS, 2000) was developed for use in cropland and pasture conditions in Texas. The TX-PI calculates a numerical rating with an additive matrix of P source potential (includes soil test P, total inorganic P rate, total organic P rate factors) and transport potential (includes soil erosion, runoff class, inorganic P application method, organic P application methods, and water body proximity factors). For the P application method factors, an East Texas version considers fertilizer incorporation and application time of year, whereas a West Texas version considers fertilizer incorporation and duration between application and crop planting. TX-PI values for the conditions of this study were the same for the East and West Texas versions, so results presented for the TX-PI apply to both versions. The resulting P index value is not designed to represent annual P loads but to assess P runoff potential. Based on that potential, critical soil test P levels are estimated for watersheds of impaired and non-impaired water bodies.

Arkansas P index. The AR-PI was developed for pastures in Arkansas (DeLaune et al., 2004a; b; Moore et al., 2000). The AR-PI calculates a numerical rating with a multi-

Table 2. Watershed characteristics and litter properties for use in determining phosphorus (P) index values.

	Cultivated watersheds					
Watershed characteristics	**Y6**	**Y8**	**Y10**	**Y13**	**W12**	**W13**
Area (ac)	16.3	20.8	18.5	11.4	9.9	11.4
Slope (percent)	3.2	2.2	1.9	2.3	2.0	1.1
Curve number	87	87	87	87	87	87
Runoff class	H	M/H	M	M/H	M/H	M
Erosion (tons/ac/yr)	0.2	0.4	0.3	0.9	0.9	1.0
Litter rate (t ac^{-1})	0	6	3	2	4	5
Ave. annual N rate (lb ac^{-1})	150	330	248	212	264	293
Ave. annual P rate (lb ac^{-1})	17	320	175	109	204	255
2000-01 Mehlich 3 (lb ac^{-1})	40.2	30.3	39.3	38.1	44.4	39.6
2001-02 Mehlich 3 (lb ac^{-1})	41.7	103.4	81.8	86.9	110.1	136.6
2002-03 Mehlich 3 (lb ac^{-1})	35.4	182.3	127.7	90.0	125.2	222.3
2000-01 crop	fallow	fallow	fallow	fallow	fallow	fallow
2001-02 crop	corn	corn	corn	corn	corn	corn
2002-03 crop	corn	corn	corn	corn	corn	corn

	Pasture watersheds			
Watershed characteristics	**SW12**	**SW17**	**Y14**	**W10**
Area (ac)	3.0	3.0	5.7	19.8
Slope (percent)	1.6	2.5	3.7	2.5
Curve number	78	78	76	80
Runoff class	M	M	L/M	L/M
Erosion (tons/ac/yr)	< 1	< 1	< 1	< 1
Litter rate (t ac^{-1})	0	0	3	6
Ave. annual N rate (lb ac^{-1})	0	0	293	154
Ave. annual P rate (lb ac^{-1})	0	0	303	161
2000-01 Mehlich 3 (lb ac^{-1})	36.0	31.8	21.6	31.8
2001-02 Mehlich 3 (lb ac^{-1})	31.2	25.2	133.0	75.2
2002-03 Mehlich 3 (lb ac^{-1})	8.8	11.0	143.4	73.2
Landuse	hay	grazing	hay	hay
Vegetation	native prairie	coastal bermuda grass	Kleingrass	coastal bermuda grass

Litter properties

	Total N	**Total P**	**Water extractable nutrients (mg kg^{-1})**			**Organic C**
Application date	**(%)**	**(%)**	**NO_3**	**NH_4**	**SRP**	**(%)**
Jul-01	2.32	2.14	211	1170	895	28.4
Sep-02	3.05	3.47	857	3775	1233	31.2

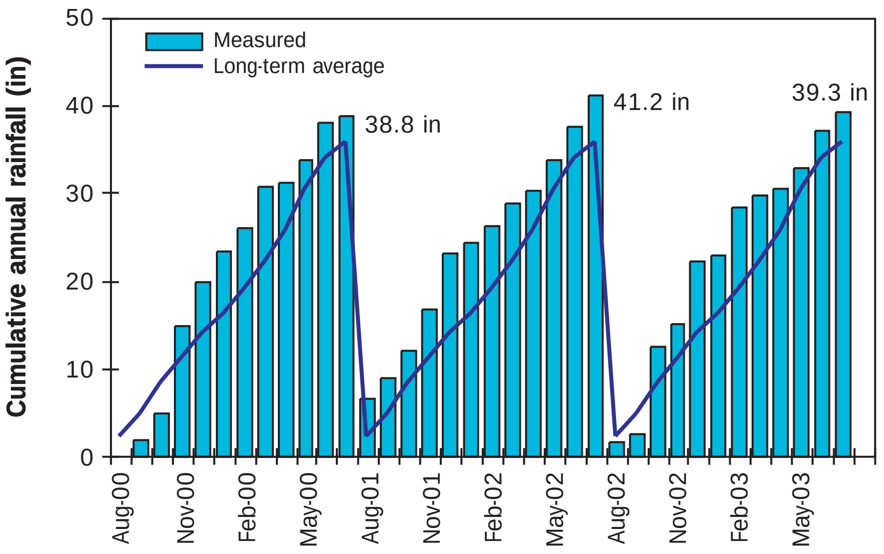
plicative matrix of P source potential (includes Mehlich 3 soil test P and soluble P application rate factors) and transport potential (includes soil erosion, runoff class, flooding frequency, application method, application timing, and grazing management factors), conservation practices, and annual precipitation. The resulting AR-PI value represents P loss potential and its current form also represents annual P loss (lb/ac^2).

Iowa P index. The IA-PI (Mallarino et al., 2002; USDA-NRCS, 2001) was designed for cropland and pasture conditions in Iowa. The IA-PI uses a multiplicative approach to combine source and transport factors. Source factors are incorporated within the three major transport mechanisms (erosion, runoff, and drainage). The erosion component estimates particulate P loss based on erosion (including sheet, rill, and gully), delivery ratio, soil P, and management activity. The runoff component estimates dissolved P loss in surface runoff based on curve number, county precipitation data, soil P, and fertilizer application. The drainage component estimates dissolved P loss in subsurface drainage based on soil properties, tile presence, county precipitation data, and soil P. The IA-PI value provides a relative risk rating for P delivery from individual fields and can be used to estimate annual P loads (lb ac^{-1}). To evaluate the IA-PI, minor changes in the precipitation component were made so that site-specific data for Texas could be used in this study.

Study site. The Riesel watersheds are located in the heart of the Blackland Prairie in Texas, an 11 million ac region noted for Houston Black Clay soils (fine, smectitic, thermic, Udic Haplustert) with strong shrink/swell potential. Infiltration into these soils occurs rapidly when soils are dry and cracked but very slowly when soils are wet. Slopes in the region generally range from 1 to 8 percent. Long-term annual rainfall averages approximately 35 in (890 mm) at the site (Harmel et al., 2003). On average, approximately 15 percent of annual rainfall exits the watersheds in surface runoff.

Figure 2

Cumulative annual rainfall, historical, and measured monthly means.



Litter application rates from 0 to 6 t ac^{-1} (0 to 13.4 mton/ha) were randomly assigned to each of the six cultivated watersheds and to two of the pasture watersheds (Table 2). No litter was applied to the native prairie watershed (SW12) or a grazed watershed (SW17) to ensure comparisons with a reference site and a grazed site. The first annual litter application occurred in July 2001 and the second occurred in September 2002. On the cultivated watersheds, which all have terraces and a grassed waterway, litter was incorporated with a disk implement within 48 hours of application. Litter was surface applied but not incorporated on the pasture watersheds. The study watersheds were scheduled to receive the first annual poultry litter application prior to corn planting in the spring of 2001. However, the combination of unusually wet conditions and cool fall and winter temperatures kept soils from drying and prevented fertilizer application (typically applied in January and February) and corn planting (typically planted from mid-February through March). The unusually wet weather pattern over central Texas in late 2000 through early 2001, in which 21.6 in (548 mm) of rain fell in four months presented a rare opportunity to quantify nutrient loading during fallow conditions. Conditions became favorable for poultry litter application in July 2001.

Based on management activities and watershed characteristics, annual P index values were determined with the Texas, Arkansas, and Iowa P indices for the ten study watersheds in each of the three study years. A summary of factors used in the Texas, Arkansas, and Iowa P indices is presented in Table 1. Watershed characteristics and litter properties needed to calculate the P index values are provided in Table 2. The mean annual soil erosion rates were determined from measured data for the specific fields. Other data needed included annual rainfall (Figure 2), presence of soil conservation practices, and drainage characteristics, which are described previously.

Water quality sampling and analysis. Water quality and flow data were collected from each watershed from August 2000 through July 2003. Flow data for this study were recorded continuously, and variable time-weighted, discrete samples were collected automatically during runoff events. All samples were handled and analyzed according to Environmental Protection Agency (EPA) approved quality assurance procedures. Total annual P loads were determined as the sum of dissolved P (PO_4-P) and particulate P (total Kjeldahl P). All samples were analyzed colorimetrically using a Technicon Autoanalyzer IIC and methods published by Technicon Industrial Systems (1973a, b, 1976). A detailed description of the data collection procedures appears in Harmel et al. (2004).

Litter and soil sampling and analysis. Annual soil samples were taken in each watershed each winter with a manual soil probe (1 in diameter). The 6 in depth cores, taken at the frequency of at least one core per 1 ac, were composited for each watershed. The soil samples were analyzed for extractable P using the Mehlich 3 procedure (Mehlich, 1984) and other constituents (data not presented).

Litter samples were also collected from the litter stockpiles immediately prior to application. Four replications were analyzed for total N and P (Technicon Industrial Systems, 1976), water extractable nutrients (Self-Davis and Moore, 2000), and organic C content (Chichester and Chaison, 1992).

Comparison of measured P loads to P index values. Measured annual total P loads from the ten watersheds were compared to P index values calculated by the Texas, Arkansas, and Iowa indices. Each of the three P indices was designed to assess P loss potential; however, the formats of the AR-PI and IA-PI allow these indices to be used to estimate annual P loads. Therefore, only the relative ability of the TX-PI was evaluated, but the absolute and relative abilities of the AR-PI and IA-PI were evaluated. The results represent three years: a fallow with no fertilizer application (August 2000 through July 2001), the initial annual poultry litter application year (August 2001 through July 2002), and the second annual poultry litter application year (August 2002 through July 2003).

Linear regression was used to evaluate relationships between P loads and P index values. Paired t-tests and non-parametric Mann-Whitney tests were used to compare mean and median P loads and index values (Minitab, 2000; Helsel and Hirsch, 1993). All tests were conducted with an *a priori* $\alpha = 0.05$ probability level. A goal of models, the P indices in this case, is to produce estimates that minimize scatter throughout the range of measured values (as represented by the coefficient of determination, r^2) and that exhibit no systematic errors (consistent over- or underestimation) for portions of the measured data range. It is with these considerations that the P indices were evaluated.

Influence of specific components of the P indices. The influence of specific components of each P index was evaluated to determine possible explanations for P index performance. The correlation between measured P losses (specifically mean, median, and maximum annual PO_4-P concentrations in runoff and total, dissolved, and particulate P loads) and P index components (specifically litter rate, Mehlich 3 soil P levels, and measured sediment losses) was analyzed. These components were chosen because they varied

Table 3. Annual runoff depth and sediment loss for the study watersheds.

Site	Runoff depth Fallow	 1st litter	 2nd litter	Sediment loss Fallow	 1st litter	 2nd litter
		in			t ac^{-1}	
Cultivated						
Y6	6.9	10.0	10.7	0.15	1.63	0.60
Y13	10.0	13.9	10.1	0.85	5.44	0.56
Y10	12.2	12.8	13.8	0.34	1.31	0.49
W12	7.9	13.9	7.1	1.22	4.87	0.51
W13	5.2	10.8	8.5	0.57	3.79	0.46
Y8	8.5	9.6	8.5	0.28	2.97	0.39
Pasture						
SW12	8.3	6.9	8.9	0.00	0.02	0.04
SW17	5.7	5.1	7.6	0.00	0.72	0.01
W10	6.5	5.0	5.2	0.00	0.02	0.01
Y14	2.3	2.6	2.6	0.00	0.02	0.00

more between watersheds than other components such as curve number. The influence of erosion variability on P index performance was also evaluated by comparing P index values with measured long-term annual average (constant) and measured annual soil erosion (variable).

Results and Discussion

Rainfall and runoff. Rainfall amount and intensity are major driving forces in P loss from land applied poultry litter. Annual rainfall totals during the study were similar each year and were slightly greater than long-term averages (Figure 2). Each year rainfall produced adequate runoff for at least twelve sampling events on the cultivated watersheds. In the first application year (2001-02), two major rainfall events (more than 4 in within 24 hr) occurred and produced a majority of the annual erosion. The ratio of runoff to rainfall for this year was 0.29 compared to 0.22 and 0.25 for the other two years. Runoff from the pasture watersheds (12 to 15 percent of annual rainfall) was much lower than from cultivated watersheds (22 to 29 percent of annual rainfall) due to increased infiltration enhanced by permanent surface cover and improved soil structure (Table 3).

Soil P levels. The fields in this study had low background Mehlich 3 soil test P levels (<45 lb ac^{-1}) at the 0 to 6 in sampling depth, but litter application caused proportional increases in soil P levels (Figure 3). The amount of P applied to increase Mehlich 3 soil test P one unit (lb ac^{-1}) averaged 9.4 lb ac^{-1} with a median of 3.5 lb ac^{-1}, which is comparable previous observations on the same soil. Torbert et al. (2002) used a 3:1 ratio (applied P amount to desired soil P increase) in building soil test P to desired levels in Houston Black Clays. Similar values of 4.1 and 4.5 lb ac^{-1} per unit increase in soil test P were reported also by Pierson et al. (2001) and Cope (1983), respectively.

Measured P transport. Substantial differences were observed in watershed P loads before and after poultry litter application (Table 4). In the first year with litter application (2001-02), average P loads from cultivated watersheds increased more than six times compared to pre-application conditions, and P loads from pasture watersheds increased more seventeen times. This large increase, compared to fallow conditions with no P addition, was quite large due in large part to excessive erosion and particulate P transport caused by two rainfall events in excess of 4 in in 24 hr (Table 4). In 2002-03, total annual P loads were 2.4 times larger from the cultivated watersheds and were more than thirteen times larger from the pasture watersheds compared to pre-application P loads. The decrease in erosion rates in both land uses in the second litter application year contributed to lower total and particulate P loads that year.

Measured total annual P loads from the six cultivated watersheds were significantly greater than from the four pasture watersheds (Figure 4, Table 4). This difference is attributed to much larger runoff volumes and particulate P loads from cultivated watersheds. For the cultivated watersheds that received litter, an average of 77 percent of the total P load was particulate P in the first litter application year. In the second application year with lower erosion rates, particulate P loads decreased to an average of 40 percent of the total load from the cultivated watersheds. In contrast, most of the P load from the pasture watersheds that received litter was in the dissolved P form. For pasture watersheds in the two years with litter application, approximately 3 percent of P load was associated with sediment, which included transported soil, litter, and plant residue. In 2001-02 the grazed pasture with no litter application (SW17) was an exception, as 90 percent of its total P load was particulate P (Table 4). The cause for this unusually high erosion rate is

Figure 3

Changes in Mehlich 3 soil test phosphorus (P) due to annual litter application.

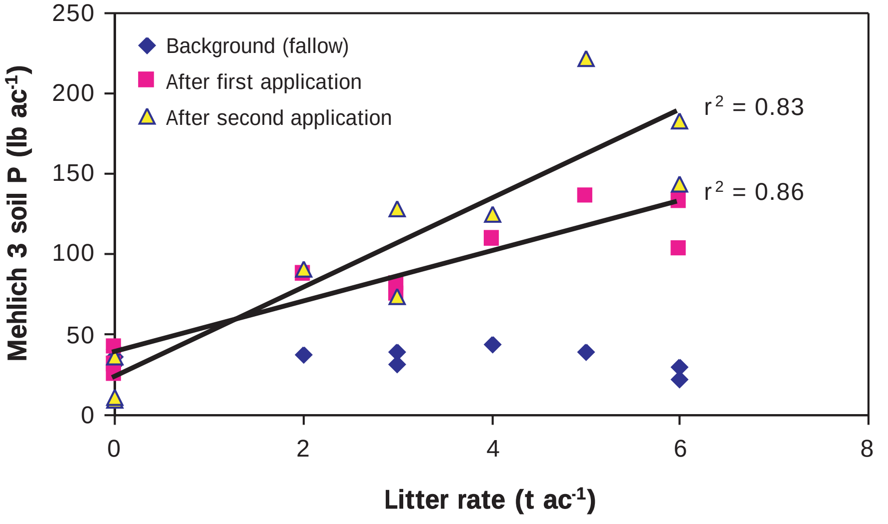


Table 4. Measured annual total, dissolved, and particulate phosphorus (P) loads and corresponding P index values.

	Tilled watersheds	P loss Total (lb ac^{-1})	P loss Dissolved (lb ac^{-1})	P loss Sediment (lb ac^{-1})	P index AR (lb ac^{-1})	P index IA (lb ac^{-1})	P index TX (rating)
2000-01	Y6	0.39	0.14	0.25	0.01	0.52	6.00
	Y13	1.53	0.51	1.01	0.01	0.91	5.00
	Y10	0.60	0.25	0.35	0.01	0.57	4.00
	W12	1.30	0.25	1.05	0.01	1.01	6.00
	W13	0.73	0.21	0.52	0.01	0.99	6.00
	Y8	0.46	0.20	0.27	0.00	0.53	5.00
2001-02	Y6	2.85	0.32	2.53	0.01	0.53	6.00
	Y13	9.50	1.20	8.30	0.71	1.44	14.50
	Y10	2.98	1.28	1.70	1.09	1.10	12.50
	W12	7.02	1.03	5.98	1.28	1.81	14.50
	W13	5.30	1.09	4.22	1.64	2.11	18.50
	Y8	5.86	1.27	4.59	2.23	1.53	12.50
2002-03	Y6	1.56	0.42	1.14	4.11	0.55	7.00
	Y13	1.66	0.79	0.87	0.67	1.53	14.50
	Y10	2.48	1.85	0.63	0.96	1.53	12.50
	W12	1.47	0.69	0.78	1.29	2.07	14.50
	W13	2.73	1.87	0.86	1.56	2.93	18.50
	Y8	2.11	1.41	0.70	1.84	2.17	18.50

	Pasture watersheds	P loss Total (lb ac^{-1})	P loss Dissolved (lb ac^{-1})	P loss Sediment (lb ac^{-1})	P index AR (lb ac^{-1})	P index IA (lb ac^{-1})	P index TX (rating)
2000-01	SW12	0.05	0.05	0.00	0.007	0.21	3.00
	SW17	0.05	0.05	0.00	0.010	0.24	3.00
	W10	0.04	0.04	0.00	0.005	0.22	3.00
	Y14	0.02	0.02	0.00	0.003	0.18	2.00
2001-02	SW12	0.11	0.07	0.04	0.01	0.20	3.00
	SW17	1.68	0.16	1.52	0.01	0.21	3.00
	W10	0.50	0.48	0.02	1.16	0.64	10.50
	Y14	0.40	0.36	0.03	2.45	1.16	15.50
2002-03	SW12	0.20	0.13	0.07	0.00	0.11	3.00
	SW17	0.27	0.25	0.02	0.00	0.14	3.00
	W10	1.03	1.01	0.01	1.23	0.78	10.50
	Y14	0.55	0.54	0.01	2.15	1.20	15.50

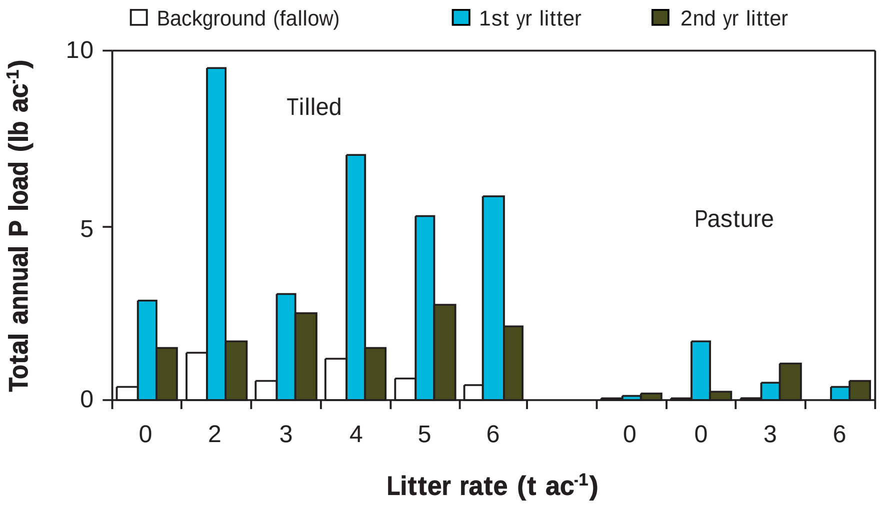
unknown. For more details regarding nutrient losses from these watersheds during the study period, see Harmel et al. (2004).

Measured P export for the cultivated watersheds receiving poultry litter in this study was larger than from comparable small watersheds in Alabama (Wood et al., 1999; Hall, 1994). In their two year study on 0.25 ac (1090 m^2) silty clay areas with conventionally-cultivated corn and no-till winter rye cover, measured annual P loads averaged 0.88 lb ac^{-1} (0.99 kg ha^{-1}) for 4 t ac^{-1} (9 Mg ha^{-1}) litter rates and 2.16 lb ac^{-1} (2.42 kg ha^{-1}) for 8 t ac^{-1} (18 Mg ha^{-1}) litter rates. Lesser P loads on the Alabama watersheds compared to the present study, which were 7.02 and 1.47 lb ac^{-1} for the 4 t ac^{-1} litter rate, are attributed to decreased transport of sediment and associated P due to a winter cover crop. In contrast, P export from pasture watersheds in this study was much lower than annual loads reported for pasture areas in Arkansas and Georgia with lighter textured soils. Edwards et al. (1996) reported mean annual total P loads of 1.41 and 3.87 lb ac^{-1} (1.58 and 4.34 kg ha^{-1}) from two fescue fields in Arkansas with a wetter climate and higher soil P levels. Pierson et al. (2001) reported mean annual soluble reactive P (SRP) loads of 6.60 lb ac^{-1} (7.40 kg ha^{-1}) from six grazed fescue and bermuda grass paddocks in Georgia with similar litter rates and soil test P levels.

Performance of Texas P index. Data for the fallow year, with no fertilizer application and low background soil P levels, were collected to represent conditions of low P loss potential (Table 4). In the fallow year, the TX-PI values for the cultivated watersheds (4.0 to 6.0) were higher than for the pasture watersheds (2.0 to 3.0), but all were representative of low P runoff potential. Similarly, total P loads were greater for the cultivated watersheds (0.39 to 1.53 lb ac^{-1}) than for the pasture watersheds (0.02 to 0.05). When data for the two land uses were grouped for the fallow year, the linear relationship between the TX-PI and total P loads was significant ($p = 0.014$) and explained substantial vari-

Figure 4

Annual total phosphorus (P) loads in surface runoff from the litter application fields.



ability in measured P loads ($r^2 = 0.55$). In the year following the first litter application, the linear relationship was not significant, and the correlation decreased ($r^2 = 0.29$). The large influence of erosion variability, and therefore particulate P transport, was evident this year and was difficult to represent in the TX-PI. In the second litter application year, the relationship between TX-PI values and total P loads was significant ($p = 0.022$) with an $r^2 = 0.50$. When data for all three years were combined across land use (Figure 5a), the relationship between the TX-PI and total P load was significant ($p = 0.001$) with an $r^2 = 0.31$. Overall, the TX-PI performed better for cultivated conditions, but this result was influenced by unusually high erosion from the grazed pasture (SW17) in the first litter application year. No tests of significant differences between TX-PI values and measured P loads were performed because the TX-PI was designed as a relative predictor of P loss potential and does not produce annual P load estimates.

These results indicate that under the conditions of this study (new litter application sites in Texas Vertisols) the TX-PI did accomplish its specified purpose of estimating the relative susceptibility of fields to excessive P loss. However, a potential limitation of the TX-PI was recognized that could affect its performance at higher soil test P levels. The TX-PI has an upper limit on its soil test P factor, but the effect of this limit was not fully experienced in this study because of relatively low soil P levels. For typical cultivated and pasture settings, a maximum rating of 8.0 for this factor is reached at Mehlich 3 soil P levels greater than 61 ppm (122 lb ac^{-1}). Thus, soils with extremely high P levels receive the same soil test P rating as soils as with 123 lb ac^{-1}. Or in other words, once the soil P levels reach the very high rating, the TX-PI is no longer responsive to increasing soil P.

Performance of Arkansas P index. The AR-PI under-estimated P loads under conditions with no applied P, which includes all watersheds in the fallow year, the control pasture watersheds (SW12 and SW17) each year, and the control cultivated watershed (Y6) in the first application year. The AR-PI showed modest improvement following litter application (Table 4). In 2001-02, the large variability in P loads from the cultivated fields, which was caused by large variability in particulate P transport, was especially difficult for the AR-PI to represent because it was designed for pastures with minimal erosion. In 2002-03, the AR-PI drastically over-predicted P loads on the cultivated control watershed (Y6) to which inorganic P was applied. This is not surprising since the AR-PI was developed for pastures fertilized with poultry litter, thus the soluble P rate factor is not appropriate for inorganic P application. Although it was designed for use in pasture settings, the AR-PI did not always perform better for pastures than for cultivated watersheds, but again

Figure 5

Texas phosphorus (P) index ratings and measured total annual P loads, a) undjusted, b) adjusted based on measured soil loss.

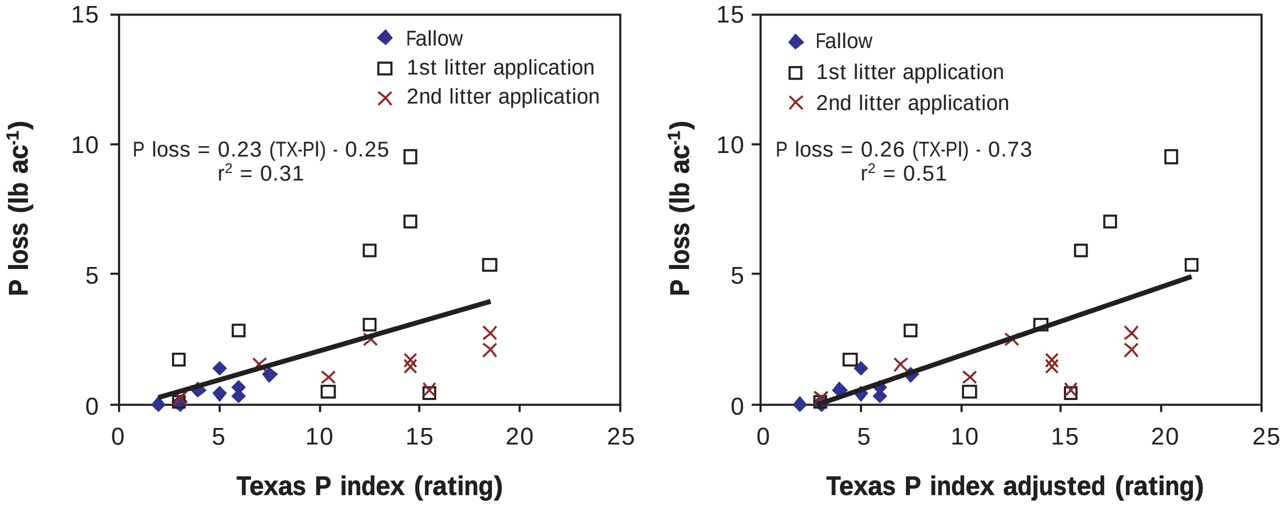
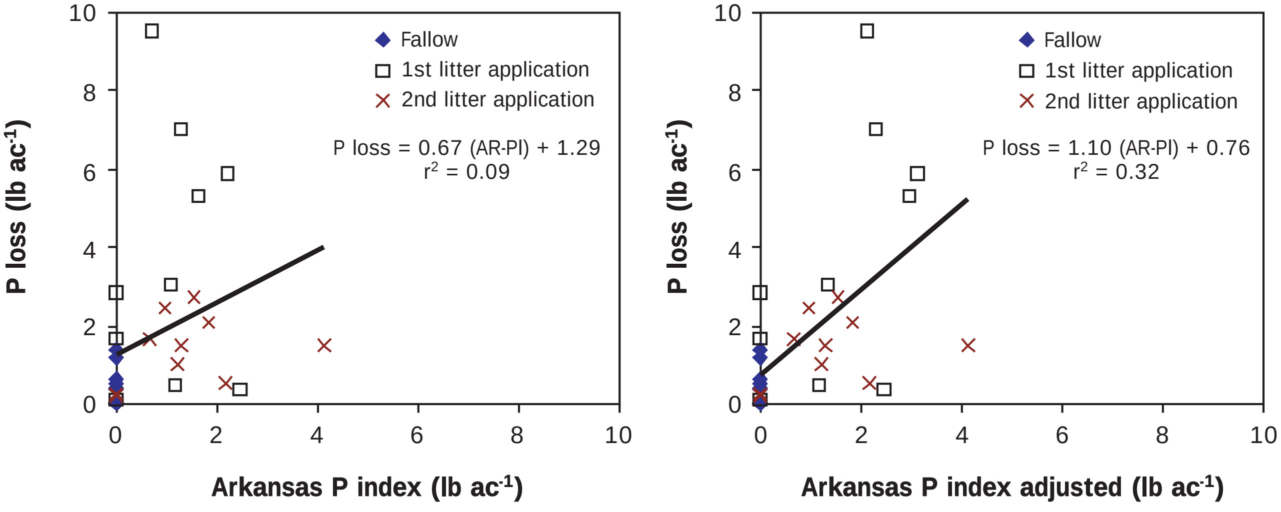


Figure 6

Arkansas phosphorus (P) Index values and measured total annual P loads, a) undjusted, b) adjusted based on measured soil loss.



this result was affected by the unusually high erosion rate (and high particulate P load) for the grazed pasture watershed with no litter application (SW17). In the second litter application year (2002-03), the AR-PI did indeed perform much better for pastures (r^2 = 0.36) than for cultivated fields (r^2 = 0.10). When the pastures were fertilized with poultry litter, the AR-PI over-predicted P loads but only slightly.

When the AR-PI values within the two land uses were grouped and plotted with total annual P loads for all three years, the resulting linear relationship was not significant and the correlation was poor with an r^2 = 0.09 (Figure 6a). When the AR-PI values were compared to mean and median annual P loads with paired t-tests and Mann-Whitney tests, annual P load estimates were significantly different than measured loads. These results indicate a relatively poor performance of the AR-PI for the conditions in the present study (cultivated and pasture fields in heavy clay soils of the Texas Blackland Prairie), which were quite different than their design conditions (small pasture plots with silt loam soils and higher soil P levels in the Ozark Highlands in Arkansas). It should also be noted that the AR-PI would not allow litter application rates that result in AR-PI values above 1.2. In this case, application rate must be reduced or management practices implemented to reduce the value to below 1.2.

Performance of Iowa P index. In each of the three study years, the IA-PI produced a significant relationship with measured P loads (all p values < 0.02) for grouped land use. In the fallow year and the second litter application year, r^2 values were 0.83 and 0.67, and very little systematic error was observed. In the first litter application year, the IA-PI performed relatively well despite the large variability in erosion (r^2 = 0.52), but the P loads were consistently under-predicted (Figure 7a). The high measured erosion and

Figure 7

Iowa phosphorus (P) Index values and measured total annual P loads, a) undjusted, b) adjusted based on measured soil loss.

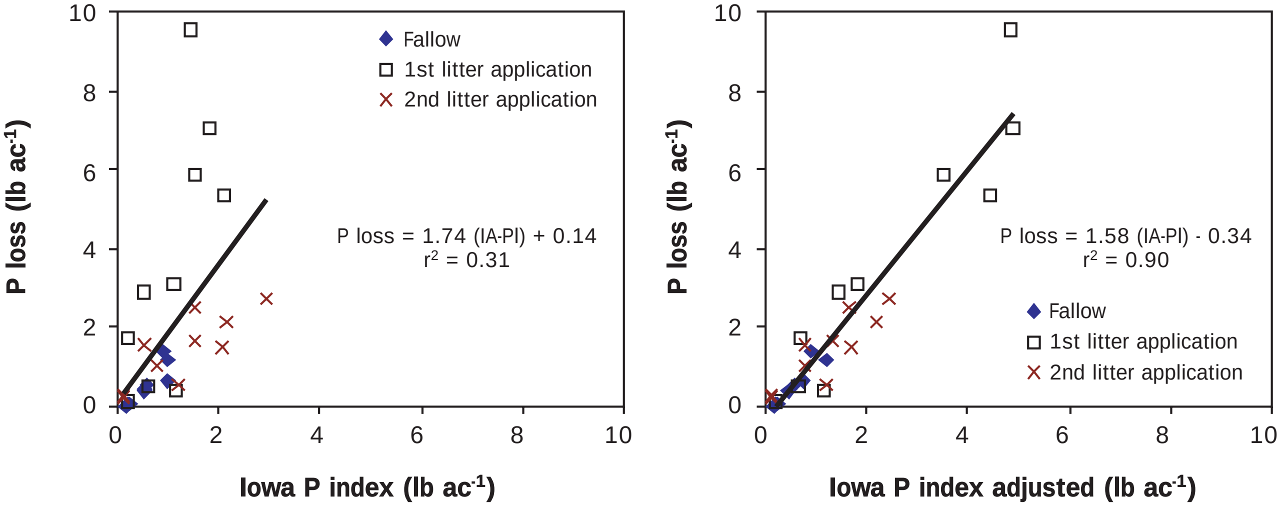


Table 5. Coefficient of determination values (r^2) between measured phosphorus (P) concentration and loads for all three years and selected P index components.

	PO_4-P concentration (mg l^{-1})			P load (lb ac^{-1})		
	Maximum	Mean	Median	Total	Dissolved	Particulate
Cultivated watersheds						
Litter rate (t ac^{-1})	0.31	0.29	0.22	0.01	0.12	0.00
Meh 3 soil P (lb ac^{-1})	0.42	0.91	0.88	0.10	0.73	0.02
AR-PI	0.20	0.16	0.13	0.07	0.17	0.03
TX-PI	0.48	0.68	0.61	0.28	0.67	0.14
IA-PI	0.44	0.76	0.69	0.15	0.61	0.05
Sed. loss (t ac^{-1})	0.27	0.00	0.00	0.91	0.07	0.96
Pasture watersheds						
Litter rate (t ac^{-1})	0.42	0.47	0.45	0.00	0.13	0.08
Meh 3 soil P (lb ac^{-1})	0.73	0.88	0.86	0.04	0.35	0.04
AR-PI	0.69	0.84	0.81	0.05	0.44	0.04
TX-PI	0.71	0.86	0.83	0.07	0.51	0.04
IA-PI	0.74	0.90	0.88	0.06	0.48	0.03
Sed. loss (t ac^{-1})	0.04	0.03	0.03	0.65	0.01	1.00
Grouped land use						
Litter rate (t ac^{-1})	0.38	0.34	0.29	0.03	0.15	0.01
Meh 3 soil P (lb ac^{-1})	0.51	0.57	0.52	0.16	0.65	0.06
AR-PI	0.36	0.35	0.32	0.08	0.23	0.04
TX-PI	0.55	0.52	0.45	0.31	0.65	0.17
IA-PI	0.39	0.29	0.24	0.31	0.69	0.17
Sed. loss (t ac^{-1})	0.14	0.00	0.00	0.92	0.18	0.97

associated particulate P rates contributed to these under-estimations.

When the IA-PI values within the two land uses were grouped and plotted with total annual P loads for all three years, a significant linear relationship resulted ($p = 0.001$) with an r^2 value of 0.31 (Figure 7a). When the IA-PI values were compared to mean and median annual P loads, the IA-PI produced median annual P load estimates not significantly different than measured loads, but mean loads were significantly different than IA-PI predictions. Based on these results, the IA-PI performed well especially since it was designed for cropland and pastures in the Midwest. The strong performance of the IA-PI can be attributed to its multiplicative nature and to its increased complexity, which resulted in improved representation of three P transport mechanisms (particulate P with erosion, dissolved P in runoff, and dissolved P in drainage).

Influence of specific components of the P indices. To attempt to explain the performance of each of these P indices, the influences of specific components were evaluated. When the correlation between measured P losses (loads and concentrations) and P index components were analyzed, several interesting results were observed. The most striking result was the difference in the ability to predict PO_4-P concentrations and P loads.

The P indices and their specific components generally correlated well with PO_4-P concentrations and dissolved P loads but did not correlate as well with total and particulate P loads (for example, see Figure 5a and 8a). Poultry litter application rate, Mehlich 3 soil test P, and each P index were all able to explain considerable variability in measured PO_4-P concentrations (Table 5). Litter rate was able to explain 42 to 47 percent of the variation in PO_4-P concentrations from the pasture watersheds but only 22 to 31 percent of the variation from the cultivated watersheds. This difference is probably due to the incorporation of litter in the cultivated watersheds, which removes most of the litter from direct contact with runoff. Mehlich 3 soil test P values correlated even better with PO_4-P concentrations with r^2 values from 0.42 to 0.91 for cultivated watersheds and 0.73 to 0.88 for pasture (Figure 9). The TX-PI and the IA-PI both performed well in terms of estimating annual average PO_4-P concentrations in runoff. The TX-PI produced r^2 values of 0.86 and 0.68, and the IA-PI produced r^2 values of 0.90 and 0.76 for the pasture and cultivated watersheds, respectively (Figure 8a, b). As shown in Figure 8c, the AR-PI performed much better on the pasture watersheds ($r^2 = 0.84$) than on the cultivated watersheds ($r^2 = 0.16$). This difference was not surprising, as the AR-PI was developed for pastures, but the TX-PI and IA-PI were developed for both cultivated and pasture conditions.

In terms of measured P loads, litter rate was not well correlated to dissolved, particulate, or total P loads, as all r^2 values were less than 0.16 (Table 5). Mehlich 3 soil test P levels were correlated to dissolved P loads, especially in the cultivated watersheds ($r^2 = 0.73$) but were poorly correlated with total and particulate P loads. Each of the P indices was also able to explain considerable variability in dissolved P loads. The AR-PI performed much better in terms of estimating dissolved P loads from the pasture watersheds ($r^2 = 0.44$) than from the cultivated watersheds ($r^2 = 0.17$). For dissolved P loads, the TX-PI and the IA-PI performed similarly with r^2 values of 0.61 to 0.67 on the cultivated watersheds and 0.48 and 0.51 on the pastures. None of the P indices or their components correlated as well with total or particulate P loads, but the TX-PI and IA-PI were correlated to total P loads for grouped land use (both $r^2 = 0.31$). Only measured annual soil loss was strongly correlated to particulate P ($r^2 > 0.96$) and total P loads ($r^2 > 0.65$).

Another interesting result was the relationship between soil test P, poultry litter application rate, and P concentrations in runoff. As previously noted, Mehlich 3 soil test P (measured annually) was correlated to PO_4-P concentrations and dissolved P loads measured in the present study. This correlation existed in spite of the complexity of soil test P measurements, such as temporal and spatial variability and the difficulty sampling soil without collecting overlying litter (Pierson et al., 2001). Several other studies have also related soil P levels to P loads and concentrations in runoff (e.g., Sharpley and Smith, 1992; Sharpley at al., 1999; Torbert et al., 2002; Torbert et al., 1996; Pote et al., 1999). However, recent manure/litter application has been shown to weaken or overwhelm the relationship between soil test P and runoff P concentrations (Sharpley et al., 2001; DeLaune et al., 2004a; Pierson et al., 2001). The present study demonstrated that concentrations of PO_4-P in runoff from field-scale watersheds receiving poultry litter were positively correlated to both application rate and to Mehlich 3 soil test P; however, the mechanisms involved and relative contribution of P from each source needs further research.

Influence of erosion. In the present study, interannual variability in erosion for individual fields was substantial. For example, erosion from the grazed control watershed (SW17) in the first application year exceeded 0.7 t ac^{-1} but was only 0.01 t ac^{-1} in the second application year. Erosion variability within years was also quite large. For example, erosion from the cultivated control watershed (Y6) was 1.6 t ac^{-1} compared to 5.4 t ac^{-1} for the cultivated watershed (Y8) with an annual litter rate of 2 t ac^{-1}. This variability has a dramatic affect on annual total and particulate P loads as shown Table 4. In spite of this variability, all three evaluated P indices include a constant soil erosion factor based on average annual erosion rate.

Results from other studies also indicated that erosion variability, which directly affects total and particulate P loads, is a major source of error in P indices (Eghball and Gilley, 2001; Sharpley, 1995). Eghball and Gilley (2001) emphasized the importance of erosion in total and particulate P loads in an evalua-

Figure 8

Relationship between phosphorus (P) index values and annual average dissolved P (PO_4-P) concentration, a) TX-PI, b) IA-PI, and c) AR-PI.

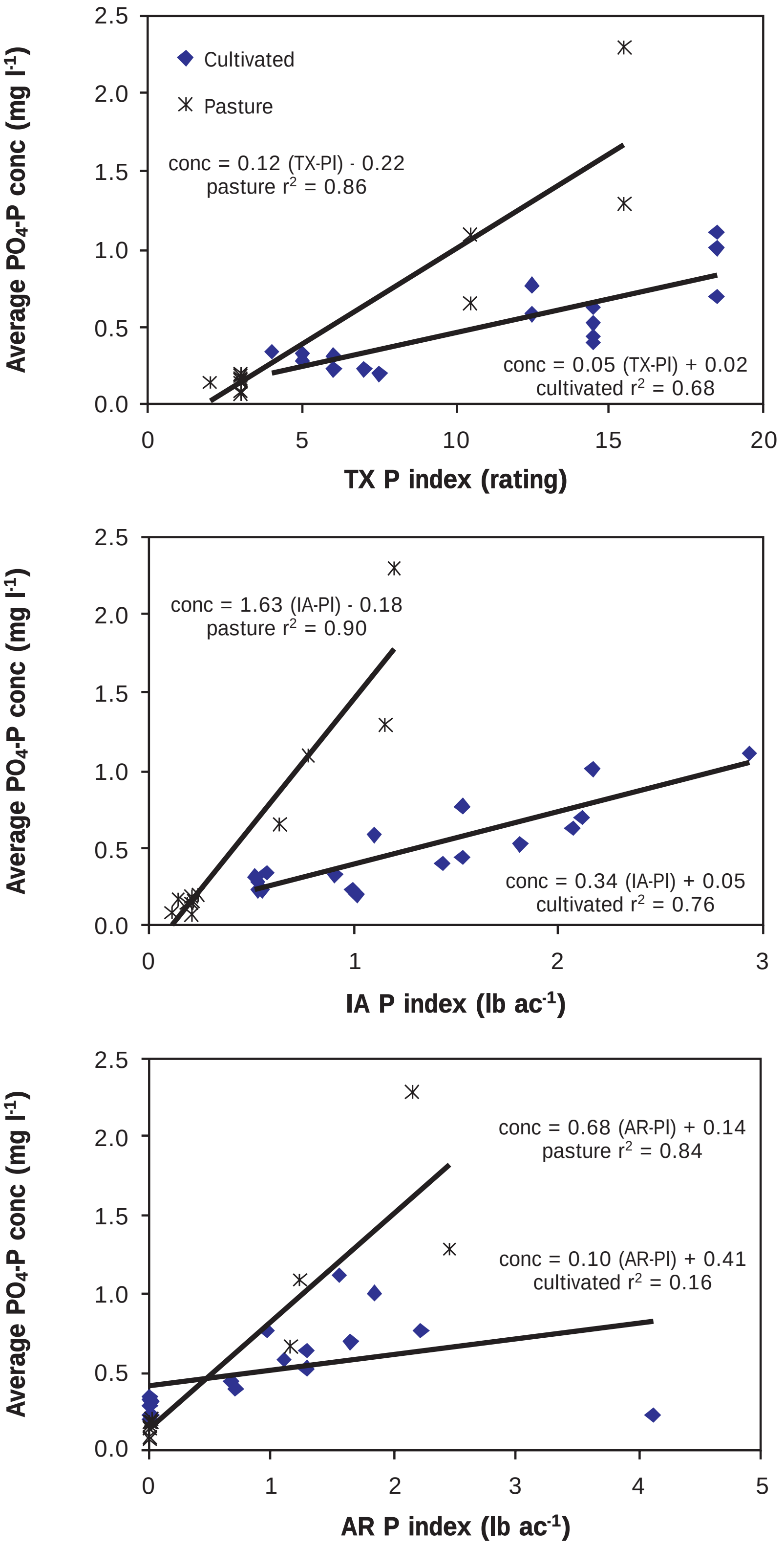
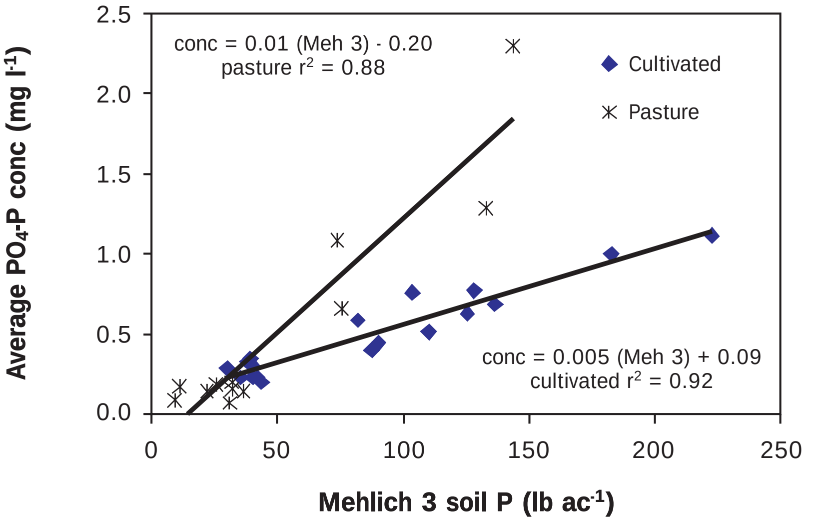


Figure 9

Relationship between Mehlich 3 soil phosphorus (P) and annual average dissolved P (PO_4-P) concentration.



tion of P index components. Erosion accounted for 78 percent and 88 percent of the variability in total and particulate P loads from plots with simulated rainfall. The results for the present study were similar as erosion accounted for 65 to 100 percent of the variability in measured total and particulate P loads from cultivated and pasture watersheds. Sharpley (1995) used observed soil loss and runoff, as opposed to estimated values, to better evaluate the original P Index (Lemunyon and Gilbert, 1993).

Similar to the procedure used by Sharpley (1995), we used measured erosion in each of the P indices to eliminate uncertainly of sediment yield estimation. The improvement in performance was substantial when measured soil losses were used instead of constant annual average erosion estimates in P index calculations (Figures 5b, 6b, 7b). The results of the regression between P index values and measured P loads showed improvement in all the Indices; however, the improvement in the IA-PI was most dramatic, as the r^2 increased from 0.31 to 0.90.

These results emphasize the importance of erosion rates on total and particulate P loads. With the influence of erosion variability in mind, the P indices could be applied with: 1) estimated annual soil erosion, but this would increase the complexity and postpone estimation until year end since rainfall data would be needed; 2) measured erosion, but if erosion were measured, P loads could be measured as well; 3) estimated annual average erosion (as is currently done), but the results of this option depend greatly on the quality of the erosion estimates and do not consider annual variability. The choice between these options should be based on the specific P index application, but it should be kept in mind that erosion variability introduces substantial error in individual annual estimates. Results from this study indicate that accurate estimates of erosion variability may be needed to adequately assess the risk of P loss for management practices alternatives.

Summary and Conclusion

In this study, P index values for the Texas, Arkansas, and Iowa versions were compared with three years of measured P loads and PO_4-P concentrations measured at ten edge-of-field monitoring stations in Texas. These monitoring stations captured surface runoff transported from cultivated and pasture fields under fallow, unfertilized conditions and after conversion to a hybrid poultry litter and inorganic N fertilization program at various agronomic rates. It is important to note that the results represent new litter application sites with initially low and still relatively low soil test P levels and that the results might be quite different for high soil P sites. It should also be remembered that these indices were developed with the realization that continued modification and improvement would be needed (and is underway) and that additional watershed-scale evaluations of the indices, such as the present study, are urgently needed (Sharpley et al., 2003; Leytem et al., 2003; DeLaune et al., 2004b).

As stated, the major objective of this paper was to evaluate the Texas P index; and under the conditions of this study, the TX-PI accomplished its specified purpose of estimating the relative susceptibility of fields to excessive P loss. Although the results varied considerably from year to year, the linear relationship between TX-PI ratings and total annual P loads was significant when data for all three years were combined across land use. Currently, the TX-PI has an additive format, which possibly would be improved by changing to a multiplicative format. Several studies, including Gburek et al. (2000) and Sharpley et al. (2003), indicate that multiplicative Indices can more realistically represent P source and P transport interactions. One result of this format is that overly strict soil P limits are not enacted on areas with little possibility of substantial offsite P transport. An example of this interaction from the present study occurred in 2001-02 when several sites had relatively low P source values; but the unusually high transport capacity, which resulted in greater P loads, was difficult to estimate.

A secondary objective was to evaluate the Arkansas and Iowa P indices. The AR-PI did not perform as well as the TX-PI in terms of representing P loss potential. The AR-PI values did not produce significant linear relationships with total annual P loads, and annual load estimates were significantly different than measured values. As expected, the AR-PI performed better on pastures receiving poultry litter application than on watersheds with alternative land use and fertilizer. An apparent flaw in the AR-PI soluble P rate factor as used with inorganic P fertilizer resulted in over-estimation of P loads. The IA-PI performed well under conditions of this study producing both reasonable relative risk potentials and annual P load estimates. The IA-PI produced significant linear relationships for annual and overall P loads and produced median annual P load estimates not significantly different than measured values.

An important difference in the ability of the P indices to predict PO_4-P concentrations and P loads was also observed. All three P indices and their soil test P and litter rate components generally correlated much better with PO_4-P concentrations and dissolved P loads than with annual total and particulate P loads. Even the TX-PI and IA-PI, which produced significant linear relationships with total P loads for grouped land use, were better correlated to dissolved PO4-P loads.

A general limitation of the P indices is their inability to capture variability in annual soil erosion, which introduces substantial error in individual annual P load estimates. Results illustrated substantial improvement when annual erosion estimates or measurements were used. The importance of another transport factor, runoff variability, was also evident as runoff volumes were substantially lower for the pasture watersheds. As Sharpley (1995) noted, the reliability of output for P indices or any model is dependent on the accuracy of input values. Although better estimates of runoff and erosion would improve the ability of P indices to estimate P loads and provide relative risk assessments, the added complexity may not be warranted in typical use.

While this evaluation focused on the determination of relative P loss potential, research on other important issues related to P index use is warranted. Expanded, in-depth evaluations are needed on the potential regulatory implications of P indices, on the use of P indices in comprehensive nutrient management plans, on incentives to prevent buildup of soil P levels, and on the linkages between soil test P levels (or P index values) to P levels in receiving waters.

Endnotes

[1] Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

[2] The original P index and many modified versions use English units in their calculations. Non-SI units were chosen and remain in use with the P index by the Natural Resources Conservation Service and other technical assistance personnel to aid in landowner adoption. Therefore, English units are presented first in this paper and accompanied by SI units where appropriate.

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