

# Soil Phosphorus, Management Practices, and Their Relationship to Phosphorus Delivery in the Iowa Clear Lake Agricultural Watershed

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## ABSTRACT

Clear Lake is on Iowa's list of impaired water bodies because of high P concentration. This study assessed soil-test phosphorus (STP), management practices, and P loads from its agricultural watershed. Management practice histories and STP for eight basins were surveyed in 1999. Soil samples (15-cm depth) were analyzed for STP with agronomic [Bray P<sub>1</sub> (BP), Olsen (OP), Mehlich 3 (M3P)] and environmental [iron oxide-impregnated paper (FeP) and water extraction (WP)] tests. Total phosphorus (TP) concentrations in water discharge from five basins were measured during two years, and TP loads were measured for two basins. The agronomic P tests showed that 46 to 83% (depending on the test) of the area tested above optimum for crops. Correlations among tests were high for OP, M3P, and FeP ( $r > 0.96$ ) and lower for BP and WP ( $r = 0.88-0.93$ ). Moldboard- and chisel-plow tillage predominated (82% of the area). Applied P (mainly fertilizer) averaged 15 kg P ha<sup>-1</sup> yr<sup>-1</sup>, and 40% of the high-testing area (M3P test) was being fertilized. The mean annual water TP concentration across five basins was 275 to 474 μg L<sup>-1</sup>. The two-year mean TP loads for the two gauged basins were 1504 and 1510 g P ha<sup>-1</sup> yr<sup>-1</sup>. Water TP concentration increased linearly with increasing STP. Relationships were stronger for M3P and FeP ( $R^2 = 0.96-0.97$  for annual means and 0.77-0.79 for storm-flow events) than for BP or WP ( $R^2 = 0.88-0.91$  and 0.59-0.69, respectively). Improving P and soil conservation practices in high-testing areas could reduce P loads to the lake.

NONPOINT-SOURCE P loss from agricultural fields has the potential to accelerate eutrophication of freshwater ecosystems. In the most recent report of water quality in the United States, the USEPA cited agriculture as the primary source of pollution in 60% of impaired river miles, 30% of the impaired lake acres and 15% of estuarine square miles (USEPA, 1998). Phosphorus, in particular, has received much attention due to its role as the limiting nutrient in many freshwater ecosystems (Sawyer, 1947; Schindler, 1977; Correll, 1998). In Iowa, many water bodies have significant water quality impairment because of increased P concentration and agriculture is often considered the primary P source (Iowa Department of Natural Resources, 2000).

The development of P indexes across the country demonstrates the recognition that P loss from agricultural fields is dependent on many factors that include source factors such as STP and P application, as well as transport factors such as site hydrology and erosion (Lemunyon and Gilbert, 1993; Mallarino et al., 2002).

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A runoff event shortly after a P application can dramatically increase P concentrations in runoff (Sharpley, 1997; Gascho et al., 1998; Sauer et al., 2000) particularly when the P is broadcast without incorporation (Sharpley, 1985; Eghball and Gilley, 1999). Because P can be strongly sorbed to soil, P associated with eroded soil particles usually is the primary form of P entering surface water bodies (Vaithianathan and Correll, 1992). Conservation tillage, such as ridge-till and no-till, has been shown as a way to reduce soil erosion and sediment P loads from agricultural fields (Johnson et al., 1979; Ginting et al., 1998; Zhao et al., 2001). Installation of artificial subsurface drainage in many agricultural fields has provided an additional pathway for P transport off fields, although increased subsurface drainage can reduce the volume of surface runoff and therefore P transport in overland flow. Transport of P in subsurface drainage often is considered negligible because of the reactive nature of P in soil, but research has shown that significant P loads from subsurface drainage can occur in some situations (Sims et al., 1998).

Soil-test P levels in many areas of the country are now above levels required to optimize crop growth (Potash and Phosphate Institute, 2001) due to excess P fertilization. High STP increases the risk of limnologically significant P concentrations reaching surface waters and accelerating eutrophication (Sharpley, 1995; Pote et al., 1996, 1999). The purpose of agronomic P testing is to estimate the amount of soil P available for crop production, and several tests are used. Most agronomic soil P tests, such as the BP, OP, and M3P tests, are based on a strong chemical extraction of poorly defined P fractions seemingly relevant for plant uptake. Increasing concerns about nonpoint-source P pollution from agriculture has prompted questions about the suitability of agronomic soil tests for environmental purposes. Several soil extraction procedures have been proposed as environmental soil P tests because they may provide better estimates of dissolved P delivery to water resources (Sharpley, 1991; Pote et al., 1996; Sharpley et al., 1996; Sims et al., 2000). The FeP test developed by Menon et al. (1989) has been slightly modified (Sharpley, 1991, 1993; Chardon et al., 1996; Chardon, 2000) and uses a sink approach to extract soil-bound P that most likely is available to aquatic organisms. Another environmental P test is based on weaker desorption reactions and uses deionized water to extract soil P (van Der Paauw, 1971; Pote et al., 1996). These tests are environmentally sound for laboratory use (because fewer chemicals are needed),

**Abbreviations:** BP, Bray-P<sub>1</sub> phosphorus; FeP, phosphorus determined with iron oxide-impregnated paper; M3P, Mehlich-3 phosphorus; OP, Olsen phosphorus; STP, soil-test phosphorus; WP, water-extractable phosphorus; TP, water total phosphorus.

but are more time consuming for use on a routine basis and their use may result in increasing soil testing costs.

While much work has been done to study P loss from soil using field plots under natural and simulated rainfall, less work had been done on a watershed scale due to difficulties in working with such large areas and many landowners. Research has shown that P losses from agricultural watersheds often occur unevenly across fields with some areas contributing disproportionately larger amounts of P and that losses often are unevenly distributed throughout the year (Longabucco and Rafferty, 1989; Gangbazo et al., 1997; Pionke et al., 1999). Storm-flow losses of P in many cases dominate P export in agricultural watersheds (Johnson et al., 1976; Pionke et al., 1996, 1999; Jordan et al., 1997c). Particular attention should be given to management practices in watershed or field areas for which P source and transport factors suggest a high risk for P loss (Gburek and Sharpley, 1998; Gburek et al., 2000; Heathwaite et al., 2000).

The relationship between STP measured by various tests and actual P delivered to surface water resources has not been studied in Iowa, although there is evidence that both STP of fields and P concentrations in streams and lakes are increasing. For example, the P concentration in Clear Lake has tripled since 1970 increasing from 60 to 190  $\mu\text{g L}^{-1}$  by 2000 (Downing et al., 2001a). The objectives of this study were to (i) survey surface STP and management practices in the agricultural area of the Clear Lake watershed and (ii) relate STP measured with agronomic and environmental soil tests with P in water discharged to the lake. This information should help in understanding the role of P levels and management practices on the amount of P delivered to lakes and in determining alternatives for improving water quality.

## MATERIALS AND METHODS

### Study Area

Clear Lake is a natural glacial lake in northern Iowa with a surface area of 1450 ha, an average depth of 2.9 m, and a relatively small watershed with a 2.3:1 land to lake ratio. The agricultural area comprises the major portion of the watershed (59%). Two small urban areas (14%) and areas of woodland, nonagricultural grassland, and wetlands (27%) comprised the rest of the watershed. Drainage from much of the agricultural area flows through a marsh (Ventura Marsh) on the west side of the lake (Fig. 1). Downing et al. (2001a) reported that previous sustained P loading had converted this marsh into a source of P to the lake. The majority of the soils formed on glacial till material and included some of the most productive soils of Iowa. Soils of the Clarion–Nicollet–Webster association (Typic Hapludoll, Aquic Hapludoll, and Typic Endoaquoll, respectively) dominate, and the surface layers (15–20 cm deep) have loam or silty-clay-loam textures. Approximately 80% of the watershed is relatively flat with slopes of <5%, although small areas have slopes up to 14 to 18%. Areas with  $\leq 2\%$  slope are artificially drained with subsurface tiles and surface inlets. These areas include small areas of high-pH,  $\text{CaCO}_3$ -affected soils such as Canisteo (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquoll) and Harps (fine-loamy, mixed, superactive, mesic Typic Calciaquoll), and also Okoboji soil (fine, smectitic, mesic Cumulic Vertic Endoaquoll) with higher organic matter than the other series.

### Soil Sampling and Testing

Soil samples were collected from fields of the agricultural area of the Clear Lake watershed in November 1999. Samples were collected using a stratified sampling approach in which predominant soil map units of each field were sampled. In a first step, ArcView GIS computer software (Environmental Systems Research Institute, 2003) was used to produce several layers of information and to identify soil sampling areas about 0.1 ha in size within the predominant soil series of each field. The layers used included digitized and georeferenced soil survey maps (1:12 000 scale), field borders, surface drainage patterns, and black and white satellite photographs (1:40 000 scale). In a second step, we verified (and modified when necessary) the location of the sampling points through use of handheld differential global positioning systems (DGPS) receivers and field observations. One composite soil sample (15–20 cores) was collected from the surface-15-cm layer of soil from each sampling area. Figure 1 shows the sample point locations. Approximately 20% of the area could not be sampled because landowners denied access to their fields.

Soil samples were dried, ground to pass a 2-mm screen, and analyzed in duplicate for STP with three agronomic and two environmental tests, as well as for ammonium acetate-extractable K, Ca, and Mg, soil pH, and organic matter. The three agronomic P tests were BP, OP, and M3P, which are supported as the basis for making P fertilizer recommendations in Iowa (Sawyer et al., 2002). The BP and M3P tests are the most commonly used in Iowa and the U.S. Corn Belt. Procedures followed for the agronomic tests were those recommended in Brown (1998) for the north-central region of the USA. The two environmental tests used were the FeP test as described by Chardon (2000) and the WP as described by Pote et al. (1996). The P extracted by all agronomic and environmental P tests was measured colorimetrically with the Murphy and Riley (1962) method.

Soil P data from the agricultural area were summarized into eight basins delineated according to drainage patterns. An inverse-distance weighted interpolation method was used to obtain interpolated STP maps for all soil tests. Iowa State University agronomic soil-test interpretation classes for corn (*Zea mays* L.) and soybean [*Glycine max* L. (Merr.)] were used to classify STP (Sawyer et al., 2002). Classes for the BP and M3P tests for all soil series of the Clear Lake area are very low (0–8  $\text{mg kg}^{-1}$ ), low (9–15  $\text{mg kg}^{-1}$ ), optimum (16–20  $\text{mg kg}^{-1}$ ), high (21–30  $\text{mg kg}^{-1}$ ), and very high (>30  $\text{mg kg}^{-1}$ ). Classes for the OP test are very low (0–5  $\text{mg kg}^{-1}$ ), low (6–10  $\text{mg kg}^{-1}$ ), optimum (11–14  $\text{mg kg}^{-1}$ ), high (15–20  $\text{mg kg}^{-1}$ ), and very high (>21  $\text{mg kg}^{-1}$ ).

### Management Practices Survey

A questionnaire was delivered to all landowners or operators from whose fields soil samples were collected to obtain information of relevant past agricultural practices used in their fields. The questionnaire requested information about crop rotation, tillage system, application rates and type of P fertilizer, and manure usage during the last five years. Because several landowners were not willing to share information from their fields or chose not to return the questionnaires, information was available for approximately 66% of the area.

### Water Quality Monitoring

Grab samples of water discharge to the lake from tributaries draining five agricultural basins of the watershed were collected regularly during two years (August 1998–July 2000) at 15-d intervals from April to September and 30-d intervals

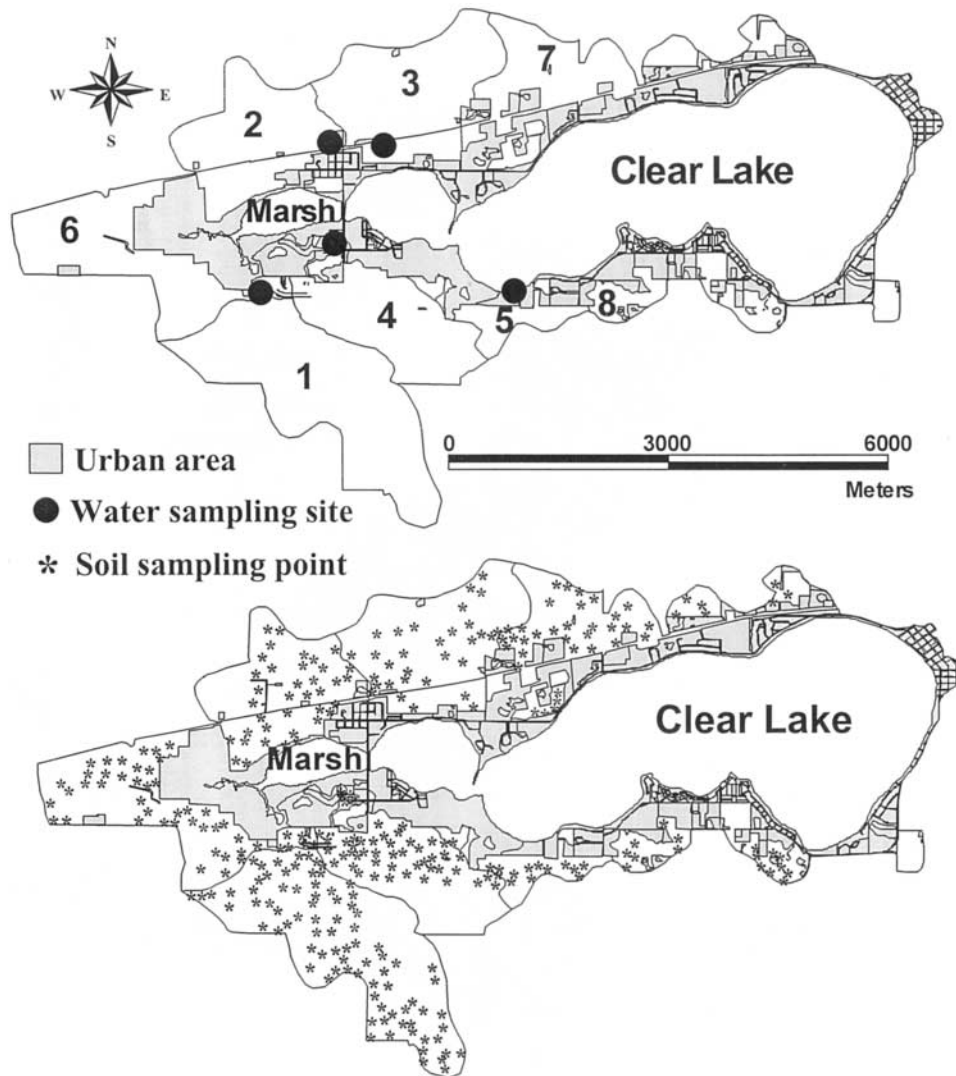


Fig. 1. Soil sample points, water sample sites, and basin identification for the Clear Lake agricultural watershed survey study.

from October to March. These monitored basins are referred to as Basins 1 to 5 in Fig. 1. Additionally, trained volunteers collected samples from the same locations during or within 24 h of storm events. Water samples were collected on 57 occasions over the two-year period, with 42 samples collected during baseflow periods and 15 samples collected during storm events. Total P in unfiltered samples was determined by digesting the samples using the persulfate method (American Public Health Association, 1998; Standard Method 4500-P B.5) and measuring P using a molybdate–ascorbic acid colorimetric method (American Public Health Association, 1998; Standard Method 4500-P E) on a Hewlett-Packard Model 8453 UV-Vis diode array spectrophotometer (Agilent Technologies, Palo Alto, CA). The sampled tributaries collected surface runoff and water drainage from subsurface tile lines, which also transported water collected at surface intake drains. Thus, we were unable to determine the proportion of P derived from surface runoff or subsurface drainage.

Water discharge to the lake from Basins 2 and 3 was continuously monitored with a Model 4250 flow meter (ISCO, Lincoln, NE). This flow meter employs an area–velocity probe deployed in a rectangular concrete channel at the point where surface water flows through a culvert. Monthly P loads were estimated as the product of water discharge and the average

TP concentration of all samples collected within each month, and were expressed as  $\text{g P ha}^{-1} \text{yr}^{-1}$ . Basin areas were determined by delineating watershed boundaries on U.S. Geological Survey topographic maps using ArcView GIS.

Regression analysis was used to relate STP estimates by each soil P test and water TP concentrations across the five basins for which TP concentration was measured. Regression analyses were conducted separately for two sets of water TP data. One data set included mean water TP across the second year of the evaluation period (August 1999–July 2000), which encompassed the soil sampling date (November 1999). The other data set included mean water TP across samples collected during 15 storm events.

## RESULTS AND DISCUSSION

### Soil-Test Phosphorus Assessment by Agronomic and Environmental Soil Tests

Descriptive statistics for mean soil-test values from each field sampled are shown in Table 1. Values of K, Ca, Mg, pH, and organic matter are typical for soils of the area. The amount of soil P extracted varied greatly

**Table 1. Descriptive statistics of soil-test values for fields of the Clear Lake agricultural watershed.†**

Statistics	Soil tests‡									
	BP	OP	M3P	FeP	WP	K	Ca	Mg	pH	OM
	mg kg <sup>-1</sup>									g kg <sup>-1</sup>
Mean	34	17	42	26	8	173	3290	384	6.6	57
Median	28	14	34	22	6	173	2818	368	6.6	49
Minimum	1	2	6	6	2	71	656	131	5.0	14
Maximum	222	34	296	129	56	502	8016	847	8.1	228
SD§	30	22	35	17	7	64	1475	117	0.7	30

† Data calculated from means of each field and for a 0- to 15-cm soil depth.

‡ BP, Bray-P<sub>1</sub> phosphorus; FeP, phosphorus determined with iron oxide-impregnated paper; M3P, Mehlich-3 phosphorus; OM, organic matter; OP, Olsen phosphorus; WP, water-extractable phosphorus.

§ Standard deviation.

between soil tests and across the watershed. The M3P test extracted the largest amount of P among the agronomic tests and the OP test extracted the lowest amount. The FeP environmental P test extracted an amount of P intermediate between the BP and OP agronomic tests, while the WP test extracted the smallest amount. These differences in amount of P extracted by the P tests are well known and were shown before for manured and not manured Iowa fields with soils similar to the soils in this watershed (Atia and Mallarino, 2002). The M3P test usually extracts similar or only slightly higher amounts of P than the BP test in Iowa soils with near neutral or acid pH and more than the BP test in high-pH, CaCO<sub>3</sub>-affected soils (Mallarino, 1997; Atia and Mallarino, 2002). Correlations between P tests (Table 2) were very high for the M3P, OP, and FeP tests ( $r = 0.96-0.97$ ). Correlation coefficients involving the BP test were lower and ranged from 0.88 to 0.92. The correlation coefficients involving the WP test were higher with the M3P or FeP tests (0.95 and 0.96) than with the BP or OP tests (0.91 and 0.93). The BP test probably correlated poorly with other tests because of the presence of some CaCO<sub>3</sub>-affected soils. Correlation coefficients involving the BP test improved when only soils with pH of <7.2 were included in the analyses. Overall, the correlations were very high considering the large variability in organic matter, pH, and other soil properties across the watershed.

Table 3 shows the distribution of field-mean STP values into agronomic interpretation classes used in Iowa (Sawyer et al., 2002). The percentage of fields testing in the high or very high classes was 46% for OP, 70% for BP, and 83% for the M3P. These differences are not surprising because agronomic P tests often provide

different estimates of P availability for crops, and without local field assessments of crop response no reasonable speculation is possible about which test provided the best estimate. No P fertilization is recommended for corn and soybean in Iowa fields testing high or very high, except for a small starter fertilizer rate for corn in some conditions (Sawyer et al., 2002). Soil test summaries of samples submitted by producers from the two counties surrounding Clear Lake (Cerro Gordo and Hancock) to the Iowa State University Soil and Plant Analysis Laboratory show that BP values (data for other tests were not available) increased markedly during the last four decades. Samples testing high or very high were 16% of the samples submitted in the 1960s but increased to 58% by 1990s (Voss, 1968; Killorn et al., 1990). Although the data from our survey and county summaries cannot be directly compared, our results suggest that the percentage of high-testing soils in the area has increased further because 70% of the fields tested high or very high in STP according to the BP test.

Mean STP values (area weighted) for eight basins are shown in Table 4. The three agronomic P tests classified the mean STP of most basins as above optimum levels for crops. The BP and M3P tests classified all basins into the high or very high classes. Only the OP test classified two basins into the optimum class. Moreover, basins testing very high were two for the OP test, six for the BP test, and eight (all basins) for the M3P test. These results further suggest that there has been uneven and often excessive P fertilization across the watershed.

### Field Management Practices

The field history information provided by the producers is summarized in Table 5 for the total area surveyed (across eight basins) and four basins for which water

**Table 2. Correlation coefficients between amounts of P extracted by five soil tests from fields of the Clear Lake watershed.**

Soil test	Correlation coefficient			
	Olsen	Bray P <sub>1</sub>	Mehlich 3	Iron oxide
	All soils			
Bray P <sub>1</sub>	0.89			
Mehlich 3	0.96	0.92		
Iron oxide	0.96	0.88	0.97	
Water	0.93	0.91	0.95	0.96
	Soils with pH of <7.2			
Bray P <sub>1</sub>	0.97			
Mehlich 3	0.97	0.99		
Iron oxide	0.96	0.96	0.97	
Water	0.93	0.95	0.95	0.97

**Table 3. Distribution of soil-test phosphorus (STP) for fields of the Clear Lake agricultural watershed within five Iowa STP interpretation classes for crop production.**

STP class	Percent of fields surveyed		
	STP method		
	Bray P <sub>1</sub>	Olsen	Mehlich 3
	%		
Very low	10	10	4
Low	14	21	8
Optimum	6	23	6
High	26	16	27
Very high	44	30	56

**Table 4. Mean soil-test phosphorus (STP) values (area weighted) and agronomic soil-test interpretation classes for eight agricultural basins of the Clear Lake watershed.**

Basin	Area ha	Soil P test <sup>†</sup>					STP class <sup>‡</sup>		
		BP	OP	M3P	FeP	WP	BP	OP	M3P
		mg kg <sup>-1</sup>							
1	535	32	16	40	24	7	VH	H	VH
2	216	46	25	54	31	10	VH	VH	VH
3	320	22	12	34	21	7	H	O	VH
4	289	28	14	34	21	6	H	O	VH
5	74	45	20	46	28	9	VH	VH	VH
6	419	35	19	41	25	8	VH	H	VH
7	202	32	17	37	24	7	VH	H	VH
8	109	40	17	41	27	9	VH	H	VH

<sup>†</sup> BP, Bray-P<sub>1</sub> phosphorus; FeP, phosphorus determined with iron oxide-impregnated paper; M3P, Mehlich-3 phosphorus; OP, Olsen phosphorus; WP, water-extractable phosphorus.

<sup>‡</sup> H, high; O, optimum; and VH, very high for corn and soybean crops according to Iowa State University (Sawyer et al., 2002).

discharge to the lake was monitored (very little information was received for Basin 5 and data are not shown). Row-crop production dominated the agricultural area, and 87% was managed with a corn-soybean rotation. A small area was managed with continuous corn (5%), and 8% was under hay or pasture. The most common tillage practice (58% of the area) was chisel plowing in combination with disking for corn residues and only disking for soybean residues. The remaining area was managed with moldboard plowing (24%), ridge tillage (11%), no tillage (2%), and subsoiling in addition to no-till or chisel or disk tillage (5%). Most producers tilled soils in the fall, which reduces residue cover and may increase the risk of soil erosion when crop canopies are not developed. Basin 1 had a significant area managed with conservation tillage (30% of its surveyed area was under ridge-tillage). The use of ridge-tillage and no-tillage can reduce P loads mainly by reducing erosion (Johnson et al., 1979; Gaynor and Findlay, 1995; Zhao et al., 2001). Thus, our survey data suggest that there is opportunity for further adoption of conservation tillage systems that could potentially decrease P loads to the lake.

The most frequently used application method for

solid, liquid, or organic P sources (47% of the area) was to incorporate them into the soil in the fall (in October or November) by plowing, disking, or injecting. The next two most frequent application methods were broadcasting in the fall without incorporation (25%) and injection or incorporation of the fertilizer into the soil before planting crops in spring (15%). The benefits of incorporating fertilizer after application is partly dependent on the erosion risk for the particular area because increased soil loss due to tillage may partly offset the effect of incorporation in reducing loss of fertilizer P. Applying P in the fall is preferred by producers because they have more time available and because the Iowa fall season typically is drier than the spring season.

On average, P fertilizers were applied 2.2 times during the last five years at a rate of 32 kg P ha<sup>-1</sup>. Only 10% of the land received organic P sources (mainly swine manure) at least once during the previous five years, and responses provided insufficient data to determine application rates. However, the STP data showed similar STP values for manured fields and nonmanured fields (within 3–6 mg P kg<sup>-1</sup> depending on the agronomic test used), which suggests that on average (and over time) similar P rates were applied with manure or fertilizer.

**Table 5. Summary of selected management practices for the fields of the Clear Lake agricultural watershed.**

Management practice	Area				
	All basins	Water monitored basins <sup>†</sup>			
	ha	1	2	3	4
		%			
<b>Primary tillage</b>					
Chisel or disk	591	41	63	84	11
Moldboard plow	248	18	10	16	78
No-till	25	0	27	0	0
Ridge-till	112	30	0	0	11
Subsoiling <sup>‡</sup>	48	11	0	0	0
<b>Cropping System</b>					
Alfalfa, legume-grass pasture	89	0	7	21	0
Continuous corn	54	0	0	0	0
Corn-soybean rotation	969	100	93	79	100
<b>Time and method of P application</b>					
Fall, injected and/or incorporated	457	61	33	24	17
Spring, injected and/or incorporated	142	20	0	0	4
Fall, surface applied	241	9	22	76	0
Spring, surface applied	134	10	45	0	79
<b>P source</b>					
Fertilizer	1002	79	100	100	100
Manure	110	21	0	0	0

<sup>†</sup> Very little and incomplete information was received for Basin 5 and data are not shown.

<sup>‡</sup> In addition to no-till or chisel or disk tillage.

**Table 6. Precipitation, total P concentration, and total P loading from the Clear Lake agricultural watershed during a two-year evaluation period.**

Month	Precipitation mm	P concentration for five basins					P loads for two basins†	
		1	2	3	4	5	2	3
		$\mu\text{g L}^{-1}$					$\text{g ha}^{-1}$	
<b>1998</b>								
August	140	372	606	314	332	338	478	348
September	46	691	242	330	209	671	62	161
October	88	185	127	100	150	124	63	60
November	28	150	135	90	130	150	21	17
December	10	237	179	213	205	190	17	19
<b>1999</b>								
January	36	198	–‡	–	–	–	64	60
February	41	817	550	502	441	–	209	248
March	32	595	311	343	337	–	93	81
April	208	186	201	176	158	–	231	158
May	192	388	259	396	365	273	244	334
June	131	411	499	219	351	245	362	373
July	283	319	894	343	388	398	418	198
M/T§	1235	379	364	275	279	299	2262	2057
August	55	160	545	173	265	290	41	19
September	55	158	1088	230	196	245	18	6
October	28	145	138	144	219	866	1	6
November	19	780	393	377	481	423	2	3
December	19	256	148	59	85	466	26	41
<b>2000</b>								
January	27	214	142	–	–	–	36	62
February	41	1158	980	1263	672	654	377	536
March	31	121	–	150	84	98	20	22
April	43	365	332	386	383	413	34	48
May	121	138	179	184	153	421	52	120
June	132	367	479	283	842	382	80	28
July	143	206	785	238	251	301	72	60
M/T	714	339	474	317	330	414	759	951
Storm flow¶		823	911	655	573	787		

† Water discharge was continuously monitored only for Basins 2 and 3.

‡ No sample was collected. Loads for Basins 2 and 3 were calculated using the average P concentration of the previous and following month.

§ Means/total. Precipitation and loading are annual totals while P concentrations are monthly averages.

¶ Mean total water P concentration measured during or within 24 h of 15 storm flow events.

The mean annual P rate over the five-year period across all fields (including years with no P application) was 15 kg P ha<sup>-1</sup>. This rate was slightly lower than the rate (22 kg P ha<sup>-1</sup> yr<sup>-1</sup>) recommended in Iowa to maintain optimum STP for the corn–soybean rotation, although there was large variability across fields in both STP levels and the amount of P applied. The amount of P applied to each field during the five-year period ranged from 10 to 216 kg P ha<sup>-1</sup>. Based on M3P interpretations, in 1999 P was applied to 49% of the high-testing area although no additional P fertilizer was needed (Sawyer et al., 2002). Moreover, for Basin 2, where all fields sampled tested above optimum levels for row crops, the mean application rate was 25 kg P ha<sup>-1</sup> yr<sup>-1</sup>, which suggests producers were maintaining high-testing soil P levels. Applying P only when deemed necessary by soil testing would keep soil P levels near the optimum class for crops and should reduce the risk of large P loads to the lake.

### Phosphorus Concentration in Water Discharge from Five Agricultural Basins

The TP concentrations in water discharge sampled at regular intervals for five basins are summarized in Table 6. The mean annual TP concentration across the five basins ranged from 275 to 379  $\mu\text{g L}^{-1}$  in the first year and 317 to 474  $\mu\text{g L}^{-1}$  in the second year. Correll

(1998) suggested that TP concentrations of more than 100  $\mu\text{g L}^{-1}$  are unacceptably high P concentrations for most freshwater bodies because it causes eutrophication and profound changes to the aquatic ecosystem. Moreover, Downing et al. (2001b) showed that water TP concentrations above 100  $\mu\text{g L}^{-1}$  yield an exceptionally large dominance of potentially toxic *Cyanobacteria* in lakes. Our results indicate that the P concentration of water entering Clear Lake is almost always larger than that value.

Monthly water TP means across the basins varied considerably over the evaluation period. Concentrations were lower from late summer (August) to the middle of winter (January). This period of time encompasses the period with the largest crop biomass and soil cover (from August to September) and the period with the lowest precipitation (October to January). Water TP concentrations during this period were near concentrations in ground water for this watershed (238  $\mu\text{g L}^{-1}$ ), which were measured in another component of the study (Downing et al., 2001a). These concentrations are greater than those reported for subsurface tile drainage (<100  $\mu\text{g L}^{-1}$ ) from Iowa field plots having BP values of <120 mg P kg<sup>-1</sup> in the surface-15-cm soil layer (Baker et al., 1975; Klatt et al., 2002). Mean water TP concentrations for 15 storm events occurring mainly during spring (Table 6) ranged from 573 to 911  $\mu\text{g L}^{-1}$  (the mean

across basins was  $748 \mu\text{g L}^{-1}$ ). There was large variability in TP concentrations across these storm events (not shown), and values ranged from 158 to  $2626 \mu\text{g L}^{-1}$ . While we could not distinguish between overland and subsurface drainage flow in this study, the much higher water TP concentrations during storm flow conditions indicate high contribution of surface runoff. This could be the case even for water discharge from field areas with subsurface drainage tiles because of the presence of surface tile inlets. These tile-drained areas typically are the wettest parts of the landscape and could be considered areas of high runoff potential. Ginting et al. (2000) reported 700 to  $6500 \mu\text{g P L}^{-1}$  in surface runoff entering surface tile inlets in a southern Minnesota field with similar soils.

Large water TP concentrations were also observed during snowmelt periods, which occurred during late February in both years (Table 6). Snowmelt occurred before soils thawed and water began flowing through subsurface drainage tiles. As snowmelt is occurring, frozen soil inhibits water infiltration. A study conducted in Canada (Gangbazo et al., 1997) showed that 90% of the total drainage during the snowmelt period was from surface runoff. Unseasonably warm temperatures during the last week of February 2000, when temperatures never fell below freezing, caused a rapid snowmelt that was augmented by 14 mm of rainfall. Water samples collected during this period averaged  $1100 \mu\text{g TP L}^{-1}$ . Fall fertilization after harvest, which was the primary fertilization method in the watershed (72%), and little conservation tillage may have contributed to the high water TP concentrations at this time.

### Phosphorus Loads From Two Agricultural Basins

The estimated annual P loads for the two gauged basins were 2262 and  $2057 \text{ g P ha}^{-1}$  (Basins 2 and 3, respectively) for the first year (August 1998–July 1999), and 759 and  $951 \text{ g P ha}^{-1}$ , respectively, for the second year (Table 6). The two-year mean TP loads were similar for the two basins ( $1504$  and  $1510 \text{ g P ha}^{-1} \text{ yr}^{-1}$  for Basins 2 and 3, respectively). Basin 2 had higher (approximately twice as much) mean STP than Basin 3 (Table 4) but had significantly less moldboard-plow or chisel-disk tillage and less surface-applied P than Basin 3 (Table 5). Other components of this study (Downing et al., 2001a; Klatt et al., 2001) showed that agricultural areas contributed 52% of the TP load to this lake (other sources were urban areas and direct contributions to the lake from rainfall and ground water flow). The P loads observed in this study are within loads ( $500$ – $4000 \text{ g ha}^{-1} \text{ yr}^{-1}$ ) reported for highly fertilized and manured agricultural watersheds in the Chesapeake Bay area (Jordan et al., 1997a,b,c). Other studies from less intensively fertilized agricultural watersheds (i.e., Clasceri et al., 1986; Nearing et al., 1993) showed P loadings encompassing a narrower and lower range ( $90$ – $580 \text{ g ha}^{-1} \text{ yr}^{-1}$ ).

Precipitation for the first year (Table 6) was above the local long-term average of 830 mm (1235 mm), while precipitation in the second year was slightly below the

average (714 mm). Phosphorus loading rates across the two basins were higher in the wet year ( $2262$  and  $2057 \text{ g P ha}^{-1}$ ) than in the dry year ( $759$  and  $951 \text{ g P ha}^{-1}$ ). Precipitation was 73% higher for the wetter year but this difference corresponded to a 2.5-fold increase in P loading, which indicates that P loading rates were highly climate dependent. Phosphorus loads in February 1999 and 2000 accounted for 23% of the total load over the two-year evaluation period, suggesting that the snowmelt period is a time of significant P loss from fields. Other research (Gangbazo et al., 1997; Ginting et al., 2000) also showed substantial P loads during snowmelt periods. The P loads observed in our study from February to July were 68% (in 1999) and 85% (in 2000) of the annual P load. This 6-mo period encompasses the snowmelt period, the months with highest rainfall, and the time of the year when crops are not fully developed. Gangbazo et al. (1997) found 70% of annual P loading occurring from late March to mid-May, while Longabucco and Rafferty (1989) found 50% of annual soluble P loading occurring during the same period. Our study probably overestimated P loads during July because in both years rainfall was greater than the long-term average for this month (113 mm) with 283 mm in July 1999 and 143 mm in July 2000.

### Relationships between Soil Test Phosphorus and Phosphorus Concentration in Water Discharge

The mean STP and water TP for the five basins in which water TP concentrations were monitored were significantly correlated. Data in Fig. 2 show that trends for mean water TP data from the second year of the study (August 1999–July 2000), which encompassed the STP sampling date, were linear and highly significant ( $P \leq 0.02$ ) for all soil P tests. The largest  $R^2$  values corresponded to the M3P, OP, and FeP tests (0.96–0.97) and the lowest values corresponded to the WP (0.91) and BP (0.88) tests. The linear coefficients of relationships between TP concentrations and STP shown in Fig. 2 and 3 cannot be directly compared with values reported in the literature for relationships between STP and P in surface runoff or subsurface drainage based on more controlled conditions. First, we could not discriminate between P lost through surface runoff or subsurface drainage and analyzed only for TP in unfiltered water samples. Second, water P analyses spanned a long period of time compared with the one-time soil sampling for STP, whereas most published studies were based on short-period evaluations mainly based on runoff simulations. However, Iowa research based on small plots established on fields with various soil series and STP ranges similar to those in this watershed has also shown linear relationships between TP in surface runoff with STP (Mallarino et al., 2001; Klatt et al., 2002).

Mean water TP data from 15 storm flow events also increased with increasing mean STP, but the relationships were weaker than for mean water TP data (Fig. 3). Although linear coefficients were almost four times larger than for annual mean water TP, the  $R^2$  values were smaller and trends sometimes were not significant

at commonly used probability levels. The relationships were strongest for the M3P ( $R^2 = 0.79$  and  $P \leq 0.05$ ) and FeP ( $R^2 = 0.77$  and  $P \leq 0.06$ ) tests. Relationships for the OP and WP tests were weaker ( $R^2 = 0.70$  and  $0.69$ , respectively) and were significant only at  $P \leq 0.08$  and  $0.09$ , respectively. The relationship for the BP test was the weakest ( $R^2 = 0.59$ ) and cannot be considered

statistically significant ( $P \leq 0.13$ ). Basin 2, which had the highest STP among the five basins for all tests, had the largest mean water TP concentration across these storm flow events ( $911 \mu\text{g L}^{-1}$ ), while Basins 3 and 4, which had the lowest STP, had the lowest mean water TP concentrations ( $655$  and  $573 \mu\text{g L}^{-1}$ , respectively).

The results in Fig. 2 and 3 show that the environmen-

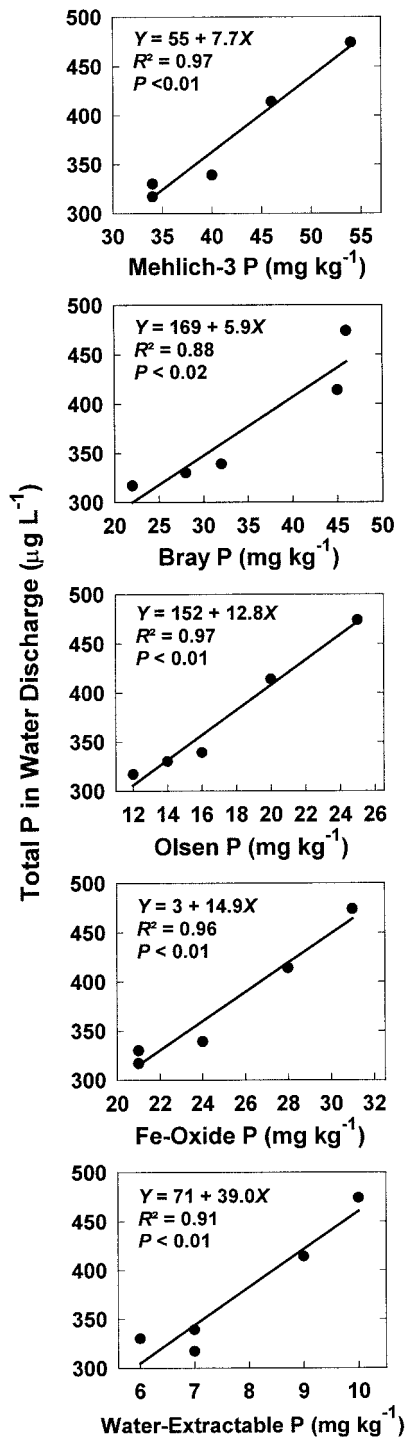


Fig. 2. Relationship between mean total P concentration in water discharge (August 1999–July 2000) and mean soil-test phosphorus (STP) measured with five soil P tests for five basins of the Clear Lake agricultural watershed.

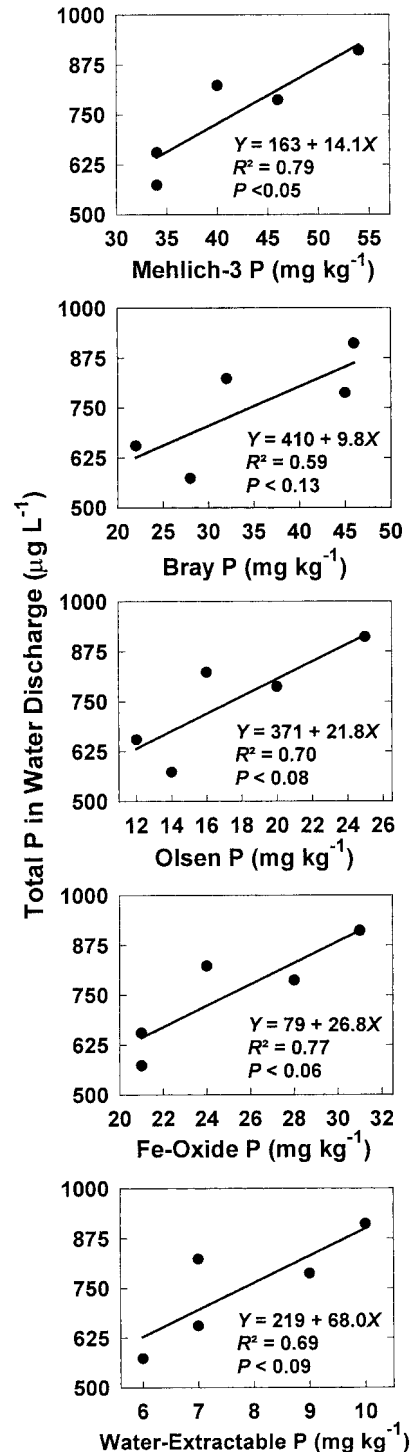


Fig. 3. Relationship between mean total P concentration in water discharge measured during 15 storm flow events and mean soil-test phosphorus (STP) measured with five soil P tests for five basins of the Clear Lake agricultural watershed.

tal soil P tests as a group were not better than the agronomic tests in describing relationships between water TP concentration and STP. The relationships for the M3P agronomic test and the FeP environmental test were the best defined for both sets of data. The relationship for the Olsen test was as good as those for the M3P and FeP tests for the annual means set, but was much weaker for the storm flow set, which is a result that cannot be explained with the methods used. The relationship for the BP test was the weakest for both sets of data. The weaker relationship for the BP test probably is explained by the underestimation of extractable P by this test in many high-pH,  $\text{CaCO}_3$ -affected soils (Mallarino, 1997).

Extrapolation of the regression lines in Fig. 2 suggests that mean annual water TP in water discharge would be 178 to 331  $\mu\text{g L}^{-1}$  for STP values considered optimum for corn and soybean production in Iowa (16–20  $\text{mg kg}^{-1}$  for the BP or M3P tests, and 11–14  $\text{mg kg}^{-1}$  for the OP test). This result and a predominance of both row-crop production and tillage in the watershed suggest that further adoption of soil conservation practices and reduced (or eliminated) P application to high-testing areas would probably be necessary to decrease TP loads. Although these practices would almost certainly reduce TP loads during storm-flow events, water TP concentrations during baseflow conditions were high and probably will not be immediately affected by management practices. Thus, it is unknown whether improved management practices would markedly decrease TP loads and within what period of time.

## CONCLUSIONS

Soil-test summaries and our STP surveys suggest that the area of high-testing soils in the Clear Lake agricultural watershed has tripled during the last four decades. Lake water monitoring data indicate that the TP concentration in Clear Lake has tripled during the last three decades. The results of this study showed high TP concentrations in water entering Clear Lake from the five monitored agricultural basins (65% of the agricultural area). The mean annual water TP concentration ranged from 275 to 474  $\mu\text{g L}^{-1}$  across five monitored basins and two years. The mean TP loads for two gauged basins across the two-year evaluation period were 1504 and 1510  $\text{g P ha}^{-1} \text{ yr}^{-1}$ . Loading rates were higher in a wet year (2262 and 2057  $\text{g P ha}^{-1}$ ) than in a dry year (759 and 951  $\text{g P ha}^{-1}$ ). Precipitation was 73% higher for the wet year but this difference corresponded to a 2.5-fold increase in P loading. While water samples were not collected from other basins comprising 35% of the agricultural area, similar STP concentrations and management practices suggest that P concentrations entering the lake from these areas would be similar. The STP survey showed that 46 to 83% of the fields (depending on the agronomic P test used) had STP levels for which P fertilization is not recommended for crop production.

The results showed that TP concentrations entering Clear Lake increased linearly with increasing STP. The environmental soil P tests as a group were not better

than the agronomic tests in describing relationships between water TP concentration and STP. The M3P agronomic test and the FeP environmental test consistently showed better relationships with mean annual water TP concentrations and water TP concentrations during storm flow events than the BP agronomic test and the WP environmental test.

The survey of management practices showed that P fertilizer or manure was being applied to much of the high-testing area of the watershed. Additionally, tillage practices known to increase the risk of soil and P loss from agricultural fields predominated in the watershed. Thus, the results suggest that use of a P index to assess the risk of P loss from fields, reducing P inputs to areas with above-optimum STP, and further adoption of improved soil conservation practices should improve water quality and the profitability of crop production in the Clear Lake watershed and other watersheds with similar conditions.

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## REFERENCES

- American Public Health Association. 1998. Standard methods for the examination of water and wastewater. 20th ed. APHA, Washington, DC.
- Atia, A.M., and A.P. Mallarino. 2002. Agronomic and environmental phosphorus testing for soils receiving swine manure. *Soil Sci. Soc. Am. J.* 66:1696–1705.
- Baker, J.L., K.L. Campbell, H.P. Johnson, and J.J. Hanway. 1975. Nitrate, phosphorus and sulfate in subsurface drainage water. *J. Environ. Qual.* 4:406–412.
- Brown, J.R. 1998. Recommended soils test procedures for the north-central region. North Central Regional Res. Publ. no. 221 (revised). Missouri Agric. Exp. Stn., Columbia.
- Chardon, W.J. 2000. Phosphorus extraction with iron oxide-impregnated filter paper (Pi test). p. 27–30. *In* G.M. Pierzynski (ed.) *Methods of phosphorus analysis for soils, sediments, residuals, and waters*. Southern Coop. Ser. Bull. 396. Available online at [http://www.soil.ncsu.edu/sera17/publications/sera17-2/pm\\_cover.htm](http://www.soil.ncsu.edu/sera17/publications/sera17-2/pm_cover.htm) (verified 30 July 2003).
- Chardon, W.J., R.G. Menon, and S.H. Chien. 1996. Iron-oxide impregnated filter paper (Pi test): I. A review of its development and methodological research. *Nutr. Cycling Agroecosyst.* 46:41–51.
- Clesceri, N.L., S.J. Curran, and R.I. Sedlak. 1986. Nutrient loads to Wisconsin lakes: Part I. Nitrogen and phosphorus export coefficients. *Water Resour. Bull.* 22:983–990.
- Correll, D.L. 1998. The role of phosphorus in the eutrophication of receiving waters: A review. *J. Environ. Qual.* 27:261–266.
- Downing, J.A., J.A. Kopaska, and D. Bonneau. 2001a. Clear Lake diagnostic report. Iowa Dep. of Nat. Resour., Des Moines.
- Downing, J.A., S.B. Watson, and E. McCauley. 2001b. Predicting Cyanobacteria dominance in lakes. *Can. J. Fish. Aquat. Sci.* 58:1905–1908.
- Eghball, B., and J.E. Gilley. 1999. Phosphorus and nitrogen runoff following beef cattle manure or compost application. *J. Environ. Qual.* 28:1201–1210.
- Environmental Systems Research Institute. 2003. ArcView GIS. ESRI, Redlands, CA.
- Gangbazo, G., A.R. Pesant, D. Cote, G.M. Barnett, and D. Cluis. 1997. Spring runoff and drainage N and P losses from hog-manured corn. *J. Am. Water Resour. Assoc.* 33:405–411.

- Gascho, G.J., R.D. Wauchope, J.G. Davis, C.C. Truman, C.C. Dowler, J.E. Hook, H.R. Sumner, and A.W. Johnson. 1998. Nitrate-nitrogen, soluble and bioavailable phosphorus runoff from simulated rainfall after fertilizer application. *Soil Sci. Soc. Am. J.* 62:1711–1718.
- Gaynor, J.D., and W.I. Findlay. 1995. Soil and phosphorus loss from conservation and conventional tillage in corn production. *J. Environ. Qual.* 24:734–741.
- Gburek, W.J., and A.N. Sharpley. 1998. Hydrologic controls on phosphorus loss from upland agricultural watersheds. *J. Environ. Qual.* 27:267–277.
- 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.
- Ginting, D., J.F. Moncrief, and S.C. Gupta. 2000. Runoff, solids, and contaminant losses with surface tile inlets draining lacustrine depressions. *J. Environ. Qual.* 29:551–560.
- Ginting, D., J.F. Moncrief, S.C. Gupta, and S.D. Evans. 1998. Interaction between manure and tillage system on phosphorus uptake and runoff losses. *J. Environ. Qual.* 27:1403–1410.
- Heathwaite, L., A.N. Sharpley, and W.J. Gburek. 2000. A conceptual approach for integrating phosphorus and nitrogen management at watershed scales. *J. Environ. Qual.* 29:158–166.
- Iowa Department of Natural Resources. 2000. Section 303(d) list of impaired waters [Online]. Available at <http://www.state.ia.us/epd/wtresrce/files/imp2002.htm> (verified 30 July 2003). Iowa DNR, Iowa City.
- Johnson, H.P., J.L. Baker, W.D. Schrader, and J.M. Lafren. 1979. Tillage systems effects on sediment and nutrients in runoff from small watersheds. *Trans. ASAE* 22:1110–1114.
- Johnson, A.H., D.R. Boudlin, E.A. Goyette, and A.M. Hedges. 1976. Phosphorus loss by stream transport from a rural watershed: Quantities, processes, and sources. *J. Environ. Qual.* 5:148–157.
- Jordan, T.J., D.L. Correll, and D.E. Weller. 1997a. Effects of agriculture on discharges of nutrients from coastal plain watersheds of Chesapeake Bay. *J. Environ. Qual.* 26:836–848.
- Jordan, T.J., D.L. Correll, and D.E. Weller. 1997b. Nonpoint source discharges of nutrients from Piedmont watersheds of Chesapeake Bay. *J. Am. Water Resour. Assoc.* 33:631–645.
- Jordan, T.J., D.L. Correll, and D.E. Weller. 1997c. Relating nutrient discharges from watersheds to land use and streamflow variability. *Water Resour. Res.* 33:2579–2590.
- Killorn, R., R. Voss, and K. Eik. 1990. Summary of soil test results. 1986–1989. Ext. Publ. ST-26 (revised). Iowa State Univ., Ames.
- Klatt, J.G., A.P. Mallarino, and B.L. Allen. 2002. Relationships between soil phosphorus and phosphorus in surface runoff and subsurface drainage. An overview of ongoing research. p. 183–189. *In* North-Central Extension-Industry Soil Fertility Conf. Proc., Des Moines, IA. 20–21 Nov. 2002. Vol. 18. Potash and Phosphate Inst., Brookings, SD.
- Klatt, J.G., A.P. Mallarino, J.A. Downing, and J.A. Kopaska. 2001. Soil P, management practices, and P delivery to water bodies: Iowa Clear Lake watershed [CD-ROM computer file]. *In* 2001 Annual meetings abstracts. ASA, CSSA, and SSSA, Madison, WI.
- Lemunyon, J.L., and R.G. Gilbert. 1993. The concept and need of a phosphorus assessment tool. *J. Prod. Agric.* 6:483–486.
- Longabucco, P., and M.R. Rafferty. 1989. Delivery of nonpoint-source phosphorus from cultivated mucklands to Lake Ontario. *J. Environ. Qual.* 18:157–163.
- Mallarino, A.P. 1997. Interpretation of soil phosphorus tests for corn in soils with varying pH and calcium carbonate content. *J. Prod. Agric.* 10:163–167.
- Mallarino, A.P., J.G. Klatt, B.L. Allen, J.L. Baker, and M. Camara. 2001. Relationship between soil P and P loss with runoff for Iowa benchmark soils [CD-ROM computer file]. *In* 2001 Annual meetings abstracts. ASA, CSSA, and SSSA, Madison, WI.
- Mallarino, A.P., B.M. Stewart, J.L. Baker, J.A. Downing, and J.E. Sawyer. 2002. Phosphorus indexing for cropland: Overview and basic concepts of the Iowa phosphorus index. *J. Soil Water Conserv.* 57:440–447.
- Menon, R.G., L.L. Hammond, and S.A. Sissingh. 1989. Determination of plant-available phosphorus by the hydroxide-impregnated filter paper (Pi) soil test. *Soil Sci. Soc. Am. J.* 52:110–115.
- Murphy, J., and J.P. Riley. 1962. A modified single solution method for determination of phosphate in natural waters. *Anal. Chim. Acta* 27:31–36.
- Nearing, M.A., R.M. Risse, and L.F. Rogers. 1993. Estimating daily nutrient fluxes to a large Piedmont reservoir from limited tributary data. *J. Environ. Qual.* 22:666–671.
- Pionke, H.B., W.J. Gburek, R.R. Schnable, A.N. Sharpley, and G.F. Elwinger. 1999. Seasonal flow, nutrient concentrations and loading patterns in stream flow draining an agricultural hill-land watershed. *J. Hydrol. (Amsterdam)* 220:62–73.
- Pionke, H.B., W.J. Gburek, A.N. Sharpley, and R.R. Schnabel. 1996. Flow and nutrient export patterns for an agricultural hill-land watershed. *Water Resour. Res.* 32:1795–1804.
- Potash and Phosphate Institute. 2001. Soil test levels in North America: Summary update. PPI/PPIC/FAR Tech. Bull. 2001-1. PPI, Norcross, GA.
- Pote, D.H., T.C. Daniel, D.J. Nichols, 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.
- 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.
- Sauer, T.J., T.C. Daniel, D.J. Nicholls, 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.
- Sawyer, C.N. 1947. Fertilization of lakes by agricultural and urban drainage. *J. New England Water Works Assoc.* 61:109–127.
- Sawyer, J.E., A.P. Mallarino, R. Killorn, and S.K. Barnhart. 2002. General guide for crop nutrient recommendations in Iowa. Publ. Pm-1688 (revised). Iowa State Univ. Ext., Ames.
- Schindler, D.W. 1977. Evolution of phosphorus limitation in lakes. *Science (Washington, DC)* 195:160–162.
- Sharpley, A.N. 1985. Depth of surface soil–runoff interaction as affected by rain fall, soil slope, and management. *Soil Sci. Soc. Am. J.* 49:1010–1015.
- Sharpley, A.N. 1991. Phosphorus extracted by iron-aluminum-oxide impregnated filter paper. *Soil Sci. Soc. Am. J.* 55:1038–1041.
- Sharpley, A.N. 1993. An innovative approach to estimate bioavailable phosphorus in agricultural runoff using iron oxide-impregnated paper. *J. Environ. Qual.* 22:597–601.
- Sharpley, A.N. 1995. Dependence of runoff phosphorus on extractable soil phosphorus. *J. Environ. Qual.* 24:920–926.
- Sharpley, A.N. 1997. Rainfall frequency and nitrogen and phosphorus runoff from soil amended with poultry litter. *J. Environ. Qual.* 26:1127–1132.
- Sharpley, A.N., T.C. Daniel, J.T. Sims, and D.H. Pote. 1996. Determining environmentally sound soil phosphorus levels. *J. Soil Water Conserv.* 51:160–166.
- Sims, J.T., A.C. Edwards, O.F. Schoumans, and R.R. Simard. 2000. Integrating soil phosphorus testing into environmentally based agricultural management practices. *J. Environ. Qual.* 29:60–71.
- Sims, J.T., R.R. Simard, and B.C. Joern. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. *J. Environ. Qual.* 27:277–293.
- USEPA. 1998. The quality of our nation's waters. EPA 841-S-97-001. USEPA Office of Water, Washington, DC.
- Vaithyanathan, P., and D.L. Correll. 1992. The Rhode River watershed phosphorus distribution and export in forest and agricultural soils. *J. Environ. Qual.* 21:280–288.
- Van der Paauw, F. 1971. An effective water extraction method for the determination of plant-available soil phosphorus. *Plant Soil* 34:467–481.
- Voss, R.D. 1968. Summary of soil test results. 1964–1967. Ext. Publ. ST-7. Iowa State Univ., Ames.
- Zhao, S.L., S.C. Gupta, D.R. Huggins, and J.F. Moncrief. 2001. Tillage and nutrient source effects on surface and subsurface water quality at corn planting. *J. Environ. Qual.* 30:998–1008.