Phosphorus Movement Through a Coastal Plain Soil After a Decade of Intensive Swine Manure Application

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ABSTRACT

Understanding the movement of phosphorus (P) in soils receiving heavy animal waste application is important for nonpoint-source pollution control. We investigated both P accumulation in soil and movement to ground water after 10 yr of intensive swine manure application (at atypical high rates) to a Coastal Plain spray field. Mehlich 3 phosphorus (M3P) was measured in soil cores collected in 1991 (following 4 yr of manure application) and 1997 (after 10 yr of application). Additionally, dissolved phosphorus (DP) was measured in ground water wells installed around the spray field. In both 1991 and 1997, the soil cores (0 to 15 cm) contained high contents of M3P (376–435 mg P kg^{-1}) indicating substantial P accumulation. After 10 yr of manure application, soil cores at a depth of 107 cm were also high in soil M3P contents (151 mg P kg^{-1}). Control soils were very low in M3P (<10 mg P kg^{-1}) throughout the soil profile. Ground water DP concentrations were initially (1992–1995) very low (<40 μg P L^{-1}), but by late 1996, DP concentrations in a few wells had increased substantially (40–480 μg P L^{-1}). In contrast, ground water control wells (1994–1998) were very low in DP (<40 μg P L^{-1}). Thus, the studied field, which received atypical high loading rates, had detectable leaching to shallow ground water as well as substantial P accumulation.

The land application of animal manure has the potential to cause environmental concerns because of P movement to nutrient-sensitive, surface water ecosystems. The continual application of large amounts of manure has contributed to soil P accumulation in excess of plant needs in several eastern Coastal Plain states (Sharpley and Halvorson, 1994; Sharpley et al., 1996; Sallade and Sims, 1997). Runoff from fields with high soil test P values can transport P-enriched sediments to surface water sources and increase aquatic P concentrations (Sharpley and Halvorson, 1994). Phosphorus enrichment of P-sensitive ecosystems contributes to eutrophication (Sims, 1993) and has been linked to *Pfiesteria* outbreaks in North Carolina coastal waters (Burkholder et al., 1997). *Pfiesteria* produces an aqueous chemical neurotoxin that is lethal to fish and may have a negative impact on the $6 billion fishing industry in North Carolina (Burkholder et al., 1997). Not surprisingly, water quality problems related to P enrichment are most severe in areas where water movement from soil to surface water is rapid and where soil P levels are excessive (Sims et al., 1998).

While the transport of P via runoff has been well established, questions have arisen about the effects of deep P leaching and transport by subsurface flow to surface water. Deep leaching of P through sandy soils that have received excessive amounts of animal manure has been reported (King et al., 1990; Kingery et al., 1994; Mozaffari and Sims, 1994; Eghball et al., 1996). Sims et al. (1998) speculated that P leaching was accelerated due to the sandy soils being easily P saturated and because of low concentrations of soil constituents primarily responsible for P retention (clays and Fe- and Al-oxides). If so, the continual application of animal manure to sandy soils in the Coastal Plain region may increase the potential of P leaching to shallow ground water and P transported by runoff.

North Carolina is experiencing P-related problems in aquatic ecosystems that have been linked to the land application of animal manure (Mallin et al., 1997; Paerl et al., 1998). These problems are partially due to a substantial amount of manure produced annually by the large swine population (9.8 million head; Nowlin, 1997). Much of the annual manure tonnage (55%) is produced in five Coastal Plain counties (Duplin, Sampson, Greene, Bladen, and Wayne), with Duplin County alone accounting for 22% (Hegg and Gerwig, 1997). Within these counties, there are substantial variations in the intensity of manure application from watershed to watershed and field to field (Stone et al., 1995). Investigating P movement at sites that have received animal waste with an intensity much greater than standard practice may provide insight into the problems of high accumulations of nutrients. Our objective was to evaluate the effects of long-term, intensive swine manure application on the soil accumulation and movement of P to ground water in a Coastal Plain soil.

MATERIALS AND METHODS

Watershed, Site, and Soil Description

The studied spray field is located in the Cape Fear River basin of the Middle Coastal Plain physiographic region of North Carolina. A description of the watershed's landscape geomorphic features, aquifers, mean rainfall, and major agricultural crops was presented by Stone et al. (1995) and Novak et al. (1998). The spray field is about 5 ha in size and has slopes ranging from 1 to 5%. Its dominant soil series is an Autryville loamy sand (loamy, siliceous, thermic Arenic Paleu-

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Abbreviations: DP, dissolved phosphorus; M3P, Mehlich 3 phosphorus; SF, spray field; TP, total phosphorus.

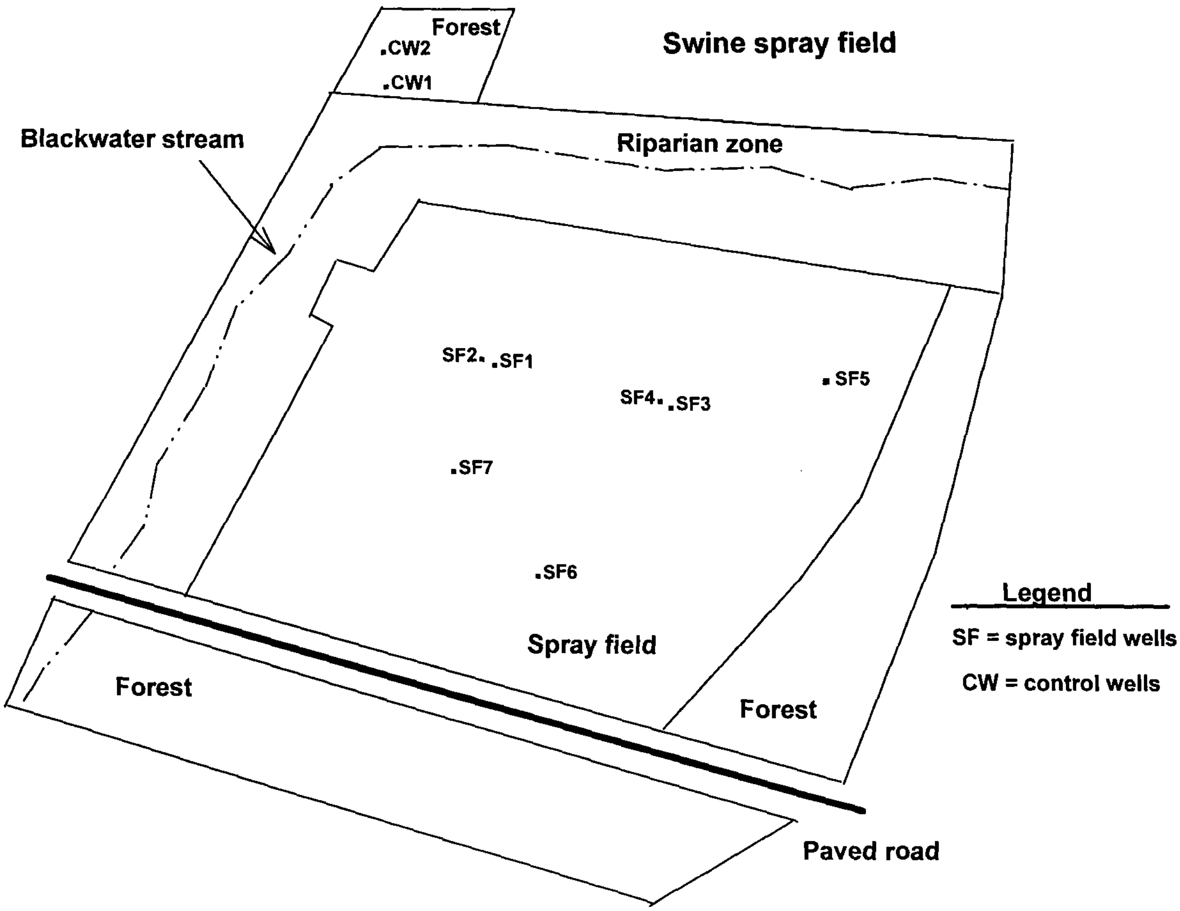

Fig. 1. Location of spray field and control wells (CW = control and SF = spray field).

dult). The spray field is bordered by a riparian zone that drains into a blackwater stream.

Swine production began at this location in August 1986 (John Bizac, Murphy Family Farms, personal communication, 1998), and swine effluent was applied in mid- to late-1987 to row crops grown in a 1-ha section of the field (Starr Maready, North Carolina Coop. Ext. Serv., personal communication, 1998). Stone et al. (1998) estimated (based on model simulations) that initial waste application rates to this area were approximately 2500 kg N ha^{-1}. If we assume that this was applied yearly from 1987 to 1989 and that the N to P ratio of swine manure is 4:1 (Sharpley and Halvorson, 1994), then approximately 625 kg P ha^{-1} yr^{-1} was applied. This amount seriously overloaded the 1-ha area with respect to N (Stone et al., 1998). The spray field was expanded in 1990 to 5 ha and planted with Coastal bermuda grass (*Cynodon dactylon* L.). The increase in spray field size would have reduced estimated application rates to 125 kg P ha^{-1} yr^{-1} from the early 1990s until 1997. A nutrient management plan for this spray field was adopted in January 1997 (Starr Maready, North Carolina Coop. Ext. Serv., personal communication, 1998). The plan was based on a 1600 swine yr^{-1} production that would generate approximately 334 kg N ha^{-1} yr^{-1} and approximately 83 kg P ha^{-1} yr^{-1}.

Well Installation and Water and Soil Collection

Seven ground water wells were installed between 1991 and 1994 in the spray field (SF, Fig. 1) as described by Stone et al. (1995). Two control wells (CW1 and CW2) that provided background P levels in ground water were also established across the stream at a site that has not received animal manure (Fig. 1). Ground water in the wells was sampled monthly from March 1992 to July 1998 using methods described previously (Novak et al., 1998).

Soil samples were collected in 1991 in 15-cm increments (0- to 183-cm deep) when wells SF1, SF3, and SF4 were installed. In 1997, sampling was repeated approximately 5-m from each well to insure minimal disturbance to the natural ground water recharge around these wells. These time periods (1991 and 1997) represent soil conditions after approximately 4 and 10 yr of swine manure application to the spray field. To corroborate that cores collected adjacent to the wells represent surface and subsurface P distribution within the spray field, 12 additional sites were sampled in 1997. Using an 8-cm diameter bucket auger, soil was collected in 1997 at intervals of 0 to 15, 15 to 45, and 45 to 90 cm. Soils were collected to deeper depths (90 to 135 and 135 to 183 cm) at 4 of the 12 sites to determine if deeper P leaching had occurred. Control soils for background soil P concentrations were also collected approximately 5-m away from the control wells using similar depth increments.

Phosphorus Measurements in Water and Soil Samples

All ground water samples were filtered (0.45 μm) to remove sediment and were analyzed for DP on a TRAACS 800 Auto Analyzer (Bran Lubbe, Elmsford, NY) using USEPA Method 365.1 (Kopp and McKee, 1983). The detection limit for DP using this method was 40 μg P L^{-1}.

Soils were extracted for plant-available P using Mehlich 3 reagent and quantified using colorimetric methods (Mehlich, 1984) with a Pharmacia LKB Biochrom (Cambridge, England)

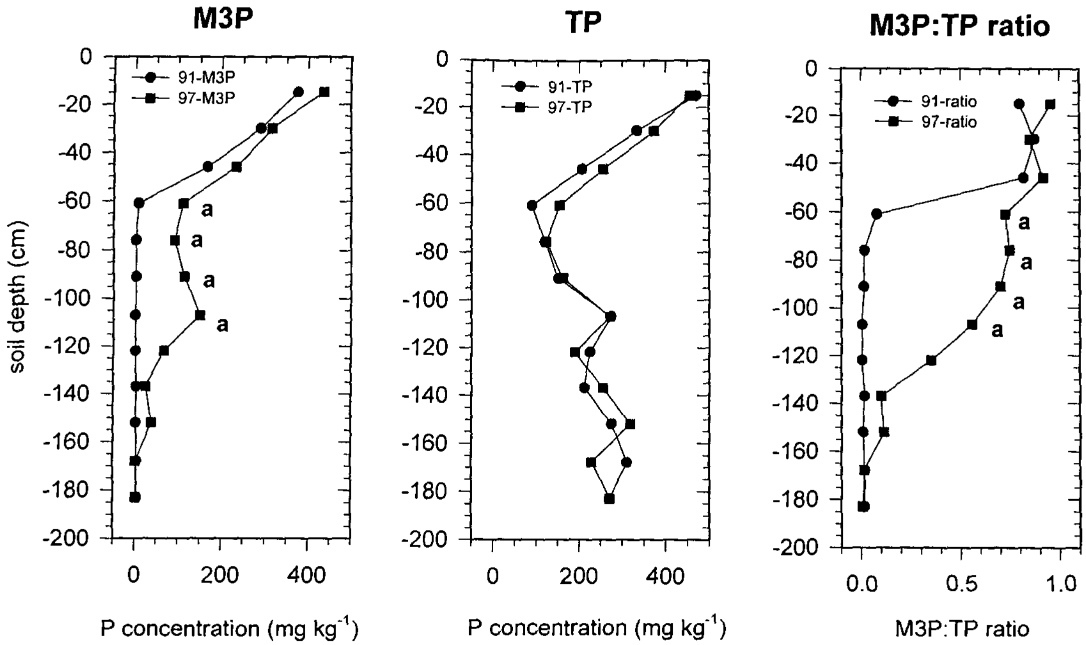

Fig. 2. Mehlich 3 phosphorus (M3P), total phosphorus (TP), and ratio of M3P to TP extracted from three soil profiles collected from the spray field in 1991 and 1997. Points followed by the letter *a* are significantly different at $P < 0.1$.

spectrophotometer. Total P was extracted using the sulfuric acid digestion method of Nelson and Sommers (1972), and TP was quantified using the ascorbic acid method (Greenberg et al., 1992) with a Technicon Autoanalyzer (Tarrytown, NY). The minimum detection limit of both forms (M3P and TP) for these methods was 0.5 mg P kg^{-1} soil. The 1991 vs. 1997 M3P, TP, and M3P to TP ratio were tested using a Students-*t* test at a 0.1 level of rejection. Regression analyses were conducted between rainfall amounts and the number of samples with DP detects and rainfall with the concentrations of DP in the wells. All statistical analyses were conducted with SigmaStat Version II software (SPSS, Richmond, CA). Ground water samples with a P detection limit below 40 μg P L^{-1} were assigned a 0 value for use in subsequent statistical analyses and plotting of results. The use of a 0 value will result in some wells having mean DP concentrations that are below the 40 μg P L^{-1} detection limit.

RESULTS AND DISCUSSION

Soil Phosphorus Distribution Patterns

The accumulation and leaching of P in the spray field were addressed by comparing both the M3P and TP concentrations and the M3P to TP ratio from soil cores collected in 1991 vs. 1997 (Fig. 2). In the three soil profiles collected in 1991, there were exceptionally high M3P values (mean = 376 mg P kg^{-1} soil) in the topsoil (0 to 15 cm) and high values (168 mg P kg^{-1}) extracted down to 46 cm. These soil test values are much higher than the range of soil M3P test values (30 to 100 mg P kg^{-1}) considered optimum for crop production (Gburek and Sharpley, 1998). This suggests that applications of swine manure between 1987 to 1991 were sufficient to contribute to the accumulation of excess P beyond plant needs and to leaching of P. Six years (1991 to 1997) of additional swine manure application to the spray field did not change the topsoil mean M3P concentrations appreciably ($P = 0.66$, 376 to 436 mg P kg^{-1}). Instead, the soil M3P concentrations increased with increasing depth, indicating P transport through the soil profile. For instance, the soil M3P concentrations at 61, 76, 91, and 107 cm in the 1991 and 1997 soil profiles were significantly different ($P < 0.1$) with the highest values detected in 1997. Similarly, the mean M3P to TP ratios between 1991 and 1997 at 61, 76, 91, and 107 cm were significantly different ($P < 0.1$). Both of these facts strongly indicate that significant amounts of M3P had leached to 107 cm in the sandy, Autryville soil profile.

The 12 additional soil profiles collected in 1997 confirmed that P accumulation and leaching had occurred across the whole spray field (Table 1). Similar to results from the three soil profiles collected in 1991 and 1997, high mean M3P concentrations were found in topsoils across the whole spray field (mean = 353 mg P kg^{-1}), and leaching of P had occurred to 90 cm (mean = 140 mg P kg^{-1}). The M3P to TP ratios through the top 90 cm were also similar to ratios in the three soil profiles collected in 1997 (Fig. 2). The high standard errors (SE) associated with some mean M3P and TP measurements (Table 1) could be related to variations in swine manure application rates across the spray field and to differences in sorption capacity of the soil profiles. Supporting this fact is the variation in the maximum depth of P leaching (M3P values measured at 90 vs. 152 cm) among soil profiles (Table 1 vs. Fig. 2).

Background soil P concentrations in two control soil profiles, located on a section of the swine farm that has not received swine manure effluent, were compared to evaluate management practices on soil P concentrations in the spray field. The control soils had very low mean M3P concentrations (Table 1, <10 mg P kg^{-1}). The mean TP concentrations below 15 cm were similar to soils in the spray field (Table 1). The ratio of M3P to TP in the control soils was very low (<0.05), indicating

Table 1. Spray field and control soils mean and standard error (SE) for Mehlich 3 P (M3P), total P (TP) and ratio of M3P to TP extracted by soil depth (spray field soil was collected in 1997, approximately 10 yr after swine manure application commenced).

	Spray field soils†					Control soils‡				
	M3P		TP		M3P to TP	M3P		TP		M3P to TP
Soil depth	Mean	SE	Mean	SE	Ratio	Mean	SE	Mean	SE	Ratio
cm	mg P Kg^{-1} soil									
0–15	353	28	404	27	0.87	7.5	2.5	203	78	0.04
15–45	195	17	231	20	0.84	5.0	0	179	76	0.03
45–90	140	44	213	40	0.66	2.5	2.1	65	1	0.04
90–135	10	3	189	48	0.05	1.0	0.5	237	10	0.004
135–138	4	1	124	40	0.03	1.0	0.4	141	15	0.007

† n = 12 for soil depths of 0–15, 15–45, and 45–90 cm and n = 4 for soil depths of 90–135 and 135–183 cm in spray field soil profiles.
‡ n = 2 for control soil profiles.

that the majority of the P in soil not treated with manure occurs in plant-unavailable forms.

In comparison with M3P concentrations in the control soils, application of swine manure for 10 yr at 83 to 625 kg P ha^{-1} yr^{-1} has resulted in the surface soils of the spray field having approximately 50 times the amount of M3P as the control soils. In fact, the calculated M3P concentration in surface soils (880 kg P ha^{-1}) of the spray field is 35 to 60 times higher than that considered optimum for row crop production in North Carolina (15 to 25 kg P ha^{-1}; North Carolina State University College of Agriculture and Life Sciences, 1994).

The buildup of plant available P in the spray field was due to the high manure application rates and the low P removal by the bermuda grass. Bermuda grass typically requires an annual fertilizer maintenance application of 39 kg P ha^{-1} yr^{-1} (North Carolina State University College of Agriculture and Life Sciences, 1994). Consequently, the P difference from the manure application (83 to 625 kg P ha^{-1} yr^{-1}) and grass fertilizer maintenance ranges from 44 to 586 kg P yr^{-1}. The large P imbalance between P applied vs. removal contributes to an accumulation of excess P in the surface soil. The P not retained by sorptive processes in the surface soil layer will eventually leach to deeper subsoil depths. Other studies have also shown that plant-available P will build up in sandy surface and subsurface soils that were intensively fertilized with animal manure for long periods (King et al., 1990; Kingery et al., 1994; Mozaffari and Sims, 1994). King et al. (1990) reported that 11 yr of swine manure effluent applied to a Paleudult soil in North Carolina resulted in a top soil test P value (Mehlich 1) between 225 and 450 mg P kg^{-1} and leaching to 75 cm. Mozaffari and Sims (1994) also reported very high surface soil test P values (Mehlich 1) and P leaching down to 60 to 75 cm in a sandy, Coastal Plain field treated with poultry manure in Delaware. Our results of P accumulation in the sandy, Autryville soil in this spray field are fairly comparable with these studies, but leaching of plant-available P in our study was deeper (90 to 152 cm).

The similar surface soil M3P concentrations between 1991 and 1997 in the spray field implies that the surface soil (0- to 15-cm deep) in this spray field is capable of retaining approximately 400 mg P kg^{-1} soil (as M3P). Based on this, a P sorption–desorption and leaching pathway is postulated. We propose that initially the sandy surface soils were capable of binding a finite amount of P from the manure. As additional manure was added, the surface soils became progressively more P saturated, allowing more P in the equilibrium solution to leach to deeper soil depths until these zones also became saturated. Leaching of P through the soil profile would continue until eventually reaching the shallow ground water. This explanation is plausible considering that Sharpley et al. (1993) reported that the P sorption capacity of an Oklahoma topsoil (0- to 30-cm deep) had substantially decreased after receiving heavy applications of poultry wastes. Similar findings of decreased P sorption capacity by soils treated with manure have been reported by Reddy et al. (1980) and Sharpley et al. (1991). These researchers postulated that the P binding sites in soil are exhausted by the continuous application of P from the manure.

Dissolved Phosphorus in Ground Water

Dissolved P was seldom detected in any wells between 1992 and 1994 (Fig. 3). However, the number of ground water P detections increased after 1996. The highest number of ground water samples with P detections (24) occurred in both 1996 and 1997. We pooled the well DP concentrations by year (Fig. 4) and found a similar pattern as shown in Fig. 3. The mean DP concentration between 1992 and 1994 was very low (<7 μg P L^{-1}). However, by 1996 a substantial increase in the mean DP concentration occurred. The highest pooled mean DP concentration (29 μg P L^{-1}) occurred in 1996. There was a decline in 1997 and 1998 in the pooled well mean DP concentration. This decline may be due to factors such as expansion of the spray field to 5 ha, manure application to other parts of the spray field, and adoption of a manure management plan in January 1997 that reduced application rates of P.

For comparative purposes, control wells CW1 and CW2 were established near the spray field to provide background DP concentrations in ground water sampled in an area not treated with animal manure (Fig. 1). From 1994 to 1998, only three DP detections (n = 82) were found in the two control wells and background DP levels were low (<5 μg P L^{-1}). Comparing the mean control well DP concentration (5 μg P L^{-1}) with the 1996 mean spray field well DP concentration (29 μg P L^{-1}) shows that the intensive application of manure to

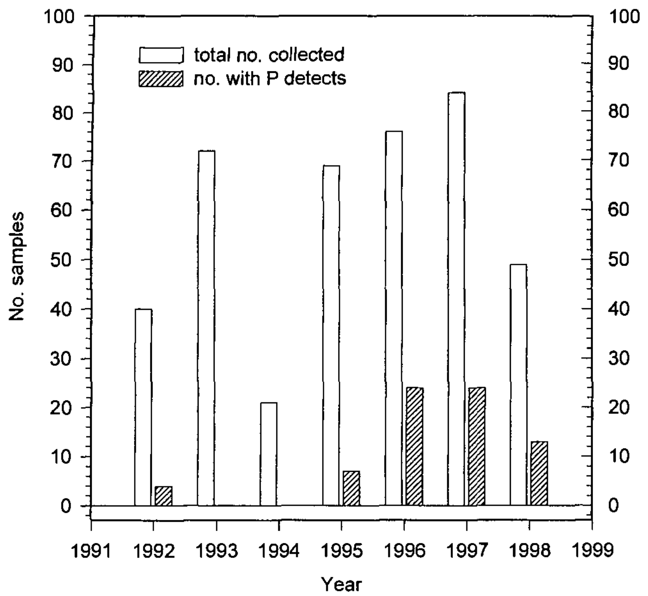

Fig. 3. Number of ground water samples collected and number with detectable DP concentration by year from the spray field wells.

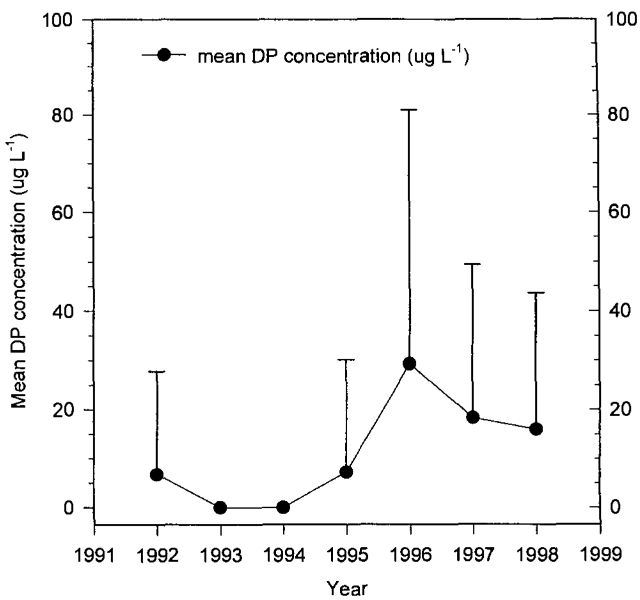

Fig. 4. Pooled mean DP concentrations by year in the spray field wells. Error bars are one standard deviation expressed in a positive direction.

the spray field has resulted in DP enrichment of ground water. In fact, the ground water has been enriched in DP by almost sixfold. This again confirms that DP has leached through the sandy soil profile and enriched the shallow ground water.

Among the seven wells placed in the spray field (Table 2), only two wells (SF4 and SF5) had frequent DP detects (50%), two wells (SF1 and SF3) had some detects (11%), and the remaining wells had few detects (5%). The SF4 and SF5 wells had the highest mean DP concentrations (40.5 and 30.6 μg P L^{-1}, respectively) when compared among the wells. These mean values are six to eight times the DP concentrations in the control wells and corroborate that DP has enriched the shallow ground water in the spray field.

There was a distinct time lag between initial manure application and P detection (Fig. 3) and enrichment of ground water by DP (Fig. 4). Swine manure application to this field began in mid- to late-1987, and by 1996 DP leachate was frequently detected in the ground water. This implies that a lag time of 9 yr was necessary, even under these intensive application conditions, for DP to reach and enrich the shallow ground water. Rainfall was postulated to influence the well P detection patterns, but subsequent regression analyses showed a poor relationship between rainfall and the number of detections and concentrations of DP in each well (r^2 between 0.002 and 0.28 and P values between 0.22 and 0.91). Variations in soil hydraulic properties, manure application management, plant P uptake, and P sorption–desorption processes probably confounded the relationship between rainfall and P detection.

Using the P leaching trends in 1991 and 1997 would assist in explaining the DP detection time lag found in the spray field wells. Leaching of M3P through the spray field soil profiles in 1991 was limited to a shallow soil depth (60 cm) and was not close to intercepting the shallow water table (Table 2, 2- to 4-m deep). Between 1991 and 1997, P leaching progressed to a deeper soil depth (between 60 and 152 cm) where P could contact and enrich the shallow ground water. This may explain why there was an increase in the number of DP detections in the spray field wells in 1996 (Fig. 3).

The concentrations and movement of P in the shallow ground water beneath the spray field is not typical for the watershed. As an example we obtained data from another swine operation in the watershed where the

Table 2. Well depth, water table mean height, number of samples analyzed, and dissolved phosphorous (DP) concentrations in wells by location.

Location	Well No.	Well Depth	Water table mean height†	No. of samples analyzed	No. of detects‡	Detects	DP§ Samples analyzed Mean	SE
		m	m	n	n	%	μg P L^{-1}	μg P L^{-1}
Spray field	SF 1	6.1	2.73	61	7	11	12.5	5.8
	SF 2	4.7	2.65	61	3	5	4.2	2.6
	SF 3	7.6	2.20	63	6	10	6.1	2.5
	SF 4	4.5	2.13	63	32	51	40.5	5.9
	SF 5	7.8	4.19	43	23	53	30.6	4.7
	SF 6	7.9	4.17	43	0	0	0	0
	SF 7	7.9	2.94	42	2	5	2.2	1.6

† Water table mean height relative to soil surface, monthly readings from 1993 to 1996.
‡ Reported number of detects greater than the DP detection limit (40 μg P L^{-1}).
§ Mean and SE calculated on a total sample analysis basis and using a 0 value when DP concentration was < the detection limit.

field received <75 kg P ha^{-1} yr^{-1} (Stone, unpublished data, 1998). Ground water monitored (1996 to 1998) for DP in several wells near the other spray field were low in DP (mean 13 μg P L^{-1}, n = 115; Stone, unpublished data, 1998). This mean DP ground water concentration is similar to the overall DP ground water concentration measured in approximately 100 wells across the watershed from 1991 to 1998 (mean 13 μg P L^{-1}, n = 2327; Stone, unpublished data, 1998).

CONCLUSIONS

In this study, which had atypically high application of waste water prior to the institution of current guidelines, we found potential water quality problems associated with P excesses. Phosphorus was found to accumulate in the soil profile and subsequently move into the shallow ground water beneath this spray field. Similar potential water quality problems are commonly recognized for excess N accumulation and movement to ground water. In fact, N application rates are the controlling factor for waste water applications in most states, and P is sometimes tacitly assumed to be a minor problem. Nonetheless, high application rates as reported in this study may overwhelm the considerable P sorptive capacity of many southeastern Coastal Plain soils and subsequently affect shallow ground waters.

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