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SPATIAL DISTRIBUTION OF SOIL PHOSPHORUS ACROSS SELECTED NEW YORK DAIRY FARM PASTURES AND HAY FIELDS

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Despite concerns that traditional soil sampling strategies are insufficient for assessing risk of surface water P contamination, there is no consensus that changes to these strategies, such as spatially explicit or discrete soil sampling within a field, represent enough of an improvement to justify the added cost. We conducted a study on four fields located on two dairy farms in Delaware County, New York, to characterize the spatial variability of P, Ca, Mg, Al, and Fe within two pastures and two hay fields at a 10-m scale and to interpret soil test P distribution relative to landscape and cultural practices. Pasture P distribution was characterized by various P "hot spots" that may be indicative of manure deposits by grazing animals. Hay fields contained large areas with elevated P relative to the rest of the field, with high-P areas occurring mostly near the gate and road where manure applications would be most accessible. Differences in soil properties associated with different soil map units also appear to partially explain P and Fe distributions in the mixed hay field. Results from a rainfall simulation study suggest that the use of a composite sampling strategy or an average P value for an entire field can potentially mask soil test P patterns such as those in the hay fields and result in an inaccurate estimation of P losses to surface waters. However, a composite sampling strategy may give a better estimation of P losses from pastures with "hot spots" because of the compositing effect whereby soluble P concentrations are affected by sorption processes that are controlled by low-P sediments. (Soil Science 2007;172:797–810)

Key words: Water quality, nutrient distribution, phosphorus spatial variability, manure management, phosphorus in pastures.

MANAGING P in soils is of concern to water quality protection, as losses of P in surface runoff can accelerate the eutrophication of surface waters (Carpenter et al., 1998; Correll, 1998). Most agronomic soil tests are well correlated with dissolved and sediment-bound P in surface runoff (Sharpley, 1995; Vadas et al., 2005; Penn et al., 2006), as well as with dissolved P in leachate (Beauchemin et al., 1998; Maguire and Sims, 2002). Thus, fate-and-transport models and P site assessment indexes typically include some measure of soil test P (STP) as an indicator of the potential for a soil to yield P to runoff (Lemunyon and Gilbert, 1993; Vadas and Sims, 2002; Daly et al., 2002; Johnson et al., 2005).

Despite the growing use of soil testing information for environmental interpretation, such as P loss potential, most soil sampling recommendations remain geared toward agronomic, rather than environmental, applications. For instance, sampling protocols for agricultural soils typically involve collecting and combining multiple samples from a field or a soil map unit within a field to create a single composite sample that represents an average condition for the inference area. This approach is efficient and

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parsimonious because it accounts for variability in soil nutrient content through mixing of spatially separate soil samples yet generates only one sample (as opposed to 10–20 samples) to be processed and analyzed for agronomic interpretation. However, this type of sampling protocol can mask differences in nutrient status related to management that may be important for environmental interpretation. There is growing concern that composite sampling may not be adequate to describe hot spots in agricultural landscapes that are of critical importance to nonpoint source pollution (Larson et al., 1997).

A variety of studies have examined spatial variability in STP (e.g., Raun et al., 1998; Solie et al., 1999; Daniels et al., 2001; Needelman et al., 2001; Juang et al., 2002). These studies point to large variability in STP across agricultural landscapes and within agricultural fields. For instance, Sauer and Meek (2003) conducted grid sampling of three pastures receiving periodic applications of poultry litter, finding that Mehlich-3 P (M3-P) concentrations were unevenly distributed, with values for individual samples ranging from 5 to 117 mg kg^{-1} in a field considered relatively low in STP. Values for individual samples ranged from 184 to 656 mg kg^{-1} in a field considered high in STP. However, not only are these types of spatial studies rare, most have focused on conventional row crops, and none have been designed to compare the differences in soil P spatial variability among pastures and hay fields.

Within-field spatial heterogeneity in STP undoubtedly affects a field's potential for P loss in runoff. Sharpley (1981) found that interactions in runoff water between dissolved P and suspended sediments were highly dynamic, resulting in changing concentrations of solution and sediment-bound P during single events. Thus, sediments suspended in overland flow that originate from different areas within a field can potentially adsorb or desorb P as runoff flows through the field. Maguire et al. (2002) found that interactions between different sediment sources can be nonlinear. By incubating mixtures of soil aggregates having different properties, they found that water-soluble P (WS-P) released by one aggregate fraction could be readsorbed by another aggregate fraction, potentially resulting in lower than expected solution P concentrations in surface waters.

Despite general concern that traditional soil sampling strategies may not provide sufficient insight into environmentally important variation in STP, there is no consensus that changes to these strategies, such as spatially explicit or discrete soil sampling within a field, represent enough of an improvement as to justify the added cost. Indeed, Sauer and Meek (2003) found that subsampling and composite sampling (simulated by obtaining the mean of the subsamples) produced average M3-P concentrations that did not differ substantially from those obtained from intensive grid sampling. Similarly, Needelman et al. (2001) concluded that simple mean STP values for individual fields were nearly as accurate as ordinary kriging across a watershed (global model) and ordinary kriging within fields (within-field model).

This study was conducted to elucidate issues surrounding the spatial variability of STP in pastures and hay fields. The objectives of this study were to (i) assess and compare the spatial variability of STP, Ca, Mg, Al, and Fe across two pastures and two conventionally managed hay fields; (ii) interpret nutrient distribution maps and consider landscape and cultural practices in an effort to explain STP distribution; and (iii) investigate the potential impact of observed variability on P concentrations in runoff.

MATERIALS AND METHODS

Site Description

The study was conducted in Delaware County, New York (42°21′N, 74°52′W), which is located in the Glaciated Allegheny Plateau and Catskill Mountain Region (Major Land Resource Area 140), a subregion of the Northeastern Forage and Forest Region (Soil Conservation Service, 1981). Farms in the watershed are predominantly dairy operations, averaging roughly 90 ha in area with approximately 75 milking cows. Typical crop rotation involves 3 years of silage corn followed by 5 years of alfalfa and/or mixed grasses. Many soils in the watershed possess fragipans that seasonally perch shallow water tables, resulting in variable source area hydrology (Needelman, et al., 2004); surface runoff occurs most frequently in the spring and fall (Walter et al., 2003).

Soil sampling took place on two dairy farms. A total of four fields were selected for study: two pastures, one alfalfa hay field, and one mixed hay field. The dominant species in the mixed hay field were orchard grass (*Dactylis glomerata*), white clover (*Trifolium repens*), and red clover (*Trifolium pratense*). The two pastures contained the same set of mixed grasses as the

hay field but were dominated by orchard grass. Before soil samples were taken (2001), the alfalfa field was in corn (*Zea mays*) production.

The fields were located on a Lewbeach silt loam soil map unit (coarse-loamy, mixed, semiactive, frigid Typic Fragiudepts), except for approximately half of the mixed hay field, which included a Willowemoc silt loam map unit (coarse-loamy, mixed, semiactive, frigid Typic Fragiudepts). Lewbeach soils are well drained, whereas Willowemoc soils are moderately well drained.

All four fields were routinely amended with lime (last application was in 2000). Pasture 1 did not receive any recent manure applications (other than direct deposits from grazing cattle), whereas Pasture 2 historically received regular manure applications before it was converted from a hay field into a pasture as part of an intensively managed rotationally grazed system. This conversion from hay to pasture took place 2 years before sampling. Both hay fields received regular dairy manure applications.

Soil Sampling, Preparation, and Chemical Analysis

Each field was sampled by taking duplicate soil core samples (0–5 cm) at 100 georeferenced sites on a 10-m grid. Soil samples were air-dried, ground, and sieved (2 mm) before analysis. Individual soil samples (200 from each field) were extracted for P with Mehlich-3 and water. Mehlich-3 extractions were conducted by shaking 2 g of air dried soil with 20 mL of Mehlich-3 solution (0.2 *M* CH_3COOH + 0.25 *M* NH_4NO_3 + 0.015 *M* NH_4F + 0.13 *M* HNO_3 + 0.001 *M* EDTA) end over end for 5 min followed by filtration with Whatman No. 1 paper (Mehlich, 1984). All Mehlich-3 extracts were analyzed for P, Al, Fe, Ca, and Mg by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Water extractions were conducted by shaking 2 g of air dried soil with 20 mL of deionized water end over end for 1 h, followed by centrifuging 1800*g* at 5 min) and filtering with 0.45-μm membranes. All water extracts were analyzed for P by the Murphy-Riley colorimetric method (Murphy and Riley, 1962).

Simulated Rainfall Study

An indoor rainfall simulation study was conducted to investigate runoff dissolved reactive P (DRP) concentrations from boxes containing different combinations of surface soils (0–20 cm) with similar properties except for substantially different M3-P concentrations. The two soil materials were collected from the U.S. Department of Agriculture–Agricultural Research Services FD-36 watershed, a site of intensive P investigation located in south central Pennsylvania. The selected soils were both from Berks channery loam soils (loamy-skeletal, mixed, active, mesic Typic Dystrudepts) with M3-P values of 220 (high P) and 18 (low P) mg kg^{-1}. The surface horizon of the Berks soils are of similar texture (silt loam) to the Lewbeach and Willowemoc soils examined in the field study. Soils were air-dried and coarsely sieved (1.4 cm) before mixing. To ensure homogeneity of the individual soils, the effectiveness of mixing was evaluated by conducting M3-P extraction on 6 subsamples from each soil and determining the coefficient of variation (CV = S.D. divided by mean M3-P concentration) for each soil. For both soils, the CV was less than 0.05. After mixing, soils were packed into shallow runoff boxes (200 cm long, 100 cm wide, and 5 cm deep) to achieve an approximate bulk density of 1.3 to 1.5 g cm^{-3}.

Treatments "high" (H) and "low" (L) each consisted of pure high- and low-P soils within each box, respectively. However, treatments "low/high" (L/H) and "high/low" (H/L) consisted of both the high- and low-P soils within the same box, with one soil occupying the upslope half and the other soil occupying the downslope half. For convention, the first letter of a treatment identifies the soil placed in the upslope portion of a runoff box. Thus, the L/H treatment was prepared by dividing the runoff box in the middle with a plastic divider and placing low-P Berks soil on the upslope side and high-P Berks soil on the downslope side. After both soils were poured into place, the plastic divider was removed. Preparation for the H/L treatment was the same except that high-P Berks soil was placed on the upslope side and low-P soil was placed on the downslope side. All treatment combinations were replicated four times.

All rainfall simulations were conducted using the National Phosphorus Research Project Rainfall Simulator Protocol (Kleinman and Sharpley, 2003). Rainfall was applied with a single TeeJet 2HH-SS50WSQ nozzle (Spraying Systems Co., Wheaton, IL) located at 2.5 m above the soil to reach terminal velocity. The rainfall simulator itself consists of a 3 × 3 × 3-m aluminum frame. Rainfall was applied with a uniformity greater than 85% at an average intensity of 75 mm h^{-1} until 30 min of runoff

was obtained. Local groundwater was used as the water source for the simulator. Runoff was collected in metal gutters at the downslope edge of each runoff box and collected in plastic containers. A runoff sample was collected from each container after thorough agitation to resuspend and mix sediments. Dissolved reactive P was determined on filtered samples (0.45 μm) and measured using Murphy and Riley's (1962) colorimetric method.

Statistical Analysis

To determine the degree of spatial autocorrelation within each field, isotropic semivariograms were created (hereafter referred to as *variograms*) for all variables using S-Plus S+SpatialStats (MathSoft, 1996, 1997). For the P variables, the nugget variance (variance at zero distance) was calculated as half the mean squared difference between adjacent samples. The nugget represents measurement error plus spatial variation at distances smaller than the shortest sampling interval. For the P variables, the mean semivariance of each small plot was added to the variograms.

Partial Mantel tests are widely used in ecology to correct for spatial autocorrelation effects when determining the correlation between variables (Legendre and Fortin, 1989; Urban et al., 2002). The partial Mantel test, an extended form of the simple Mantel test, estimates partial correlation. This test can be run using three or more dissimilarity matrices in a multiple regression framework (Smouse et al., 1986). The magnitude of correlation independent of spatial autocorrelation is estimated using the Mantel r statistic, which is bounded between -1 and 1 and is comparatively small, even for statistically significant variables. A permutation test is used to calculate the significance of Mantel r, because the elements of a distance matrix are not independent. During the permutation test, the rows and columns of the distance matrices are rearranged to recompute the Mantel r.

Routines to run the partial Mantel test in S-Plus were obtained from Urban et al. (2002). Partial Mantel tests were carried out separately for independent variables M3-P and WS-P using dependent variables Ca, Al, Fe, and Mg (in each case including geographic distance). The statistical significance of Mantel r was estimated using 10,000 permutations. Dependent variables were added in a procedure analogous to forward stepwise multiple regression. The variable with the largest individual partial Mantel r was added first; additional variables to add were chosen by determining which variable most decreased the P value of the overall partial Mantel test. All means, CV analysis, and correlation procedures were determined using the standard procedures of SAS Institute (1998). Data were tested for normality (Kolmogorov-Smirnov statistic, $n > 50$) and "skewness" by the UNIVARIATE procedure of SAS. Results of the normality test indicated that two fields (Pasture 2 and alfalfa) failed with regard to M3-P soil concentrations. However, based on the "skewness" parameter and visual observation of the normal probability plots and box plots, no data transformation for those two fields was conducted.

RESULTS AND DISCUSSION

Mean Soil P Concentrations

All fields possessed elevated soil P levels, despite variable land use and management histories (Table 1). Mean M3-P concentrations of all four fields exceeded the crop requirement threshold of 50 mg P kg^{-1} identified by Beegle (2002), and the means from three of the fields exceeded the water quality protection threshold of 150 mg kg^{-1} proposed by Sims et al. (2002). The elevated M3-P concentrations primarily reflect historical application of manure on the fields. The lowest M3-P concentrations were found in the pasture soils, presumably because they had not received manure applications (other than deposits from grazing dairy cows) for at least 2 years before sampling. Mehlich-3 P values were significantly correlated to soil WS-P concentrations for all fields (Pasture 1, Pasture 2, alfalfa, and hay fields had r values of 0.89, 0.72, 0.65, and 0.50, respectively).

Soil P Spatial Autocorrelation and Distribution

Autocorrelation indicates that points closer together are more similar than points further apart (i.e., points are spatially dependent, and there are real distribution patterns). In general, M3-P for Pasture 1 and both hay fields exhibited strong autocorrelation and Pasture 2 exhibited moderate autocorrelation (Fig. 1), indicating that the data for all fields are spatially dependent and are not random at the 10-m grid sampling scale. Although Pasture 1 shows strong spatial dependency, the two hay fields show greater spatial dependence compared with the pastured fields, as indicated by the smooth slope approaching the sill. These results somewhat

TABLE 1

Mean, minimum, maximum, CV, and skewness for M3-P and WS-P among 100 samples collected at each site

Site	M3-P					WS-P				
	Mean	Minimum	Maximum	CV	Skewness	Mean	Minimum	Maximum	CV	Skewness
	(mg kg^{-1})									
Pasture 1	138	39	586	43	4.4	17.5	3.4	124.6	70	5.61
Pasture 2	156	0	346	26	0.12	11.8	2.4	34.5	62	0.98
Alfalfa hay	192	124	366	21	0.86	16.4	5.0	36.1	35	0.59
Mixed hay	187	113	279	21	0.71	16.2	6.2	36.2	45	0.92

differ from Sauer and Meek (2003), who noted spatial dependence of M3-P concentrations in only one of two pastures. However, Sauer and Meek (2003) may not have identified autocorrelation because of the larger grid sampling scale (30 m) used in their study.

The nugget values (y axis intercept) were generally greater for the pastures than for the hay fields, indicating greater short-range variability. The Pasture 1 field had a greater sill value (distance at which variance reaches a maximum) than did the other fields, whereas the alfalfa hay had a lower sill than the other fields (Fig. 1). Phosphorus distributions across the two pastures in our study indicated "hot spots" at which M3-P was elevated at several random points (Fig. 2). This was more evident in Pasture 1 than Pasture 2 probably because of the more recent history of manure applications to Pasture 2. In comparison, the higher degree of spatial dependence and lower short- and long-range variability in the hay fields was evident in observation of M3-P

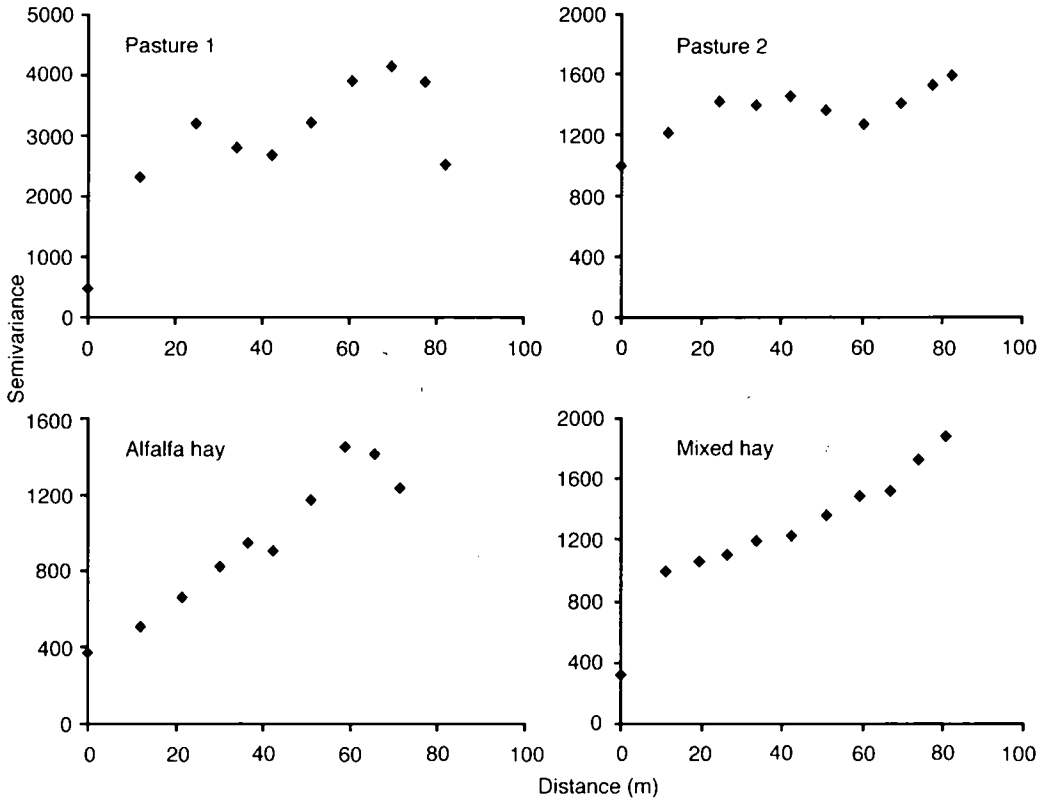

Fig. 1. Variograms for M3-P concentrations among 100 soil samples taken on a 10-m grid from four sites: Pasture 1, Pasture 2, alfalfa hay, and mixed hay.

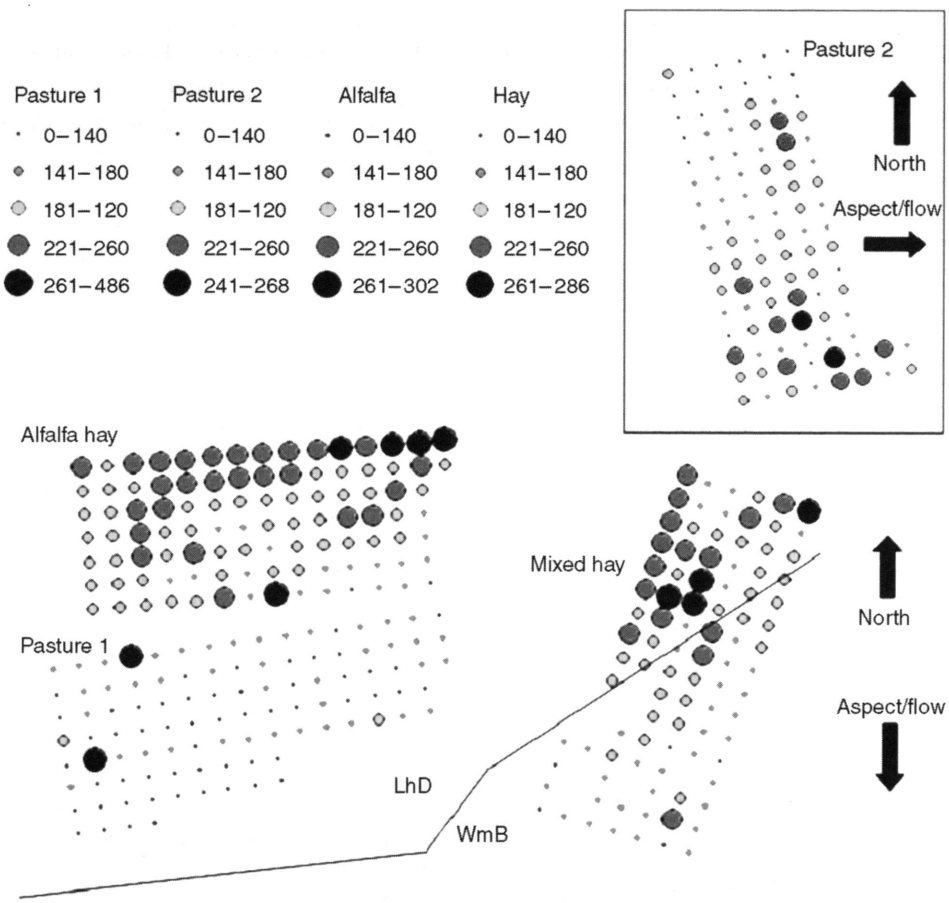

Fig. 2. Soil M3-P concentrations (mg kg^{-1}) among 100 samples taken on a 10-m grid from four sites: Pasture 2, alfalfa hay, Pasture 1, and mixed hay. Note that Pasture 2 is located on a different farm than the Pasture 1 and hay sites. The solid line indicates change in soil map unit: LhD = Lewbeach 18%–35%; WmB = Willowemoc 2%–5% slope.

distribution. In contrast to the "hot spot" patterns in the two pastures, P distributions across the two hay fields showed large areas that generally have higher or lower M3-P (Fig. 2). For example, M3-P concentrations in the alfalfa hay field tended to be greatest at the north end of the field, with concentrations decreasing toward the south side (especially the southeastern corner). Similarly, M3-P concentrations across the mixed hay field were highest at the north end of the field and decrease toward the south.

In general, variograms for WS-P were similar to those for M3-P, which is not surprising because these values were significantly correlated for each field (Fig. 3). Variograms for all fields exhibit spatial autocorrelation, although this trend is weak for the Pasture 2 field (apart from the nugget value). The alfalfa hay field exhibited autocorrelation for WS-P that was intermediate between the Pasture 1 and the mixed hay fields. As observed for M3-P, the variogram for WS-P in Pasture 1 was not smooth and possessed the greatest nugget and sill value, indicating greater short- and long-range variability. The alfalfa hay field had the lowest semivariance, as it did in the M3-P variograms. The nuggets were substantially lower than the other data points in these variograms; this differs from the nuggets of the Pasture 2 and alfalfa hay fields for the M3-P variable. Spatial patterns of WS-P distribution (Fig. 4) reflect the characteristics of the variograms and approximate the respective spatial patterns of M3-P distribution (Fig. 2).

Interpreting Soil P Variability

Spatial trends in soil P were most likely a function of feces deposition and manure application history within individual fields. As such, "hot spots" in the pastures can be attributed to the distribution of feces by pastured cattle, whereas the clustering of P in the alfalfa and hay fields can be attributed to manure application practices (Figs. 1, 2, 3, and 4). For instance, a reasonable explanation for the systematic clustering of P at the north end of the alfalfa field is that this area is relatively flat and adjacent to the gated entrance to this field from the road leading from the dairy barns (Fig. 2). A similar explanation can be applied to the cluster of high M3-P samples located in the northwest corner of the mixed hay field (Fig. 3). The distinct split in WS-P concentrations evident in Fig. 4 is associated with a former field boundary. Until 1998, the hay field was divided into two separate fields with different manure management histories. Again, the two pastures showed less systematic P distribution (Figs. 1, 2, 3, and 4) and greater variability (Table 1) compared with the hay fields. Areas of elevated P concentrations in the pastures are associated with zones of pastured cattle concentration, such as around areas of preferred pasture grasses, shade, or water (Matthews et al., 1994).

In addition to cultural practices, soil differences explain some of the trends in the spatial distribution of P in the mixed hay field. As illustrated in Fig. 2, the M3-P distribution within the mixed hay field is systematically higher in the northwestern corner, coinciding with the transition from the Lewbeach map unit (northwest) to Willowemoc map unit (southeast). Notably, WS-P does not exhibit the close tie with soil map unit (Fig. 4). There are several possible explanations for the association between M3-P and soil map unit within the mixed hay field. Figure 5D indicates that the distribution of soil Mehlich-3 Fe is the inverse of M3-P (i.e., the well drained northern side has higher P and less Fe compared with the southern side, which

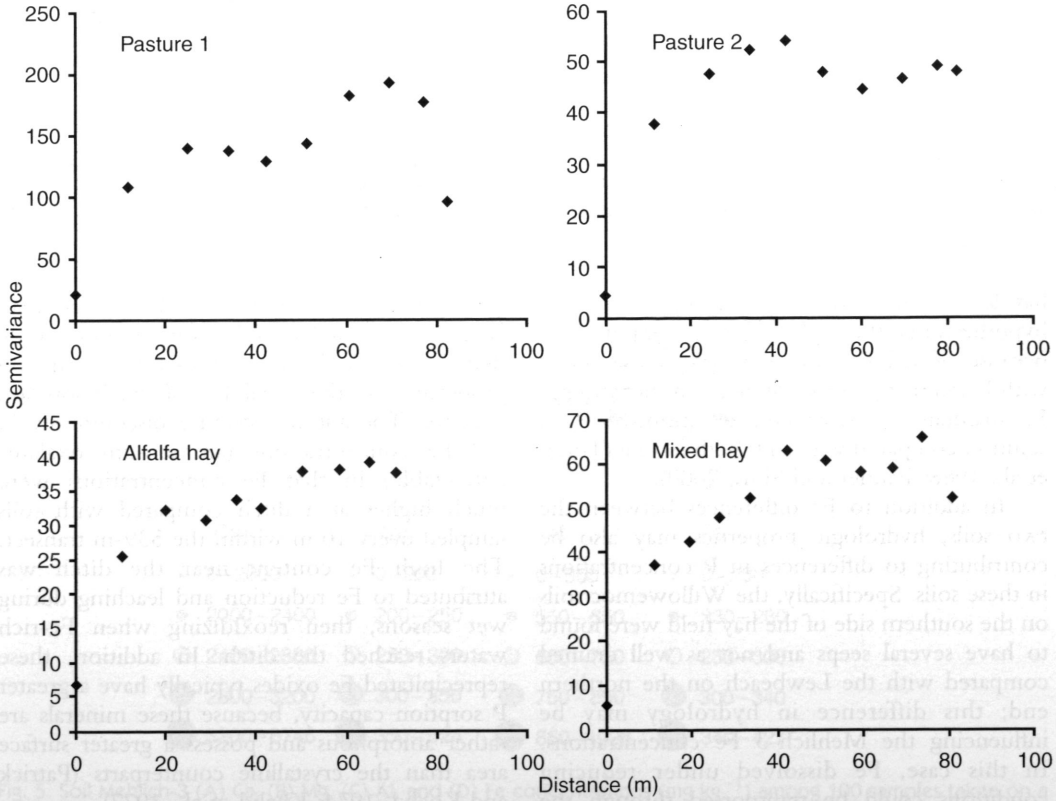

Fig. 3. Variograms for WS-P concentrations among 100 soil samples taken on a 10-m grid from four sites: Pasture 1, Pasture 2, alfalfa hay, and mixed hay.

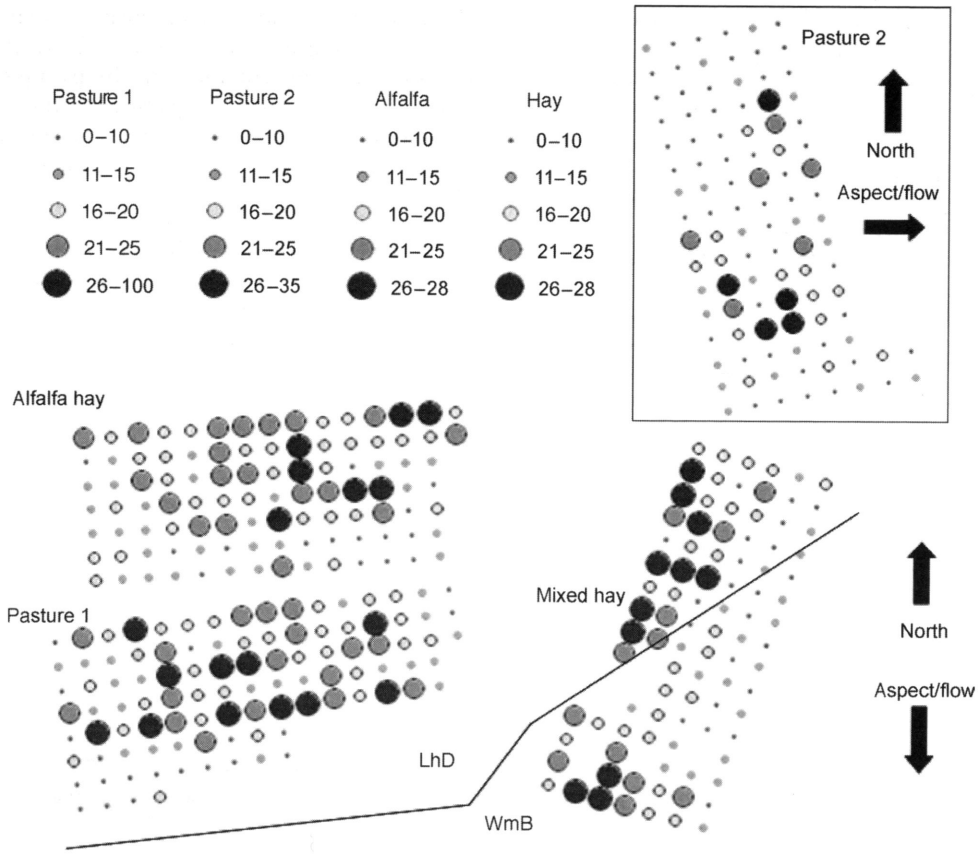

Fig. 4. Soil WS-P concentrations (mg kg^{-1}) among 100 samples taken on a 10-m grid from four sites: Pasture 2, alfalfa hay, Pasture 1, and mixed hay. Note that Pasture 2 is located on a different farm than the Pasture 1 and hay sites. The solid line indicates change in soil map unit: LhD = Lewbeach 18%–35%; WmB = Willowemoc 2%–5% slope.

has less P and more Fe). In support of the hypothesis that the "split" in P concentrations is because of soil Fe, soils that are not saturated with P and that possess a higher concentration of Fe maintain a lower concentration of P in solution compared with soils with less Fe (Toreu et al., 1988; Pautler and Sims, 2000).

In addition to Fe differences between the two soils, hydrologic properties may also be contributing to differences in P concentrations in these soils. Specifically, the Willowemoc soils on the southern side of the hay field were found to have several seeps and not as well drained compared with the Lewbeach on the northern end; this difference in hydrology may be influencing the Mehlich-3 Fe concentrations. In this case, Fe dissolved under reducing conditions could be transported through the subsoil and reoxidized at the seeps located on the southern side of the mixed hay field, resulting in an accumulation of Fe. Lookman et al. (1996) noted a similar condition in a study that investigated the relations between soil properties and the variability of soil P sorption capacity. The authors found a discontinuity in soil Fe concentrations (ammonium oxalate-extractable) in that Fe concentrations were much higher at a ditch compared with soils sampled every 10 m within the 539-m transect. The high Fe content near the ditch was attributed to Fe reduction and leaching during wet seasons, then reoxidizing when Fe-rich waters reached the ditch. In addition, these reprecipitated Fe oxides typically have a greater P sorption capacity, because these minerals are rather amorphous and possess a greater surface area than the crystalline counterparts (Patrick and Khalid, 1974; Khalid et al., 1977).

The partial Mantel test is a useful method for investigating potential influences of soil

properties and cultural practices (in this case, manure applications). Partial Mantel tests were conducted on each field data set to determine if Mehlich-3-extractable Ca, Mg, Al, and Fe were distributed similarly to P. In addition, simple correlation analysis between P and the other elements also proved to be insightful. Results of the partial Mantel tests indicated that soil M3-P was positively correlated (distributed) with Ca, Mg, or both among Pastures 1 and 2 and the alfalfa hay field (Table 2). Results of the simple correlations were similar (Table 3). This may be an effect of previous manure applications, because dairy manure will typically increase the Ca and Mg content of a soil while simultaneously increasing P content (Kalbasi and Karthikeyan, 2004). The close relationship of P with Ca and Mg may also indicate the presence of Ca and Mg phosphates. The formation of Ca and Mg phosphates are likely under this situation because

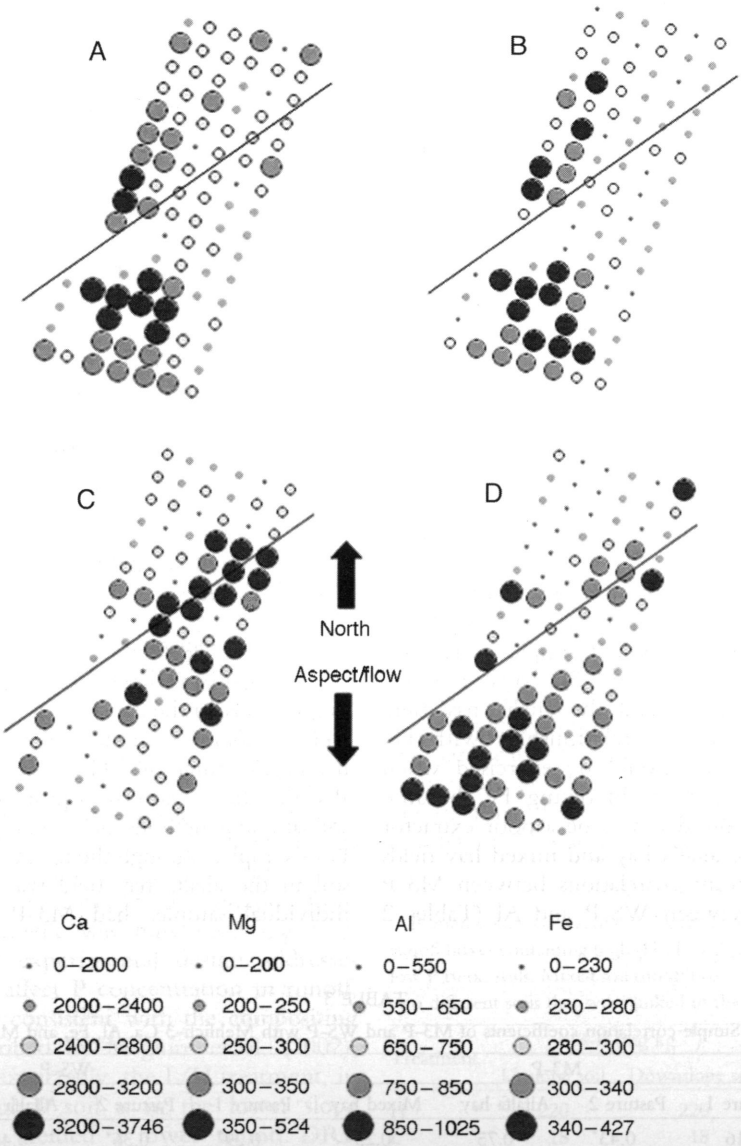

Fig. 5. Soil Mehlich-3 (A) Ca, (B) Mg, (C) Al, and (D) Fe concentrations (mg kg^{-1}) among 100 samples taken on a 10-m grid from the mixed hay field site. The solid line indicates change in soil map unit: soils on the northern side of the solid line are in a Lewbeach silt loam unit (18%–35% slope), whereas soils on the southern side are in a Willowemoc silt loam unit (2%–5% slope).

TABLE 2

Mantel r values from spatial correlation of M3-P and WS-P with Mehlich-3 Ca, Al, Fe, and Mg

Element	M3-P				WS-P			
	Pasture 1	Pasture 2	Alfalfa hay	Mixed hay	Pasture 1	Pasture 2	Alfalfa hay	Mixed hay
Ca	0.08	0.17*	0.54*	0.08	0.21*	0.11	0.13*	0.09
Al	−0.01	−0.02	0.11	−0.15*	−0.02	−0.02	−0.07	0.24*
Fe	−0.06	0.00	0.08	−0.03	−0.07	0.29*	0.13*	0.17*
Mg	0.87	0.00	0.57*	0.00	0.85*	0.12	0.13	0.17

*Significant r value at $P = 0.01$.

these fields have a history of consistent (and recent) dolomitic lime applications. Nair et al. (1995) found that Ca- and Mg-associated P was the dominant soil P fraction (~70% of total P) among active and abandoned dairy systems in South Florida's Lake Okeechobee watershed. In their study, P forms were estimated using a chemical fractionation method. For the soils used in this study, Penn and Bryant (2006) found that 40 of the more P-concentrated soils possessed Ca and Mg phosphates, as determined by chemical speciation modeling. The authors attributed this observation to fact that these soils regularly received dairy manure and/or lime (calcium carbonate) additions. The partial Mantel test also showed that WS-P was distributed with Mg and/or Ca in Pasture 1 and the alfalfa hay field (Table 2). Among simple correlations, Ca and Mg were well correlated with WS-P in all fields (Table 3).

Several fields also had significant correlations between P and Mehlich-3-extractable Fe based on partial Mantel tests and simple correlation coefficients (Tables 2 and 3). Most notably, WS-P in Pasture 2 and the alfalfa hay field showed the strongest relationships with Fe. However, caution should be exercised when making interpretations involving Fe, because Mehlich-3 is considered to be a poor extractor of soil Fe. The alfalfa hay and mixed hay fields showed significant correlations between M3-P and Al and between WS-P and Al (Tables 2 and 3). For the mixed hay field, soil Al was negatively correlated with M3-P (based on Mantel) and WS-P (based on simple correlations) (Tables 2 and 3). Soils containing high levels of Al tended to possess lower concentrations of extractable P. As previously explained with Fe, this is expected because soils with high levels of Al maintain low concentrations of P in solution until the soils become saturated with P (Pautler and Sims, 2000; Penn et al., 2005). However, according to the Mantel correlations, WS-P was positively correlated with soil Al. The reason for this discrepancy is unknown.

Figures 4 and 5A-C illustrate that the WS-P distribution at the mixed hay field was very similar (i.e., positively correlated) with Ca and Mg distribution, yet opposite (negatively correlated) of Al distribution. Again, there are likely many factors contributing to these observations, such as natural variability in soil Al content and manure and lime application history.

Implications of Variability

The spatial variability of soil P has significant implications for the transport of P to surface waters and our ability to model and predict losses of P from agricultural soils. The large variability in soil P within fields can pose a problem to traditional soil sampling methods such as composite sampling. For example, although the mean concentration of soil in the alfalfa hay field was 192 mg kg^{-1}, individual samples had M3-P concentrations

TABLE 3

Simple correlation coefficients of M3-P and WS-P with Mehlich-3 Ca, Al, Fe, and Mg

Element	M3-P				WS-P			
	Pasture 1	Pasture 2	Alfalfa hay	Mixed hay	Pasture 1	Pasture 2	Alfalfa hay	Mixed hay
Ca	0.16	0.43*	0.75*	0.25	0.29*	0.36*	0.44*	0.39*
Al	0.06	−0.12	0.36*	−0.02	−0.22	−0.23	−0.04	−0.55*
Fe	0.06	−0.24	−0.03	−0.32*	−0.08	−0.59*	−0.36*	−0.04
Mg	0.87*	0.65*	0.66*	0.15	0.86*	0.50*	0.40*	0.47*

*Significant r value at $P = 0.01$.

ranging from 141 to 260 mg kg^{-1}. As P in runoff is correlated with M3-P (Pote et al., 1996; Vadas et al., 2005; Penn et al., 2006), runoff originating from different parts of a field can be expected to vary widely in P concentration. Furthermore, compositing soil samples can produce estimates of STP that differ significantly from the arithmetic mean of the individual cores used to create the composite sample.

The compositing effect was described by Maguire et al. (2002) as the phenomenon that when two soil fractions are mixed, the measured WS-P is always less than the average WS-P (i.e., the average WS-P of the two individual soils), indicating that WS-P released by one aggregate fraction could be readsorbed by another. The authors concluded that this readsorption of P may result in surface water P concentrations less than expected and attributed it to the P buffering capacity of soil. As runoff containing dissolved P and sediment moves across a field, the dissolved P can readsorb onto soil or sediment, whereas the suspended sediments can desorb or adsorb P, depending on the solution concentrations and P buffering capacity of the sediment. Therefore, as runoff flows downhill (from north to south in Fig. 3) from the alfalfa hay field to Pasture 1, runoff P concentrations originating from the top of the alfalfa hay field would be elevated (due to higher soil P concentrations) but would be potentially readsorbed as that runoff encounters soils and sediment at lower parts of the field as well as moving across Pasture 1.

This effect is evident upon observation of the simulated runoff experiment results in which two soil materials with very different M3-P contents (high = 220 mg kg^{-1} and low = 18 mg kg^{-1}) were placed together but unmixed in the same runoff boxes (Table 4). Whereas the arithmetic average DRP concentration in runoff from the H and the L treatment was 0.17 mg L^{-1}, the observed concentration from the H/L treatment was only 0.09 mg L^{-1}. Although the experimental design addresses processes that affect P concentration in runoff, the results are consistent with the compositing effect as described by Maguire et al. (2002). Somewhat unexpectedly, the L/H treatment, in which the high-P soil is in the lower slope position, also yielded a lower runoff DRP concentration than the arithmetic mean, as opposed to a concentration closer to, but lesser than, the H treatment. Under these experimental conditions, we postulate that runoff from the upper half of the box contained low-P sediments that readsorb soluble P originating from the high-P soil in the lower half of the box. It is unclear whether this is an important process under field conditions where sediments derived from upslope positions may be redeposited over some distance and replaced by newly detached sediments derived from lower slope positions. The effect may only occur as a boundary condition when runoff from a low-P soil flows across the upper edge of a high-P soil in a lower slope position. Despite this uncertainty, these results do suggest that the use of a composite or average field STP value may not accurately estimate runoff DRP concentrations in fields with high P variability that have patterns of P distribution (strong spatial dependency), especially if the downslope part of a field is lower in STP compared with the upslope. In addition, these results suggest that the use of a stream buffer zone possessing low soil P concentrations could be effective in reducing P input to surface waters.

Another factor to consider when evaluating the effectiveness of a single composite P value in estimating runoff P losses is variation with respect to the runoff contributing area. Because there may be zones of saturation within the landscape that are the predominant sources of surface runoff generation (Dougherty et al., 2004), runoff P concentrations will be more dependent upon soil P concentrations within these source areas. Additionally, source areas for runoff generation are dynamic and will expand and contract with changes in soil water content, resulting in the variable source area concept (Ward, 1984). These variable source areas typically represent only a small part of the landscape (Gburek and Sharpley, 1998; Srinivasan et al., 2002; Needelman et al., 2004), thus they are very important in the transfer of P to surface waters. For instance, if

TABLE 4

Runoff dissolved reactive P (DRP) concentrations from runoff boxes containing high (H), low (L), and both high and low P Berks soils. Mixed soil runoff boxes (3 and 4) consist of two different soils that were linked in the middle of the box

Treatment	M3-P (mg kg^{-1})		Runoff DRP (mg L^{-1})
	Upslope soil	Downslope soil	
H	220	220	0.30
L	18	18	0.04
H/L	220	18	0.09
L/H	18	220	0.13

All runoff DRP values were significantly different at P 0.05.

only the lower half of the mixed hay field (Fig. 2) is generating runoff, then the composite P value for that field would overestimate potential P concentrations in runoff because the bottom (southern) half of the mixed hay field is lower in soil P compared with the upper half (Fig. 3). However, spatial variability in P distribution may not have the same implications for pastures, because the variability in pastures, as represented by Pasture 1, is more spatially random compared with the two hay fields (Figs. 1, 2, 3, and 4). A composite sample from Pasture 1 may be more suitable for use in estimating P loss in runoff. The compositing effect may act similarly to moderate DRP concentrations in runoff as it does in the composite sample for STP determination. Therefore, runoff originating from virtually any section of Pasture 1 would be similar in P concentration because the P distribution is more spatially random. However, the results of this study suggest that there is need for further research on the topic of P adsorption-desorption dynamics in runoff as it moves across the landscape.

CONCLUSIONS

As expected, fields in which manure P was applied either more recently or for a greater period (alfalfa and mixed hay) contained higher soil M3-P and WS-P concentrations than fields in which manure applications have ceased (Pastures 1 and 2). In addition, soil M3-P and WS-P was spatially autocorrelated for all four fields, indicating that points closer together are more similar than points further apart (i.e., there are real patterns to the P distribution). However, based on the results of the autocorrelation (variogram) and simple statistics (CV), P distribution among the hay fields were less variable, less spatially random, and more clustered (i.e., stronger spatial dependency) compared with the pastured fields where P distribution was more random and spatially independent with several P "hot spots." Higher P concentrations were observed in areas near the gate and road and where manure applications would be the most easy and accessible. The high-P area within the mixed hay field corresponds with changes in slope, drainage, and soil map unit.

The most important implication of the observed spatial variability of P is with respect to the use of single-composite soil test values for P-loss prediction indexes and models. Specifically, the field average or composite P value was very different from a large percentage of individually sampled soils. Where we observed real patterns in P distribution, a single composite sample might not have accurately represented the portion of the field that controls P concentration in runoff unless these patterns were known and sampling strategies were adjusted accordingly. Conversely, where autocorrelations were relatively weak and spatial distribution patterns were more random, as in the pastures, the use of single composite samples for STP would appear to be a more appropriate indication of P concentration in runoff, because the compositing effect that occurs during sampling would also affect P concentration in runoff. The results of this study also suggest that low-P buffer areas may be very important in reducing P loading to surface waters. More research is needed to assess P adsorption-desorption from sediments moving in overland flow under field conditions.

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