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Fate and transport of phosphorus-containing land-applied swine slurry in a karst watershed

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Abstract

Phosphorus distribution in pasture soils underlain with karst geology was determined on a 0.10-ha grid in 2014, 2016, and 2018. Two fields (Fields 1 and 12) received swine slurry from a concentrated animal feeding operation, whereas another (Field 5) received mineral fertilizer. All fields were grazed by cattle and periodically hayed. Mean Mehlich-3 extractable P in the top 10 cm increased ($p \leq .05$ level) for Fields 1 (59–91 mg kg^{-1}) and 12 (63–122 mg kg^{-1}) between 2014 and 2018, with little change for Field 5 (45–47 mg kg^{-1}). Over the 5-yr monitoring period, P and N runoff averaged a respective 1.0 and 2.4 kg ha^{-1} yr^{-1} from Fields 1 and 12 or 1.4 and 2.5% of P and N applied in swine slurry. Field 5 P and N runoff averaged a respective 1.9 and 2.8 kg ha^{-1} yr^{-1} or 6.6 and 4.4% of that applied as mineral fertilizer. Findings confirmed that long-term application of P, as fertilizer or manure, in excess of pasture uptake, result in a rapid accumulation of P near the soil surface, and thus, increase nutrient loss via surface runoff. Mehlich-3 P increased in the top 10 cm of soil (143–255 mg kg^{-1}) in edge-of-field buffer zones of 30 m on Fields 1 and 12, where no manure was applied. This illustrates the complexity of cattle grazing areas as additional nutrient sources that must be managed to minimize off-site nutrient transport that are particularly important in karst watersheds.

1 | INTRODUCTION

An increase in the concentration of P at the surface of pasture soils that receive P as mineral fertilizer or manure in amounts exceeding plant uptake has been widely documented over the last 30 yr (Pierson et al., 2001; Sharpley, Smith, & Bain, 1993; Slaton et al., 2004). A similar increase in soil P concentration in cropped soils has also occurred, albeit at a slower rate due to the ability to tailor fertilizer formulations and rates, and a potentially greater uptake of P in harvested crops (Lanyon, 2005; Schneider et al., 2019; Sims, Edwards, Schoumans, & Simard, 2000; Withers et al., 2019). Once P in soils increases above optimum Mehlich-3 extractable soil phosphorus (M3P) levels for crop production, even optimum management

Abbreviations: AFO, animal feeding operation; CAFO, concentrated animal feeding operation; CNMP, comprehensive nutrient management plan; ICAP-AES, inductively coupled plasma–atomic emissions spectrometer; M3P, Mehlich-3 extractable soil phosphorus; NMP, nutrient management plan.

strategies to lower M3P levels back to below optimum levels through crop removal is a slow process (Bruulsema, Peterson, & Prochnow, 2019; Coblentz et al., 2004; Rowe et al., 2016). As a result, attention has focused on development and implementation of a nutrient-management-planning framework to guide the application of fertilizer and manure at rates to maintain optimal productivity and protect designated uses of water resources (Osmond et al., 2017; Sharpley et al., 2017; USDA-NRCS, 2020a).

In certain areas of the United States, such as northwestern Arkansas, litter from broiler poultry (*Gallus gallus domesticus*) production (i.e., manure combined with in-house bedding material as litter) has provided a low-cost fertilizer for area pastures grazed by beef cattle (*Bos primigenius taurus*). The use of broiler litter as a fertilizer-P source has been mutually beneficial to livestock production, providing revenue from the sale of litter as a substitute for mineral fertilizer and increased forage production, reducing the risk of erosion and allowing an increase in grazing density. However, the continued application of manure based on forage-N uptake applies P in excess of plant uptake, which has led to an increase in surface soil P and potential for P runoff, contributing to downstream water-use impairment (Daniels et al., 2001; Duncan et al., 2017; Withers, Sylvester-Bradley, Jones, Healey, & Talboys, 2014; Zhang et al., 2019b). Soil-P enrichment from the long-term application of broiler litter contributed to litigation between Oklahoma, where increased algal growth in recreational and drinking water sources were observed, and Arkansas, which was the apparent upstream major source of nutrients accelerating the incidence and density of algal growth in Oklahoma (DeLaune, Haggard, Daniel, Chaubey, & Cochran, 2006; State of Oklahoma v Tyson Foods, 2005). The litigation led to the requirement of state-approved nutrient management plans (NMPs) prior to land application of P or N in several transboundary watersheds, including the Illinois River and Eucha–Spavinaw Watersheds.

In other livestock sectors, swine animal feeding operations (AFOs) with liquid manure systems were subject to state permitting and utilization of USDA-NRCS technical assistance. As a result, AFOs were required to operate under the guidance of federal comprehensive nutrient management planning (CNMP) guidelines (USDA-NRCS, 2020b). In 2012, a new swine concentrated animal feeding operation (CAFO) was permitted by the Arkansas Department of Environmental Quality to operate in the Buffalo River Watershed, which contains the first National River established in 1972 and is an important recreational and tourist area in northwestern Arkansas (National Park Service, 2020). The Buffalo River Watershed also contains substantial areas of underlying karst geology. Swine slurry produced by the CAFO was applied to 17 grazed and/or hayed pasture fields at rates allowed in the farm's CNMP.

Core Ideas

- Soil P increased in pastures receiving swine slurry at rates greater than plant uptake over 6 yr.
- Biannual grid sampling showed soil P hot spots in areas where cattle were fed, and shade was available.
- The portion of fertilizer P in runoff was more than swine slurry due to infiltration of the latter.
- Reducing P runoff must manage the rate and timing of nutrients applied and cattle loafing areas.

There is limited information detailing the fate and transport of nutrients applied under NMP requirements, particularly in karst watersheds (Jarvie et al., 2014). Thus, grid-soil samples were collected biannually (between 2014 and 2019) in two fields receiving swine slurry and one field receiving mineral fertilizer. The study fields were also instrumented with continuous water monitoring stations to measure surface runoff exiting the fields over 5 yr (2014–2018). This observational study provides information on the spatial and temporal variation of P in soil and surface runoff as a function of applying swine slurry or mineral fertilizer in accordance with CNMP requirements in the real-world setting of a privately operated farm in a karst watershed.

2 | MATERIALS AND METHODS

2.1 | Field management

The three agricultural fields included in this study are located in the Big Creek Watershed, a subwatershed of the Buffalo River Watershed, Arkansas (Figure 1). Dominant soils for the three fields and their management are reported in Table 1. Annual rainfall amounted to 105, 159, 90, 104, and 121 cm in 2014, 2015, 2016, 2017, and 2018, respectively, whereas average rainfall for the region is 117 cm (National Park Service, 2020). The permitted CNMP required the establishment of 30-m buffers, where no swine slurry could be applied, adjacent to all sinkholes, ponds, and streams (Figure 2). Application of slurry on slopes >15% in Field 1 was also prohibited by the CNMP, and farm owners

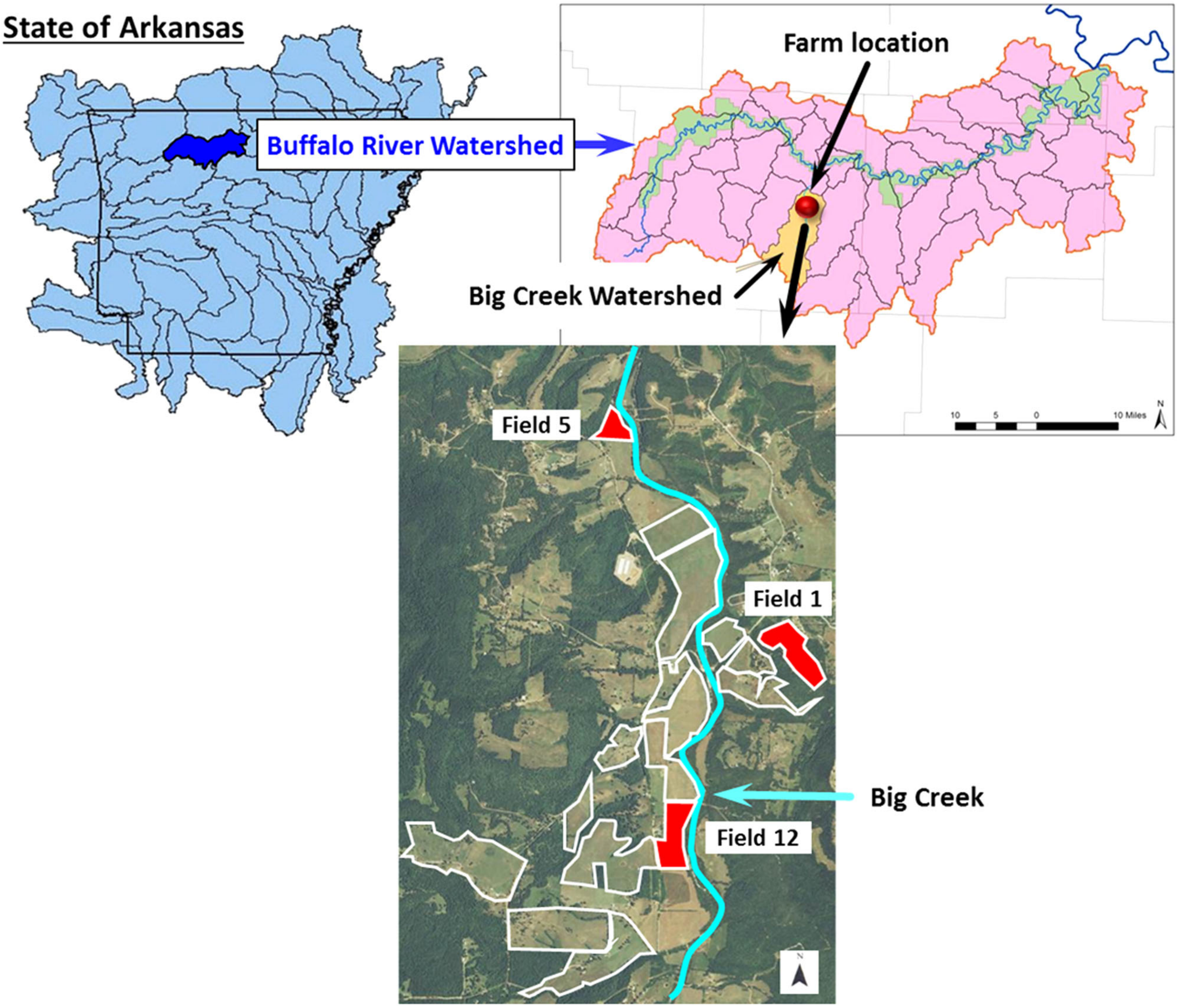

FIGURE 1 Location of Buffalo River Watershed, Big Creek Watershed, farm, and fields studied in Arkansas

TABLE 1 Field properties and management

Field	Area	Management	P and N applied as: 2004–2012[a]	P and N applied as: 2014–2018	P and N applied 2004–2012 P	P and N applied 2004–2012 N	P and N applied 2014–2018 P	P and N applied 2014–2018 N
	ha				kg ha^{-1} yr^{-1}			
1	6.3	Grazed at 0.5 animal units ha^{-1}	Poultry litter	Swine slurry	50	120	60	74
5	10.8	Hayed and grazed at 0.3 animal units ha^{-1}	Poultry litter	DAP[b]	50	120	28	64
12	9.6	Hayed and grazed at 0.3 animal units ha^{-1}	Poultry litter	Swine slurry	50	120	92	131

[a] 4.5 Mg ha^{-1} poultry litter every 2 yr.
[b] DAP, diammonium phosphate.

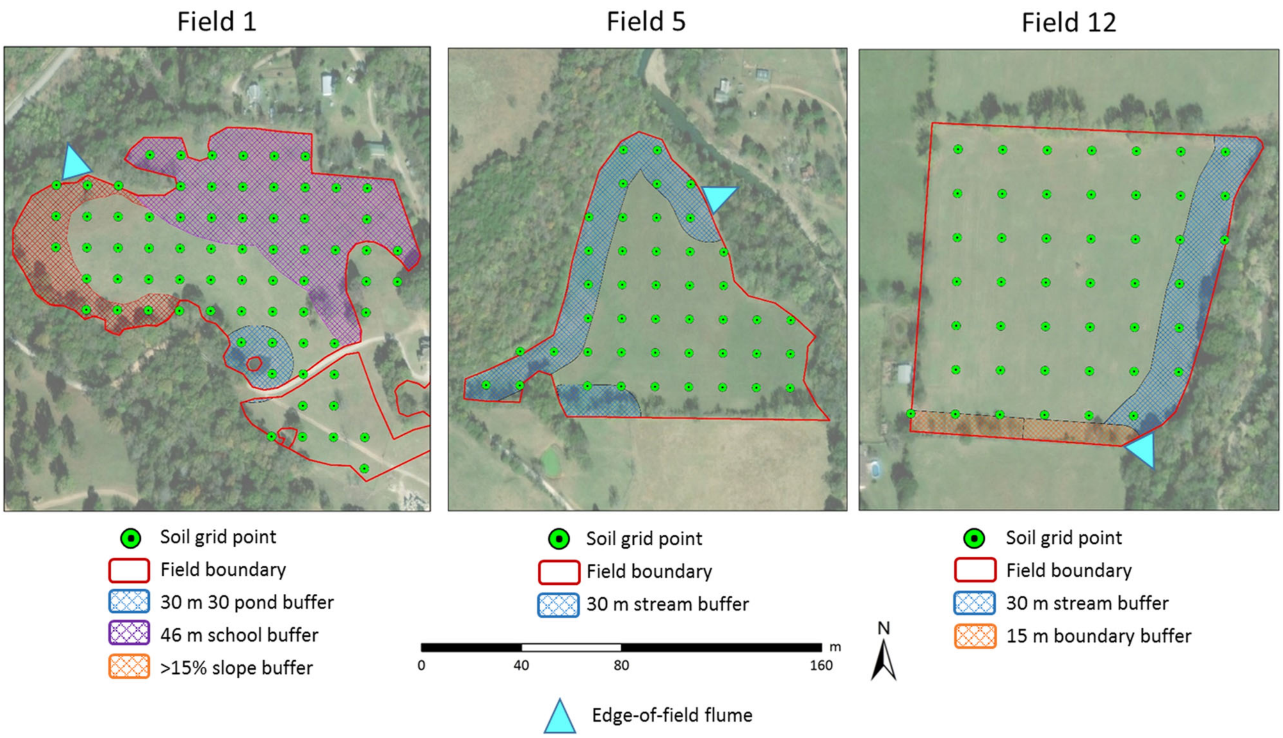

FIGURE 2 Field boundaries, location of georeferenced 0.10-ha grid points used to collect soil samples from Fields 1, 5, and 1 in 2014, 2016, and 2018, buffers where no swine slurry can be applied, and edge-of-field flume monitoring surface runoff

implemented an additional 15-m buffer on Field 12 along the southern neighboring field boundary (Figure 2).

In the 10-yr prior to CAFO operation and land application of swine slurry produced on the farm (2004–2014), the three fields received poultry litter every 2 yr, which amounted to 25 and 60 kg ha^{-1} yr^{-1} of P and N, respectively (Table 1). Since 2004, the three fields have been grazed, on average, at 0.5 and 0.3 animal units ha^{-1} for Field 1 and Fields 5 and 12, respectively, and hay was periodically cut on Fields 5 and 12. In 2014, Fields 1 and 12 started receiving swine slurry, which added more P and N than in prior years as poultry litter (Table 1). Field 5 received only diammonium phosphate each year, and data from Field 5 provides a reference point for continued, normal pasture management in the region (Table 1). It should be noted that applications of swine slurry to Fields 1 and 12 were made in accordance with the required CNMP for farm operation, whereas the application of fertilizer to Field 5 was based on landowner preference and was not under the mandate of the CNMP.

Soil survey and ground penetrating radar (conducted by Natural Resources Conservation Service, NRCS) of Fields 1, 5, and 12 showed soils varied in depth across and among fields (Big Creek Research and Extension Team, 2019). Field 1, dominated by Noark silt loam (Typic Paleudults), had an overlying layer of soil that varied from zero (rock outcrops) to 50 cm. Fields 5, dominated by Razort sandy clay loam (Mollic Hapludalfs) and 12 dominated by Spadra clay loam (Typic Hapludults) adjacent to Big Creek, had soils varying in depth from 80 to 150 cm deep. The deeper soil profiles for Fields 5 and 12 were adjacent to Big Creek, with the thinner soils at a higher elevation on the side of a hill, on the field further from the Creek. Land slopes ranged from 2 to 20% for Field 1, 0.2 to 1.0% for Field 5, and 0.5 to 2.0 for Field 12.

2.2 | Grid soil sampling

Grid sampling of soil in Fields 1, 5, and 12 was conducted biannually in February 2014, February 2016, and March 2018 to best reflect potential changes over time, while minimizing interfering with land management operations. A 0.10-ha grid layer was used to generate sample point locations in ArcGIS (ESRI, 2014) and coordinates loaded into a global positioning system (GPS) unit (GPSMap 64st, Garmin International) so that biannual soil grid sampling could be collected at predetermined locations (Figure 2). Soil samples consisted of five cores collected at depths of 0–10 and 10–20 cm within a 1.5-m radius of each GPS point location and combined into one composite sample for each grid point, per soil depth, per field. Where coarse fragments stopped the core sampler from penetrating below 10 cm on Field 1, no sample was collected beyond that point. In

2018, 10- to 20-cm depth soil samples were not collected for Field 1.

2.3 | Soil analysis

All composite core samples were dried at 60 °C and ground to pass through a 2-mm sieve. Any material that would not crush by manual mortar and pestle to pass the 2-mm screen was discarded. Particle-size analysis of samples collected in 2014 was conducted by the hydrometer method (Huluka & Miller, 2014). All analyses used subsamples of oven-dried, ground material. Soil pH was determined in a 1:2 soil/water mixture (Sikora & Kissel, 2014); soil organic matter by weight loss on ignition (Zhang & Wang, 2014); total C and N by thermal combustion analysis (Provin, 2014); total P by alkaline oxidation (Leytem & Kpomblekou-A, 2009); and cation exchange capacity (CEC) using neutral NH_4OAc (Sikora et al., 2014). Mehlich-3 P, Al, and Fe were extracted from soil by shaking 2 g of soil with 20 ml of reagent for 5 min (Mehlich, 1984) and concentrations were determined using an inductively coupled plasma–atomic emissions spectrometer (ICAP-AES; Zhang, Hardy, Mylavarapu, & Wang, 2014a).

Following soil analyses, the spatial analyst tool "Spline with Barriers" was used within ArcGIS (ESRI, 2014) to create spatial distribution maps depicted in Figure 3. By inputting the geo-referenced results of the grid soil sampling and defining the field boundary (barrier), the tool produced a smooth surface of minimum curvature values using the spline interpolation method.

2.4 | Swine slurry sampling and analysis

A foot valve liquid manure sampler was used to collect composited samples of slurry from the entire depth of the slurry pond profile in April of each study year, to represent the homogenized swine slurry resulting from agitation prior to and during land application (VanDevender, 2010). The pH and electrical conductivity were determined by electrode (Wolf, 2003a, 2003b), solids gravimetrically after drying at 105 °C (Hoskins, Wolf, & Wolf, 2003), and nitrate-N and ammonium-N concentrations colorimetrically (Peters, Wolf, & Wolf, 2003). Total N was determined following Kjeldahl digestion (Watson, Wolf, & Wolf, 2003); total P, K, and Ca following microwave assisted nitric and hydrochloric acid digestion (Wolf, Watson, & Wolf, 2003); and water-extractable P following extraction of slurry with water (Wolf, Moore, Kleinman, & Sullivan, 2009). The P, K, and Ca concentrations were determined via ICAP-AES.

2.5 | Runoff measurement

Autosamplers collected edge-of-field surface runoff from Fields 1, 5, and 12. Each sampler was programed to initiate sample collection when a stage height exceeded 2 cm in the 45 cm (1.5 ft) tall H flume on Field 1 and 30 cm (1 ft) tall H flume on Fields 5 and 12. Water samples collected during a storm event were composited in a 10-L bottle enclosed in the ISCO sampler, which provided a flow-weighted, composite sample for each runoff event. A subsample was filtered (<0.45 µm) at the time of collection and kept at 4 °C until analysis by ICAP-AES within 8 h of collection.

2.6 | Runoff water analysis

Runoff water sample analyses included dissolved P (EPA 365.1) and nitrate-N (EPA 300.0) on a filtered sample and total P (APHA 4500-P J; EPA 365.1) and total N (APHA 4500-P J; EPA 365.1) on unfiltered samples (USEPA, 2004, 2020). Suspended sediment concentration in the collected runoff water samples was determined gravimetrically as the difference in weights between oven-dried (105 °C) unfiltered and filtered (<0.45 µm) water samples.

2.7 | Statistical analyses

Statistical analyses were performed by using unpaired *t* tests ($p \le .05$) and one-way analysis of variance comparing M3P concentrations from Fields 1, 5 and 12 using JMP statistical software (Lehman, O'Rourke, Hatcher, & Stepanski, 2013). Statistical analysis of M3P concentrations for each field were made on a whole-field, slurry-application, and field-buffer-zone basis. Analyses were also conducted separately by soil sample depth.

3 | RESULTS AND DISCUSSION

3.1 | Grid soil sampling

Physiochemical soil properties involved in the fate of applied P are reported in Table 2. Constituent concentrations in swine slurry applied to the fields were averaged over the 5-yr study and are reported in Table 3.

On a whole-field basis, M3P concentrations in the 0- to 10-cm depth increased by a respective 32 and 59 mg kg^{-1} for Fields 1 and 12 between 2014 and 2018 soil sampling ($p < .05$; Table 4). For the slurry application zone of Fields 1 and 12, M3P concentrations increased ($p < .05$) 50 and

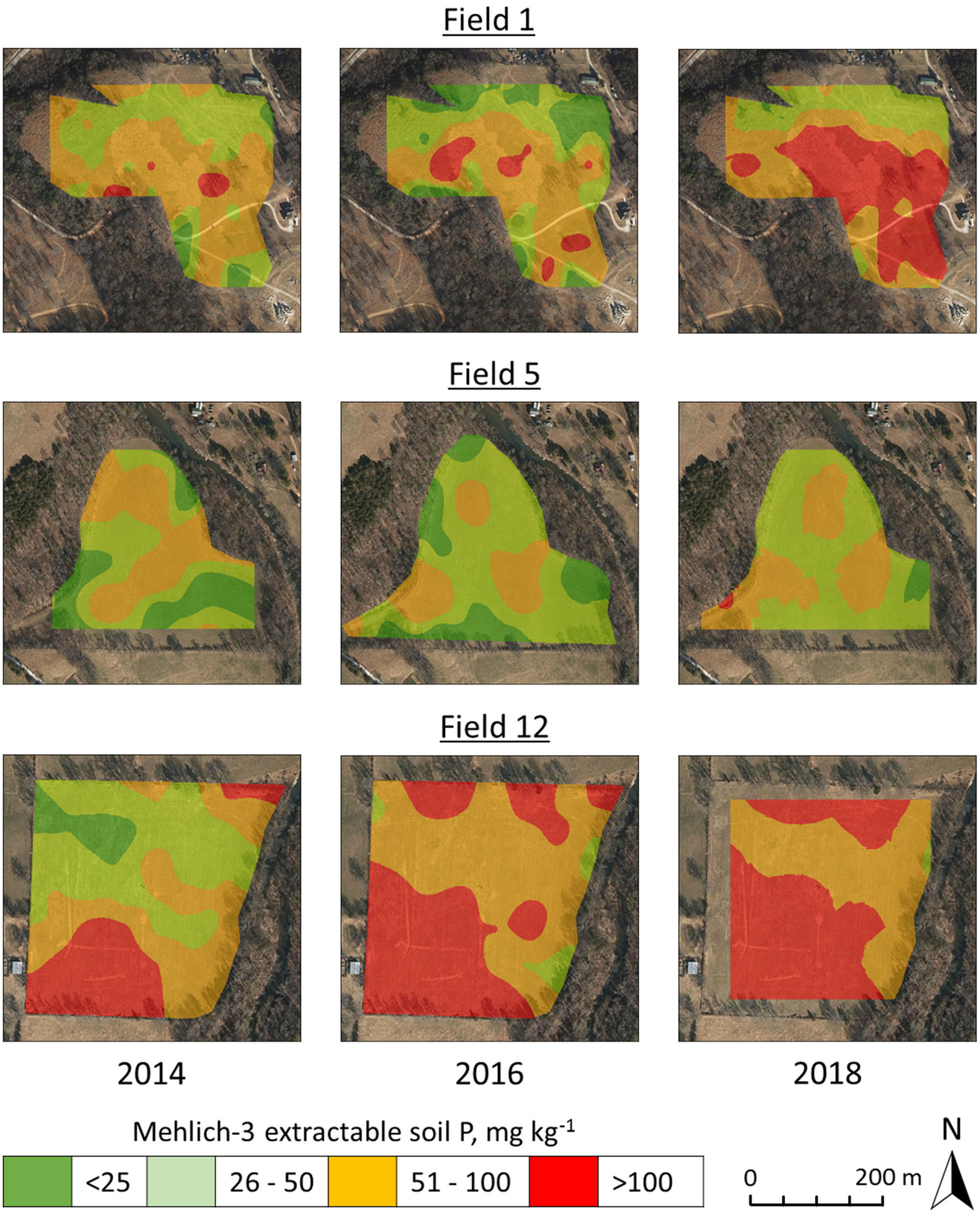

FIGURE 3 Spatial distribution of Mehlich-3 extractable soil P in the 0- to 10-cm soil depth on Fields 1, 5, and 12 for grid soil sampling in February and March of 2014, 2016, and 2018

TABLE 2 Soil properties

Field	Soil series	Particle-size Sand	Silt	Clay	pH	CEC	Total C	Total N	Total P	Total Ca	Mehlich-3 extractable Al	Fe
		%				$cmol_c\ kg^{-1}$	$g\ kg^{-1}$	$mg\ kg^{-1}$				
1	Noark silt loam	16	64	20	6.15	10.94	13.25	1,367	448	1,315	600	111
5	Razort sandy clay loam	42	30	28	5.81	11.46	17.37	1,861	725	1,283	829	143
12	Spadra clay loam	41	29	30	5.99	14.38	18.17	1,933	705	1,697	884	154

70 mg kg^{-1} over the same period, respectively. In the buffer zone of each field, where no slurry was applied (the buffer zone of Field 5 did receive mineral fertilizer), M3P concentrations only numerically increased between 2014 and 2018 (Table 4).

The spatial distribution of M3P concentrations in the 0- to 10-cm soil depth of Fields 1, 5, and 12 for 2014, 2016, and 2018 grid sampling are depicted in Figure 3 (whole field basis). The ranges in M3P of <25, 25–50, 50–100, and >100 mg kg^{-1} reflect Land-Grant University soil fertility and plant response categories of deficiency, optimum for cool-season grasses, little response to additional P expected for cool- and warm-season grasses, and no plant growth response expected to added P, respectively (Espinoza, Slaton, & Mozaffari, 2006).

It is evident from the spatial distribution maps of M3P concentrations that accumulation of P occurred in some areas within the top 10 cm of Fields 1 and 12 (Figure 3). These areas are generally located around points of shade on Fields 1 and 12 (northern boundary of these fields), where cattle congregated. For Field 12, the area of M3P concentrations greater than 100 mg kg^{-1} occurs on the southwest corner of the field and is located at the gated entrance to the field, where cattle are routinely fed hay during non-grazing months. The area with a M3P concentration greater than 100 mg kg^{-1} expanded with each biannual soil sampling, with maximum M3P concentration of 147, 193, and 256 mg kg^{-1} from the 2014, 2016, and 2018 grid-sampling results, respectively (Figure 3). Additional individual points with elevated P levels in these fields may be due to cowpats that may no longer be visible at the surface.

It should be noted that accumulation of M3P in the southwest corner of Field 12 was evident in the 2014 grid soil sampling (Figure 3), which was completed 31 Jan. 2014 prior to the first application of swine slurry to Field 12 on 22 Apr. 2014. In fact, the largest M3P concentration of 256 mg kg^{-1} in the 2018 sampling was measured in the buffer zone of Field 12, where no swine slurry has been applied. Similarly, and in the 2014 and 2016 grid sampling, maximum M3P concentrations were comparable in the slurry application (147 and 193 mg kg^{-1}, respectively) and buffer zones (147 and 190 mg kg^{-1}, respectively; Figure 3). Clearly, in-field spatial variation in M3P concentrations for Fields 1 and 12 are a function of land and grazing management, along with swine slurry application.

For the 10- to 20-cm soil depth, a 44% increase in M3P concentration between 2014 and 2018 ($p < .05$) was determined on a whole-field basis for Field 12, although for Field 5, which received mineral fertilizer between 2014 and 2018, M3P concentrations decreased 27% (Table 5). On a zonal basis, only Field 12 exhibited a 67% increase in M3P concentration in the slurry application zone, Field 5 exhibited a 26% decrease in M3P concentration, whereas there

TABLE 3 Constituent concentration of swine slurry sampled from the profile of holding pond averaged for semi-annual samplings between 2014 and 2019

Constituent	Concentration	Range
pH	7.6	7.4–7.9
Electrical conductivity, μS cm^{-1}	12,413	10,060–14,770
Solids, %	3.73	2.51–5.57
Total N, mg L^{-1}	2,614	1,514–3,970
Ammonium-N, mg L^{-1}	1,147	875–1,577
Nitrate-N, mg L^{-1}	0.058	0.035–0.175
Total P, mg L^{-1}	1,285	253v2,916
Water-extractable P, mg L^{-1}	177	138–202
Total K, mg L^{-1}	1,363	1,054–1,537
Total Ca, mg L^{-1}	1,069	102–2,355

was no change in M3P concentration in the 10- to 20-cm soil depth in the buffer zone of all three fields (Table 5). These results suggest that some downward movement of P likely occurred in Field 12 in the zone where slurry was applied and cattle grazed.

3.2 | Surface runoff

The annual flow and loss of P, N, and sediment in surface runoff for 2014 through 2018 are reported in Table 6. The greater nutrient runoff from Fields 5, 12 were dominated by major storm events during 2015, when annual rainfall exceed annual average by 42 cm. These storm events resulted in approximately twice the volume of runoff in 2015 (5,232 and 9,741 m^3 ha^{-1} yr^{-1}, respectively) than the other 4 yr combined (2,728 and 4,521 m^3 ha^{-1} yr^{-1}, respectively; Table 6). Additionally, Fields 5 and 12 are adjacent to Big Creek, which breached its banks and flooded these fields in May and December 2015. In contrast to Fields 5 and 12, surface runoff from Field 1 was largest in 2017. Despite less P applied in mineral fertilizer to Field 5 between 2014 and 2018 (28 kg ha^{-1} yr^{-1}) than for Fields 1 and 12 that received slurry (60 and 131 kg ha^{-1} yr^{-1}, respectively), the 5-yr mean loss of dissolved and total P were greater from Field 5 than from Fields 1 and 12 (Table 6).

The annual loss of P and N in surface runoff averaged for the 5 yr of monitoring from Field 1 were 1.5 and 2.8%, respectively, of that applied in slurry, whereas for Field 12 losses averaged 1.2% P and 2.1% N, respectively, of that applied (Table 7). For Field 5, loss of P and N averaged 6.6 and 4.4%, respectively, of that applied in mineral fertilizer (Table 7). Nutrient losses measured from the three fields were similar to P losses reported from other fields in the same region. For example, pastures in northwestern Arkansas, also in the karst region of the Boston Mountains/Ozark Highlands, receiving poultry litter (Bolster et al., 2019) had losses ranging from 1.05 to 1.62 kg P and 0.35 to 1.41 kg N ha^{-1} or 1.6 to 2.3% of applied P and 0.3 to 1.1% applied N (Table 7).

The runoff collection station for Field 1 was located at the base of a hill. The existing nutrient management plan for Field 1 restricted slurry application to the flat hilltop only and slurry was not directly applied to the slope. Consequently, the sloped area effectively served as a vegetated buffer. The greater percentage of nutrient loss from Field 5 relative to Field 12 was likely a combination of commercial mineral fertilizer P being more soluble than that from the swine slurry (Sharpley & Moyer, 2000), differences in surface hydrology, and a lack of vegetative buffers, as no swine slurry was applied. As these are permanent pastures, commercial fertilizer may settle at the soil surface and be unincorporated within the soil itself until rainfall occurs, which may have promoted surface runoff-P losses, while infiltration of slurry may help rapidly incorporate the soluble portions of P into the soil, which likely minimized surface runoff-P losses.

4 | CONCLUSIONS

Findings from this case study of grid soil sampling between 2014 to 2018 reinforced current nutrient management understanding that the annual application of P, as fertilizer or swine slurry, in amounts greater than uptake of P by pasture vegetation result in an accumulation of P at the soil surface and thus, potential for nutrient runoff. The P accumulation rate is largely determined by the magnitude of P application above expected P removal, with further increases in M3P eventually limiting P additions as fertilizer or swine slurry in future iterations of nutrient management planning. Given the variation in rainfall-driven runoff from year to year, there was no consistent trend of increasing loss of P or N over the 5 yr of

TABLE 4 Mean and lower and upper 95% confidence intervals for Mehlich-3 extractable P concentration in the 0- to 10-cm soil depth collected in 2014, 2016, and 2018 grid sampling of Fields 1, 5, and 12 based on the whole field, slurry application zone, and no application buffer zones

	Mehlich-3 extractable soil P											
	Field 1				Field 5				Field 12			
Year	No. samples	Mean[a]	Lower[b]	Upper[b]	No. samples	Mean[a]	Lower[b]	Upper[b]	No. samples	Mean[a]	Lower[b]	Upper[b]
	mg kg^{-1}											
Whole field												
2014	71	59 b	49	69	33	45 a	38	52	40	63 b	49	77
2016	71	57 b	47	66	44	39 a	33	45	45	104 a	90	117
2018	71	91 a	81	100	44	47 a	41	53	45	122 a	109	135
Slurry application zone												
2014	39	65 b	51	78	23	50 a	43	58	31	56 b	41	70
2016	39	73 b	60	87	28	42 a	35	49	34	107 a	93	120
2018	39	115 a	101	128	28	45 a	38	52	34	126 a	112	140
Buffer zone												
2014	32	52 ab	42	62	10	33 a	17	50	9	81 a	38	124
2016	32	38 b	27	48	16	34 a	21	47	11	95 a	60	130
2018	32	62 a	52	72	16	51 a	38	64	11	112 a	77	147

[a]For a given field and zone, means followed by the same letter are not significantly different as determined by unpaired *t* test with $\alpha < .05$ level of probability.
[b]Lower and upper 95% confidence limits of Mehlich-3 extractable soil P as determined by analysis of variance.

TABLE 5 Mean Mehlich-3 extractable soil P concentration in the 10- to 20-cm soil depth collected in 2014, 2016, and 2018 grid sampling of Fields 1, 5, and 12 based on the whole field, slurry application zone, and no application buffer zones. In 2018, 10- to 20-cm soil depth samples were not collected for Field 1

Year	Field 1 No. of samples	Field 1 Mean[a]	Field 5 No. of samples	Field 5 Mean[a]	Field 12 No. of samples	Field 12 Mean[a]
		mg kg^{-1}		mg kg^{-1}		mg kg^{-1}
Whole field						
2014	26	20 a	44	45 a	39	36 b
2016	69	27 a	44	27 b	45	50 a
2018	–	–	43	33 b	35	52 a
Slurry application zone						
2014	17	20 a	17	46 a	31	33 b
2016	35	38 a	28	27 b	34	47 a
2018	–	–	27	34 b	28	55 a
Buffer zone						
2014	9	19 a	5	43 a	8	49 a
2016	34	15 a	16	27 a	11	58 a
2018	–	–	16	31 a	7	36 a

[a] For a given field and zone, means followed by the same letter are not significantly different as determined by unpaired *t* test with $\alpha < .05$ level of probability.

TABLE 6 Annual flow and loss of P, N, and sediment in surface runoff from Fields 1, 5, and 12 for 2014 to 2018

	Flow	Dissolved P	Total P	Nitrate-N	Total N	Sediment
	m^3 ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}				
Field 1						
2014	630	0.34	0.49	0.13	0.81	45.6
2015	551	0.17	0.25	0.10	0.72	17.7
2016	20	0.02	0.02	0.01	0.05	1.2
2017	3,629	2.55	3.44	1.43	8.13	203.1
2018	118	0.15	0.17	0.20	0.50	2.8
Mean	990	0.65	0.87	0.37	2.04	54.1
Field 5						
2014	34	0.02	0.03	0.00	0.02	1.3
2015	5,231	1.30	5.00	0.68	7.82	1,655.5
2016	136	0.16	0.18	0.04	0.23	3.6
2017	1,015	0.84	1.11	0.79	1.70	11.7
2018	1,543	1.99	2.95	0.37	4.22	150.8
Mean	1,592	0.86	1.85	0.38	2.80	364.6
Field 12						
2014	NR[a]	0.00[a]	0.00	0.00	0.00	0.00
2015	9,741	2.01	3.68	1.37	8.30	359.9
2016	32	0.01	0.02	0.02	0.13	18.2
2017	4,489	1.19	1.93	0.69	5.16	508.4
2018	NR[a]	0.00	0.00	0.00	0.00	0.00
Mean	4,754	0.64	1.13	0.42	2.72	221.6

[a] NR, no runoff occurred from Field 12 during 2014 and 2018.

TABLE 7 Loss of P and N in runoff from Fields 1, 5, and 12 in the Big Creek Watershed and from fields in Arkansas and Oklahoma

Site	Site years	Management	Total P Applied	Total P Runoff	Total P Loss as a percent of applied	Total N Applied	Total N Runoff	Total N Loss as a percent of applied	Reference
			kg ha^{-1} yr^{-1}		%	kg ha^{-1} yr^{-1}		%	
Field 1	5	Grazed pasture with swine slurry	60	0.87	1.5	74	2.04	2.8	This study
Field 5	5	Fertilizer grazed and hayed pasture	28	1.85	6.6	64	2.80	4.4	This study
Field 12	5	Grazed and hayed pasture with swine slurry	92	1.13	1.2	131	2.72	2.1	This study
Dumas, AR	15	Cotton–corn rotation	27	1.19	3.1	102	4.20	2.8	Daniels et al. (2019)
El Reno, OK	32	Native grass	0	0.97	–	0	0.11	–	Sharpley and Smith (1994)
	29	Wheat	13	1.64	12.2	71	9.21	13.1	
Washington Co., AR	4	Grazed pasture with poultry litter	67	1.05	1.6	134	0.35	0.3	Bolster et al. (2019)
	4	Grazed pasture with poultry litter	90	1.62	1.8	179	0.74	0.4	
	4	Hayed pasture with poultry litter	67	1.53	2.3	134	1.41	1.1	
	7	Hayed pasture	0	0.07	–	0	0.32	–	
Woodward, OK	14	Native grass	0	0.02	–	0	0.20	–	Sharpley and Smith (1994)
	8	Native grass	26	0.34	1.3	101	1.65	1.6	
	8	Wheat	26	1.92	7.4	103	7.25	7.0	

monitoring with slurry application to Fields 1 and 12 or mineral fertilizer application to Field 5.

Interpretation of M3P accumulation in surface soils following fertilizer or swine slurry application is complicated by the grazing management of the studied fields, which created well-defined areas of M3P accumulation adjacent to farm ponds, field gates, and shade trees, where cattle loafing occurred.

An added complication, albeit a reality of "real-world" agricultural farming, was the fact that, from producer interviews, grazing density increased gradually and, in 2018, was twice that in 2014 for Fields 1 (0.5–1.0 animal units ha^{-1}) and 12 (0.3–0.6 animal units ha^{-1}). Increased grazing density was in response to increased forage growth afforded by swine slurry applications and in part led to M3P accumulations in specific areas of Fields 1 and 12. As grazing and nutrient management of these fields influenced nutrient accumulation in soil and loss in runoff, it can be concluded that efforts to minimize nutrient runoff from these sites must include adaptive management of both the rate and timing of nutrient applications (as mineral fertilizer, swine slurry, and poultry litter), as well as grazing, to preserve water quality in sensitive watersheds, particularly those with underlying karst geology, such as the Buffalo River Watershed.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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