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Managing soil nutrient buildup by rotating crops and fertilizers following repeated poultry litter applications

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Abstract

Applying poultry litter (PL) to meet a crop's P need is the most recommended PL management practice but may not be the most ideal. In this study, alternative management strategies that included the rotations of crops and fertilizers were tested. Cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.] were grown in rotation and fertilized with five fertility treatments, which included an unfertilized control, a standard fertilization with conventional synthetic fertilizers (Std), P-based PL application every year for 5 yr (P5L), N-based PL application every year for 5 yr (N5L), and N-based PL application each of the first 2 yr and a synthetic N application at the same rate as the Std in the last 3 yr (N2L). The level of residual soil mineral elements was assessed after 5 yr of imposing these treatments. The results showed that, relative to the Std, the N5L treatment elevated extractable soil P, Cu, and Zn by >100% and soil K and Mg by ≈90%. After 5 yr, soil nutrient levels in the N2L treatment were comparable to the P5L treatment, which did not lead to any nutrient buildup. Rotating crops was not a reliable practice for purposes of managing soil nutrient buildup. The results overall show that applying PL at a relatively high rate to meet the N need of cotton for a few years and suspending the application for 2–3 yr during which only synthetic N fertilizer is applied offers an effective and sustainable PL management strategy in row crop production systems.

1 | INTRODUCTION

Poultry litter (PL), which has proven to be an excellent row crop fertilizer (Tewolde & Sistani, 2014; Tewolde et al., 2016), is composed of mostly organic matter (≈60%) and is a rich source of all mineral elements needed for healthy plant growth (Tewolde et al., 2005a, 2005b). However, the mineral elements in PL do not exist in proportions needed for plant growth. For example, a typical broiler litter supplies more P than crop plants can use when applied to meet the crop's N need. This is because the N/P ratio in the litter is far less than the N/P ratio in crop plants. The total N/P ratio of broiler litter is about 2:1 (Tewolde, McLaughlin, et al., 2016), and only 1:1 if based on plant available N. Under optimal production, the N/P uptake ratio of crops varies from 1.5:1 for cereal crops to 20:1 for oilseed and legume crops (Sadras, 2006). Cotton's (*Gossypium hirsutum* L.) N/P ratio is about 6:1 (Tewolde et al., 2005b), and the synthetic fertilizer application for cotton in the southeastern United States of about 5:1

Abbreviations: ICP-OES, inductively coupled plasma–optical emissions spectroscopy; M3Cu, Mehlich 3–extractable Cu; M3Fe, Mehlich 3–extractable Fe; M3K, Mehlich 3–extractable K; M3Mg, Mehlich 3–extractable soil Mg; M3Mn, Mehlich 3–extractable Mn; M3P, Mehlich 3–P; M3Zn, Mehlich 3–Zn; N2L, N-based PL application each of the first 2 yr and a synthetic N application at the same rate as the Std in the last 3 yr; N5L, N-based litter application every year for 5 yr; P5L, P-based PL application every year for 5 yr; PL, poultry litter; Std, standard fertilization with conventional synthetic fertilizers.

(≈140 kg N ha^{-1} vs. ≈ 20 to 30 kg P ha^{-1}) resembles the uptake ratio. When PL is applied to meet the N need of cotton, that amount of PL supplies P in excess of the crop's ability to use it (Tewolde et al., 2007). For example, applying 7.5 Mg ha^{-1} PL that contains 30 g kg^{-1} total N (15 g kg^{-1} plant-available N) supplies the full N requirement of a typical cotton crop in the southeastern United States (112 kg ha^{-1}) (Tewolde, McLaughlin, et al., 2016). This PL rate would also supply nearly 90 kg ha^{-1} total P versus the typical recommended P application of 20–30 kg ha^{-1}. The excess 60–70 kg ha^{-1} that cotton does not use remains in the soil. The same applies to other elements with similar imbalances as P.

Core Ideas

- Applying 7.9 Mg ha^{-1} PL for 5 yr elevated extractable soil P, Cu, and Zn by >100%.
- Suspending high PL applications for 2–3 yr reduced residual nutrients to near initial levels.
- This new strategy was as effective as the P-based PL application.
- The new strategy may have benefits for increasing yield and reducing cost.
- Crop rotation may help reduce P buildup but was not as reliable as the fertilizer rotation.

Repeating PL application for several years based on the crop's N requirement leads to the accumulation of P and other elements not taken up by the crop in the soil. Such accumulations have been shown to occur in 2–5 yearly applications in the southeastern United States (Adeli et al., 2008; Gascho & Hubbard, 2006; Mitchell & Tu, 2006; Schomberg et al., 2009; Tewolde et al., 2007). Continuing the application longer than 2–5 yr can lead to unsustainably high soil nutrient levels (Sharpley et al., 2004) that may require some remedial measures. Other nutrients that accumulate during a few years of repeated PL applications include Cu and Zn (Adeli et al., 2008; Adeli et al., 2007; Gascho & Hubbard, 2006; Mitchell & Tu, 2006; Schomberg et al., 2009). Schomberg et al. (2009) reported P and Zn accumulation of >200% relative to the initial level and suggested the development of strategies for removing excess nutrients following repeated long-term litter applications. Sharpley et al. (1993) reported that 72% of the applied P from broiler litter is retained in the soil profile.

Although remedial measures should be developed and used on soils with already elevated nutrient levels, we believe preventing the buildup of excess nutrients in soils with little or no history of litter application may be the best approach for a sustainable integration of animal manures in row cropping systems. One such approach is the P-based manure application, which is the most studied and recommended manure fertilization strategy to prevent P buildup (Eghball & Power, 1999; Maguire et al., 2008). Applying PL or other manures so that the P supply equals expected P removal in the harvested crop leaves little or no excess P in the soil. However, this approach may not always be an ideal strategy. The amount of PL applied based on the P need typically is low and does not supply enough N to meet the crop's N need. As a result, the P-based PL application has to be supplemented with N from other sources, usually synthetic sources, a practice that increases the cost of production because of the additional trips over the field to apply the N fertilizer. Management strategies that are cost-effective, sustainable, and compatible with current crop production systems in the region need to be developed as alternatives to P-based litter management.

Rotating crops with known differences in nutrient uptake and removal may be an effective strategy for managing land-application of PL. Cotton, corn (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.] are the most commonly rotated row crops in the southeastern United States. These crops are known to vary in the amount of minerals they remove with their respective harvested products, seed and lint for cotton and grain for corn and soybean. This variation is a function of the amount of harvested portion of the crops and the concentration of the elements in the seed or harvested plant part. The concentration of most mineral elements in the corn grain is far less than the concentration in cotton or soybean seed. For example, the concentration of P averaged across several sources is 4.05 g kg^{-1} in corn compared with 7.67 g kg^{-1} in cotton seed and 5.15 g kg^{-1} in soybean seed (He et al., 2013; Heckman et al., 2003; Nathan, Sun, & Dunn, 2006; Rochester, 2007; Tewolde et al., 2007; Tewolde et al., 2010; Tewolde et al., 2019). Corn, however, removes more than twice the P amount in harvested grain (40.5 kg ha^{-1}) than in harvested cotton seed (15.5 kg ha^{-1}) or soybean (18.0 kg ha^{-1}) with yields typical for the southeastern United States (He et al., 2013; Heckman et al., 2003; Nathan et al., 2006; Rochester, 2007; Tewolde et al., 2007, 2010, 2019). The biomass yield that is removed from the soil is the primary basis for this difference. Of the three crops, corn yields the most biomass that is removed at harvest (≈10 Mg ha^{-1} grain) (Tewolde et al., 2009) followed by soybean (≈3,500 kg ha^{-1} seed) (Bender et al., 2015). Cotton produces the least amount of biomass that is removed at harvest. Cotton yields about 3,600 kg ha^{-1} seedcotton that is removed at harvest but only about 60% of that is seed, which contains much of the mineral elements in seedcotton (Tewolde, McLaughlin, et al., 2016). The other 40% of the seedcotton is lint, which contains very little mineral elements. Of the three crops, cotton removes the least amount of mineral elements from the soil. Soybean removes as much K as, or slightly more K than, corn. Therefore, growing continuous cotton (which is a common practice in the region) fertilized with poultry litter as the primary fertilizer can result in a buildup of PL-derived elements (Adeli et al., 2008; Tewolde et al., 2018). Growing cotton in rotation with either corn or soybean or both likely would minimize nutrient buildup as found by Adeli et al. (2008) and Tewolde et al. (2018).

Rotating fertilizers with or without crop rotation systems may also be an effective strategy to prevent the buildup of excess P and other PL-derived nutrients from repeated applications. This strategy was suggested by Tewolde et al. (2007) for managing the buildup of PL-derived P when the PL is applied to supply N. In this strategy, PL would be applied to meet the N need of the target crop every year for a few years. Such application would meet all mineral nutrient needs for crops like cotton and eliminate the need to apply any other fertilizer, thereby being more cost-effective. However, it is well established that applying PL to meet the N need leads to the buildup of excess P and possibly other elements in the soil. Suspending PL application and returning to conventional inorganic N fertilization in subsequent years will likely result in mining the P and other excess elements from the soil, reducing the P concentration to the initial levels at which point PL fertilization may be resumed. The viability of this strategy separately or in conjunction with crop rotation, however, has not been tested. The objective of this study was to determine whether detrimental buildup of nutrients due to repeated PL application to the same soil can be managed by rotating fertilizers between PL and synthetic N fertilizers and rotating the most commonly grown row crops (cotton, corn, and soybean) in the southeastern United States.

2 | MATERIALS AND METHODS

The study was conducted from 2010 to 2014 in the field at the Mississippi Agricultural and Forestry Experiment Station (MAFES) at Mississippi State University in Verona, MS, in a Leeper fine sandy loam soil (fine, smectitic, nonacid, thermic Vertic Epiaquepts). According to NRCS, the Leeper series consists of very deep, somewhat poorly drained soils that formed in clayey alluvium on flood plains of the Alabama, Mississippi, and Arkansas Blackland Prairie (USDA-NRCS, 2019).

2.1 | Experimental setup

The study consisted of two factors: crop rotation with four levels and fertility strategies with five levels. The crop rotation treatments included CCCCC, CCMMB, CMBBM, and CMCBM where each letter represents cotton (C), corn (M), and soybean (B) planted in 2010, 2011, 2012, 2013, and 2014. The five fertility levels included an unfertilized control, a standard fertilization with conventional synthetic fertilizers to meet crop nutrient requirements (Std), and three PL fertilization treatments. The PL fertility treatments included P-based litter application every year for 5 yr (P5L), N-based litter application every year for 5 yr (N5L), and N-based litter application every year in the first 2 yr and synthetic N application at the same rate as the Std in the last 3 yr (N2L). All fertilized treatments were targeted to receive equivalent plant-available N regardless of the source. The N recommendation for the region is 100 kg ha^{-1} for cotton and 224 kg ha^{-1} for corn. The N5L and N2L treatments received PL based on cotton N requirement whether planted with cotton, corn, or soybean. The P-based treatment (P5L) received PL that supplied enough P to replace expected P removed by cotton at harvest. Based on these criteria, the P5L treatment received a 5-yr average of 2.5 Mg ha^{-1} yr^{-1} PL and the N5L treatment received 7.9 Mg ha^{-1} yr^{-1} PL (Table 1). When corn was planted in a rotation, the P5L and N5L treatments received the same PL rates as for cotton (2.5 and 7.9 Mg ha^{-1} yr^{-1}, respectively). However, synthetic N in addition to the N supplied by the PL was applied to meet the corn N need for optimal corn yield because the PL applied for cotton does not satisfy the N need for corn. The target N rate for corn was 224 kg ha^{-1}. No synthetic N was applied to any of the treatments if planted with soybean in the rotation. Phosphorus and K fertilizers were applied to the Std treatment for optimal yield of the respective crop based on soil analysis and recommendations from Mississippi State University Extension Service, Soil Testing Laboratory. The design was a randomized complete block with split-plot treatment structure and four replications, where the crop rotation treatments were assigned to main plots and the fertility treatments to sub-plots. Each sub-plot consisted of four 30.5-m long rows spaced 0.97 m apart.

2.2 | Plot management

The field was initially prepared in 2010 by conventional tillage, which included field cultivation, chisel harrowing, bedding, and a one-pass field preparation using a PrepMaster bed conditioner implement (Bigham Brothers). In subsequent years, the plots were managed as minimum tillage in which the beds were reformed without cultivation or breaking the beds. The plots were then prepared using the PrepMaster for PL application and planting. According to the manufacturer, the PrepMaster cuts and distributes stalks and conditions the top of the bed by flattening and firming the seedbed (http://bighamag.com/bed-preparation/prepmaster/).

Each spring, PL was procured from regional broiler chicken operations and applied before planting corn, which is the earliest of the three crops. The PL each season was from total cleanout of chicken houses and was uncomposted when delivered to the research site (other than unintended composting that may have occurred while waiting for application). The PL was applied as a surface broadcast using a commercial manure spreader and lightly incorporated into the soil within

TABLE 1 Poultry litter and synthetic N rates applied to cotton, corn, and soybean in a study that investigated the sustainability of poultry litter fertilization in a cotton–corn–soybean crop rotation system

	Applied poultry litter					Applied synthetic N[a]								
	All three crops					Cotton					Corn			
Treatment	2010	2011	2012	2013	2014	2010	2011	2012	2013	2014	2011	2012	2013	2014
	Mg ha^{-1}					kg ha^{-1}								
UTC[b]	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P5L	2.4	2.4	2.2	2.9	2.5	65	70	69	64	69	202	197	175	195
N5L	7.8	7.7	9.6	6.7	7.9	0	0	0	0	0	133	121	138	132
N2L	7.8	7.8	0	0	0	0	0	112	87	99	133	242	240	224
Std	0	0	0	0	0	101	95	112	87	99	220	242	240	224

[a]No synthetic N was applied to soybean in any year. [b]UTC, unfertilized control.

TABLE 2 Chemical properties of background soil and poultry litter used in a study that investigated the sustainability of poultry litter application at Mississippi Agricultural and Forestry Experiment Station at Verona, MS

Sampling/ application date	Moisture	Total N	Total C	P	K	Mg	Ca	Cu	Fe	Mn	Zn
	g kg^{-1}							mg kg^{-1}			
Background soil[a]											
28 Apr, 2010	—	1.12	10.2	0.058	0.23	0.08	2.07	0.92	262	85	2.91
Broiler litter											
29 Apr. 2010	274	26.9	226.0	18.1	28.4	6.32	29.2	95	702	483	434
9 May 2011	220	27.6	230.4	15.6	30.5	6.54	22.7	298	1,872	699	448
29 Mar. 2012	373	26.8	211.7	11.8	23.2	5.75	17.9	251	759	499	334
16 May 2013	220	33.1	234.8	21.5	23.8	6.22	31.7	104	853	454	420
24 Apr. 2014	261	23.3	202.2	10.5	22.0	5.56	18.7	227	1,182	526	347

[a]Values of soil P, K, Mg, Ca, and the micronutrients are Mehlich 3–extractable amounts. Values of all nutrients in poultry litter are total amounts.

1 d usually by running a Do-all seedbed conditioner implement. The incorporation with the Do-all implement involved spike tooth harrowing, smoothing the top of the bed by moving soil down to lower parts, and mixing the PL with soil in the process. The spreader was equipped with load cells that allowed the determination of the actual amount applied to each plot, which deviated from the target rate because the application was based on calibration of the spreader. Whereas the two target rates were 2.2 and 7.5 Mg ha^{-1} yr^{-1}, the actual amounts applied based on the spreader scale were a 5-yr average of 2.5 and 7.9 Mg ha^{-1}. Table 2 shows the dates of application and chemical analysis of the PL.

The synthetic N applied to the respective treatment was in the form of liquid UAN (32% N) in 2010–2013 and in the form of granular NH_4NO_3 (34% N) in 2014. In 2010–2013, the UAN was applied by injecting a calibrated amount into soil slits opened by the applicator about 15 cm to one side of the corn or cotton row to a depth of about 8–10 cm. In 2014, a weighed amount of NH_4NO_3 was applied by hand to each plot. The synthetic N applications were made around the pin-head square stage for cotton and split-applied at planting and at the V6 stage for corn. Based on soil test results, P and K fertilizers were recommended for the Std treatment under cotton and soybean only in 2014. Phosphorus (20 kg P ha^{-1}) in the form of triple superphosphate (0–46–0, N–P_2O_5–K_2O) and K (28 kg K ha^{-1}) in the form of KCl (0–0–60, N–P_2O_5–K_2O) were manually broadcast-applied by hand on 13 May 2014 to the Std plots under cotton and soybean.

The three crops were planted each spring according to the schedule based on the treatment. Corn was planted as early as late March and as late as mid-May, cotton was planted usually in May, and soybean was planted late April to mid-May (Table 3). The seeding rates were an average of 69,000 seeds ha^{-1} for corn, 139,000 seeds ha^{-1} for cotton, and 337,000 seeds ha^{-1} for soybean. Cotton varieties planted were ‘PHY 485 WRF’ in 2010 and ‘PHY 499 WRF’ in 2011–2014 (PhytoGen Seed Company, Dow AgroSciences LLC). The corn variety ‘DKC 64–69′ (DeKalb Genetics Corporation) was planted in all 4 yr that corn was included in the rotation. Soybean varieties included ‘Pioneer P94Y90’

TABLE 3 Dates of planting and harvest of corn, cotton, and soybean at Mississippi Agricultural and Forestry Experiment Station at Verona, MS where the sustainability of poultry litter application was investigated

	Planting date			Harvest date		
Year	Cotton	Corn	Soybean	Cotton	Corn	Soybean
2010	8 Jun.	NA	NA	18 Oct.	NA	NA
2011	10 May	10 May	NA	27 Sept.	9 Aug.	NA
2012	17 May	29 Mar.	24 Apr.	17 Oct.	23 Aug.	23 Sept.
2013	28 May	16 May	16 May	21 Oct.	19 Sept.	3 Oct.
2014	21 May	24 Apr.	6 May	7 Oct.	4 Sept.	1 Sept.

Note. NA, not applicable.

in 2012 (Pioneer Hi-Bred International), 'Armor DK 4744′ in 2013 (Armor Seed), and 'Pioneer P49TR80' in 2014. Corn was not in the rotation in 2010 and soybean was not in the rotation in 2010 and 2011. All plots were irrigated on 10 July 2013, 18 July 2013, and 7 Aug. 2013 to about 35–45 mm. No irrigation was applied in any of the other 4 yr. The crops were managed according to local practices regarding pest control and other management needs.

2.3 | Data collection

Soil samples were collected five times during the 5 yr period using a standard (2.54-cm inner diameter) soil probe. The first set of samples was collected on 27 Apr. 2010 before any treatment was imposed to establish the background chemical properties of the soil. On this day, five cores, one from each subplot, were collected to 15 cm depth and composited by main plots in each replication. Four subsequent samples were collected on 31 Oct. 2011, 7 Nov. 2012, 25 Oct. 2013, and 30 Apr. 2015, all of which represented samples after imposing the treatments and harvesting the crops. On these days, three to four core samples were collected from the middle two rows of each subplot and composited.

All soil samples from all days were prepared for chemical analysis by air-drying and crushing to pass a 2-mm screen and stored for chemical analysis. The samples were analyzed for total C, total N, and Mehlich 3–extractable P, K, Ca, Mg, Cu, Mn, Fe, and Zn (Mehlich, 1984) after further crushing subsamples inside glass vials with three stainless steel rods on a roller device (Arnold & Schepers, 2004). Total C and N content of the samples was analyzed on approximately 1.0 g soil by an automated dry combustion method using an Elementar Vario MAX CN analyzer (Elementar Americas Inc.). Extractable P, K, Ca, Mg, Cu, Mn, Fe, and Zn were determined by extracting 2 g of the air-dried and crushed soil with 20 ml Mehlich 3–extractant and analyzing by inductively coupled plasma–optical emissions spectroscopy (ICP-OES) (Varian, Vista Pro; Varian Analytical Instruments).

The PL applied each year was also analyzed for total N and C content by the same method as the soil samples. Litter total P, K, Mg, Ca, Cu, Mn, Fe, and Zn were analyzed each year using ICP–OES after ashing ≈0.2-g ground samples in a muffle furnace at 500 ˚C for 4 h, digesting the ash with 1.0 ml 6 *M* HCl for 1 h followed by 40 ml solution of 0.0125 *M* H_2SO_4 and 0.05 *M* HCl for an additional 1 h. Soil pH was measured in a 1:1 soil/water suspension with a standard laboratory pH electrode.

2.4 | Statistical analysis

All data were subjected to analysis of variance as a randomized complete block design with split-plot treatment structure using the PROC MIXED procedure of the Statistical Analysis System. Years (or sampling date) were included in the analysis as a repeated measures effect. Fertility and rotation treatments were set as fixed effect factors, replication as a random effect factor, and the interaction of replication by fertility within rotation treatments as subjects for repeated measure covariance (Littell, Milliken, Stroup, & Wolfinger, 2002). Models with different covariance structures of the repeated measures were used to choose a covariance structure most effective in describing data variability for each nutrient. The data were further analyzed using the chosen covariance structure to obtain the F-test for the fixed effects and mean comparisons. Differences between two treatments were declared significant if $P \leq .05$ based on LSD test unless specified otherwise.

3 | RESULTS AND DISCUSSION

Extractable nutrients from soil samples taken after crop harvest in each of the 4 yr (2011–2014) were affected by both fertility and rotation treatments (Table 4). The interaction between fertility and rotation was not significant for any of the elements, thus, the data will be presented as fertility and rotation main effects. The rotation by year interactions were

TABLE 4 Test of significance of the fixed effects of rotation, fertility treatments, year, and their interactions on extractable soil elements in the 0 to 15-cm depth

Effect	pH	P	K	Ca	Mg	Cu	Fe	Mn	Zn
	Pr > F								
Rotation (R)	.101	<.001	.381	.020	<.001	<.001	<.001	.002	.003
Fertility (F)	.004	<.001	<.001	.619	<.001	<.001	<.001	.043	<.001
R × F	.985	.763	.850	.999	.340	.787	.591	.985	.667
Year (Y)	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
R × Y	.026	.162	<.001	.001	.669	.474	.673	.986	.442
F × Y	.743	<.001	<.001	.451	<.001	<.001	.602	.999	<.001
R × F × Y	1.000	1.000	.493	.996	1.000	.642	.999	1.000	.429

significant for some elements, which suggests rotation affected these elements some years. The fertility × year interactions were significant for most elements, which shows the data need to be presented separately for each year.

3.1 | Rotating fertilizers is an effective PL management strategy

3.1.1 | Macronutrients

Phosphorus is the most important element that accumulates in the soil when poultry litter is applied repeatedly to the same soil. In this study, as expected, two applications of 7.9 Mg ha^{-1} yr^{-1} PL (a rate intended to meet the full cotton N need) added a 2-yr total of 262 kg ha^{-1} PL-derived P (Tables 1 and 2) and increased Mehlich 3–P (M3P) by >80% relative to the Std after harvest in 2011 (Figure 1). The soil initially (28 Apr. 2010) had 58 mg kg^{-1} M3P. The Std treatment, which received no P application from any source, had an average across rotations of 36.8 mg kg^{-1} M3P on 31 Oct. 2011, after growing two crops of cotton and corn. The N5L and N2L treatments on this sampling date had an average of 70.0 mg kg^{-1} M3P, 89% more than the Std. Repeating the 7.9 Mg ha^{-1} yr^{-1} PL application for another 3 yr for the N5L treatment continued to elevate the level of M3P to more than three-fold of the Std after 5 yr (101 vs. 33 mg kg^{-1}). The lower P-based application also increased M3P relative to the Std to a lesser degree. After 5 yr of annual application, this treatment (P5L) increased M3P by 35% relative to the Std. This increase, however, may not mean the P-based application supplied P in excess of the amount removed by the harvested cotton. It may just mean that the Std treatment depleted soil P by about 35% as no P was applied to the Std throughout the 5 yr because the soil had sufficient P for cotton according to Mississippi State University soil analysis and recommendation. Therefore, we believe the P-based litter application (P5L) maintained the initial soil P level, the N-based application (N5L) elevated it, and the Std lowered it. After 5 yr, the N5L treatment increased M3P by 124% relative to the P5L treatment (101 vs 45 mg kg^{-1} P).

Our results show that, as many have found before (Eghball & Power, 1999; McGrath et al., 2010), the P-based PL application is an effective poultry litter management method (Maguire et al., 2008; Moore et al., 1995). However, the P-based application does not supply the full N amount for optimal cotton yield and must be supplemented with synthetic N application, which requires another field trip adding to the cost of production. In this study, we included the N2L treatment to test if applying PL at the N-based rate for 2 yr and suspending PL application for 2–3 yr would serve the same purpose as the P-based treatment (P5L) without the additional cost. The results show that, after two applications of 7.9 Mg ha^{-1} yr^{-1}, the N2L treatment elevated M3P by 97% relative to the Std (72.6 vs. 36.8 mg kg^{-1}) (Figure 1). After suspending PL application and returning to the practice of fertilizing with just synthetic N for the last 3 yr, the M3P level decreased to be comparable to the P-based PL application (49.7 vs. 45.0 mg kg^{-1}).

The results show that the application of PL may be made in at least two ways to manage P buildup in the soil. One approach is to apply PL each year to supply P equivalent to the amount of P that can be removed with the harvested crop or to meet the P need of the crop. Because this PL rate does not supply adequate N, additional N in the form of synthetic fertilizers should be applied each year. This management system, however, requires yearly application of small amounts of litter, adding to the cost of production. An alternative approach is to apply a higher rate of PL to meet the N need of cotton for one to two seasons and suspend the PL applications in subsequent years until the P level is drawn down to the initial or desired level. During the years when PL is not applied, a full rate of synthetic N is applied to meet the crop's N need. One advantage of this practice is that soils that have a short history of PL fertilization are more productive when returned to fertilization with synthetic N than soils without PL application history or with a history of low PL rates (Tewolde, Sistani, et al., 2016). The other advantage of the PL cessation practice

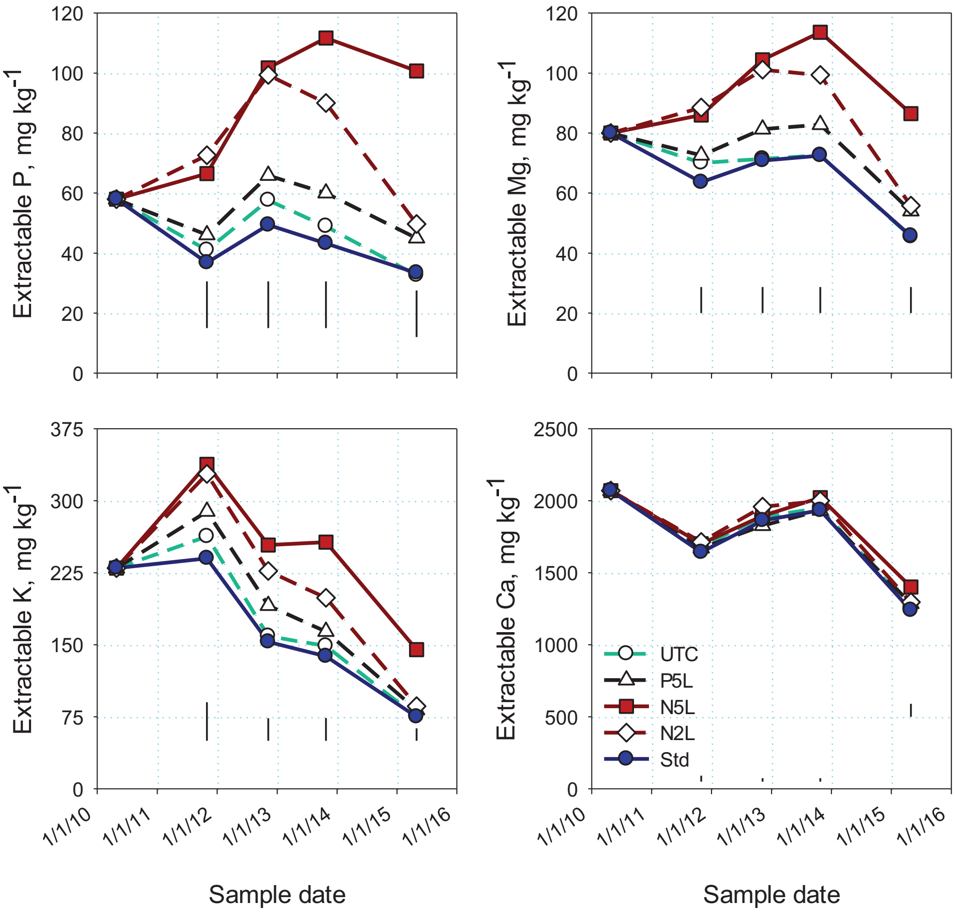

FIGURE 1 Concentration of Mehlich 3–extractable P, K, Mg, and Ca from soil (0 to 15-cm depth) that received poultry litter and on which cotton, corn, and soybean were grown in rotation from 2010 to 2014. The values for the first day (28 Apr. 2010) represent nutrient levels based on samples taken prior to imposing treatments. The other values represent nutrient levels from samples taken after harvest each year. Each data point is an average across four replications and four rotation treatments as there was no treatment by rotation interaction. Vertical bars denote LSD for comparing two treatment means at $P = .05$. Absence of vertical bar denotes no two treatments means are different from each other at that particular sampling date

is lower cost of production not only with the application operations but also because usually only synthetic N is required in subsequent crops. In most cases, residuals from the previous PL application have been shown to be sufficient for optimal cotton yield. However, caution is necessary when using the cessation approach. The excess P applied with the relatively high PL application in the first 2 yr remains in the soil beyond the first 2 yr and becomes vulnerable to potential losses by runoff and leaching. Therefore, this approach should only be used in soils with lower risk of runoff and leaching losses. Such risks, however, may be mitigated through management approaches such as planting winter cover crops in those years with high extractable soil P buildup (Tewolde et al., 2015).

Similar to M3P, Mehlich 3–extractable K (M3K) also accumulated in the soil when fertilized with PL compared with the Std treatment. After 2 yr of 7.9 Mg ha^{-1} yr^{-1} PL application, M3K of the N5L and N2L increased by >35% relative to the Std (Figure 1). The N5L treatment, which continued to receive PL at this rate for an additional 3 yr, had 93% more M3K than the Std treatment on 30 Apr. 2015 (end of the 2014 study). The Std received no K fertilization during the 5-yr period, whereas the N5L treatment received an average of 192 kg K ha^{-1} yr^{-1} from 7.9 Mg ha^{-1} yr^{-1} PL for 5 yr. The P5L treatment, which received an average of 55.6 kg K ha^{-1} yr^{-1} from 2.5 Mg ha^{-1} yr^{-1} PL for 5 yr, had 9.3% greater M3K than the Std on 30 Apr. 2015. The N2L was similar to the P5L treatment in M3K on 30 Apr. 2015.

When compared against the initial levels, however, M3K did not show accumulation due to PL application; instead it declined across the seasons. Mehlich 3 K of the N5L declined from 230 mg kg^{-1} on 28 Apr. 2010 to 145 mg kg^{-1} on 30 Apr. 2015 (Figure 1). The M3K decline for the N5L treatment which received an average of 192 kg K ha^{-1} yr^{-1} (or a 5-yr total of 960 kg K ha^{-1}) from PL, seems to suggest this amount was not adequate to maintain the initial soil K levels. However, the average amount of K removed from the soil in harvested plant parts by the N5L treatment was an average across years and the four rotation treatments of 43 kg ha^{-1} yr^{-1}

(21–63 kg K ha^{-1} yr^{-1}) (Tewolde, unpublished data, 2021). This K removal amount is consistent with reported K removal amounts for the three crops: 20–30 kg ha^{-1} for cotton (Tewolde, et al., 2010), 40–45 kg ha^{-1} for corn (Heckman et al., 2003; Nathan et al., 2006; Tewolde, et al., 2019), and 50–65 kg ha^{-1} for soybean (Bender et al., 2015; Nathan et al., 2006). The highest PL rate (N5L) supplied an average of 192 kg ha^{-1} yr^{-1} K, which implies that 149 kg ha^{-1} yr^{-1} remained in the soil because an average of only 43 kg ha^{-1} yr^{-1} was removed at harvest. The discrepancy between our expectation of K buildup for the N5L treatment and the lack of our soil test to reflect this buildup suggests one of two possibilities. The first is that the K was lost to deeper soil profiles through leaching. But data for M3K at the 15–30-cm depth did not show that K was lost to deeper soil profiles. At the end of the study on 30 Apr. 2015, the N5L treatment had an average of 82% more M3K in the 0–15-cm depth (Figure 1) but had essentially the same M3K as the other four treatments (average across the five treatments of 46 kg ha^{-1}) at the 15–30-cm depth (data not shown). Whereas the possibility of some K movement below the 0–15-cm depth exists, much of the applied K for the N5L treatment that was not removed at harvest likely was stored somewhere in the soil but not captured in the soil analysis. We believe this K, as also explained by Tewolde et al. (2018), was tied up in plant parts that were returned to the soil at the time of harvest but had not decomposed and released the K at the time soil samples were collected.

Potassium accumulation in the soil as a result of PL applications usually is not a concern. To the contrary, our results show K depletion should be the concern when fertilizing crops with PL especially when soybean is the primary crop and the application rate is based on the P need. Soybean is known to remove a substantial amount of K from the soil with harvested seed. For example, Bender et al. (2015) reported a K removal of 66 kg ha^{-1} with 3,531 kg ha^{-1} harvested seed. In our study, soybean removed nearly 90 kg ha^{-1} K with an average seed yield of 4,560 kg ha^{-1} (Tewolde, unpublished data, 2021). So, our results show that, rather than a concern of soil K buildup, monitoring extractable K in the soil so that levels do not decline below crop needs should be the primary strategy of PL management.

Mehlich 3–extractable soil Mg (M3Mg), relative to the Std treatment, also accumulated in the soil in response to PL application based on cotton N need. The N5L treatment which received 7.9 Mg ha^{-1} yr^{-1} PL had >35% more M3Mg on 31 Oct. 2011 and 89% more M3Mg than the Std treatment at the end of the 5 yr on 30 Apr. 2015 (Figure 1). The P5L treatment which received the P-based PL rate showed only slightly higher M3Mg than the Std, which suggests that no Mg buildup occurs if PL is applied based on the P need of cotton (although Mg buildup is not usually a concern). Extractable Mg of the N2L declined to the level of the P5L treatment on 30 Oct. 2015 when PL application was stopped after 2 yr of 7.9 Mg ha^{-1} yr^{-1} of application. Extractable Ca was not affected by the treatments although the highest PL application seemed to slightly increase it (Figure 1).

3.1.2 | Micronutrients

Zinc and Cu are two microelements known to accumulate in the soil following repeated applications of PL (Adeli et al., 2007; Schomberg et al., 2009). Consistent with past findings, the levels of Mehlich 3–extractable Zn (M3Zn) and Mehlich 3–extractable Cu (M3Cu) in our study were elevated by the higher rate (N-based) PL applications. Relative to the Std, M3Zn of the N2L treatment increased by 52% (2.38 mg kg^{-1} for the Std vs. 3.63 mg kg^{-1} for the N2L) and M3Cu increased by 21% (1.08 mg kg^{-1} for the Std vs. 1.31 mg kg^{-1} for the N2L) after two applications of 7.9 Mg ha^{-1} yr^{-1} (Figure 2). Continuing to apply this same rate (7.9 Mg ha^{-1} yr^{-1}) for an additional 3 yr elevated M3Zn from 1.33 mg kg^{-1} for the Std to 4.41 mg kg^{-1} for the N5L treatment (a 232% increase) and M3Cu from 0.87 mg kg^{-1} for the Std to 1.75 mg kg^{-1} for the N5L (a 101% increase).

Relative to the Std treatment, the lower rate (P-based) PL application also elevated extractable Zn and Cu after 5 yr but not so clearly after 2 yr. After applying 2.5 Mg ha^{-1} yr^{-1} PL for 5 yr, M3Zn increased from 1.33 mg kg^{-1} for the Std to 2.48 mg kg^{-1} for the P5L treatment (an increase of nearly 87%) and M3Cu increased from 0.87 mg kg^{-1} for the Std to 1.02 mg kg^{-1} for the P5L treatment (a 17% increase) (Figure 2). The alternative application strategy, in which PL was applied at the N-based rate (7.9 Mg ha^{-1}) for the first 2 yr and suspended for the next 3 yr, resulted in extractable Zn and Cu very similar to the P-based PL application strategy on 30 Apr. 2015. After 2 yr on 31 Oct. 2011, the N2L treatment clearly had greater M3Zn and M3Cu than the P5L treatment. The difference between these two treatments on 31 Oct. 2011 was that the P5L treatment received two applications of 2.5 Mg ha^{-1} PL (a total of 5.0 Mg ha^{-1}) whereas the N2L received two applications of 7.9 Mg ha^{-1} PL (a total of 15.8 Mg ha^{-1}). This difference in the total PL applied over the 2 yr was clearly reflected in the extractable Zn and Cu on 31 Oct. 2011, where the N2L treatment had 38 and 16% greater M3Zn and M3Cu, respectively, than the P5L treatment. After discontinuing the application for the N2L treatment and continuing to apply the 2.5 Mg ha^{-1} yr^{-1} for the P5L treatment for an additional 3 yr, the levels of M3Zn and M3Cu for the N2L treatment decreased to the level of the P5L treatment.

These results suggest, regardless of whether PL is applied based on P need (P5L treatment) or the alternative strategy (N2L), both Zn and Cu likely will accumulate in the soil. The accumulation of these elements in the soil, however, may not be a great concern with these two PL application strategies

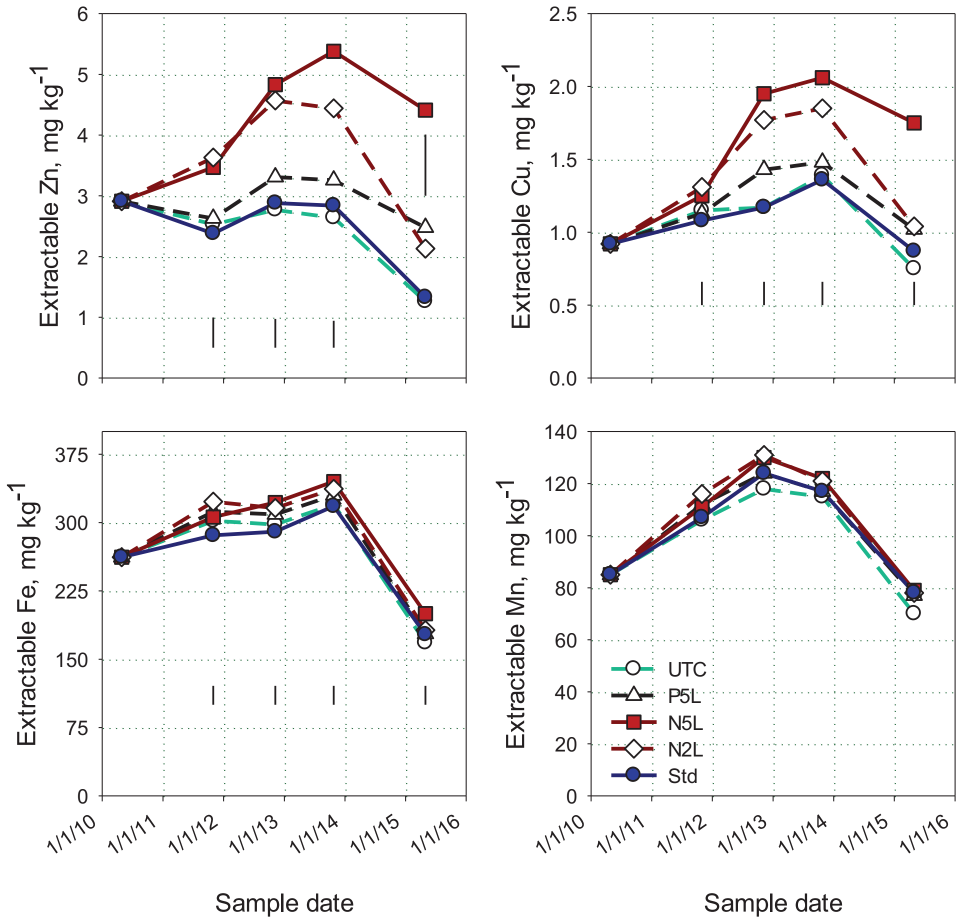

FIGURE 2 Concentration of Mehlich 3–extractable Zn, Cu, Fe, and Mn from soil (0 to 15-cm depth) that received poultry litter and on which cotton, corn, and soybean were grown in rotation from 2010 to 2014. The values for the first day (28 Apr. 2010) represent nutrient levels based on samples taken prior to imposing treatments. The other values represent nutrient levels from samples taken after harvest each year. Each data point is an average across four replications and four rotation treatments as there was no treatment by rotation interaction. Vertical bars denote LSD for comparing two treatment means at $P = .05$. Absence of vertical bar denotes no two treatments means are different from each other at that particular sampling date

practiced for a relatively short time (5–10 yr). Elevated levels of soil Cu have been reported in vineyards (Ruyters, Salaets, Oorts, & Smolders, 2013) and other agricultural soils (Shabbir et al., 2020, Stowhas et al., 2018) worldwide. However, soil Cu elevations do not necessarily mean toxicity even when the levels are as much as 20–30 times the normal unaffected soil levels (Ruyters et al., 2013). Zinc can also be toxic to plants (Fontes & Cox, 1998) if accumulated but its accumulation and toxicity do not appear to be a widespread concern. Whether the levels of Zn and Cu can elevate to toxic levels due to relatively low PL applications similar to the rates of the P5L and N2L treatments in our study should be investigated in long-term studies.

Mehlich 3-extractable Fe (M3Fe), similar to M3Zn and M3Cu, also accumulated in the soil in response to the PL applications but the magnitude of accumulation was much smaller than M3Zn and M3Cu. Applying 7.9 Mg ha^{-1} yr^{-1} PL (N5L) resulted in as much as 13% greater M3Fe than the Std treatment in 2015 (200 vs. 177 mg kg^{-1}) (Figure 2). The P-based PL (P5L) application increased M3Fe in 2011 but not so clearly in the other years. Differences among the three PL treatments in M3Fe were small and inconsistent. These results that suggest Fe accumulation in the soil due to repeated PL applications should not be of great concern. Iron, as one of the most abundant elements in Earth's crust, is a ubiquitous element in the soil. The amount added to soils with low rates of PL application often is small relative to the native amount already present in the soil. Its availability to plants, which is dependent on the soil pH, likely is more important than its accumulation. This dependence is reflected in the M3Fe levels across sampling dates in this study. Soil pH was highest (6.02 when averaged across the five treatments) and M3Fe was lowest in the last sampling date among the five dates (Table 5; Figure 2).

Mehlich 3–extractable Mn (M3Mn), unlike the three other micronutrients measured in this study, was not affected by

TABLE 5 pH of soil (0 to15-cm depth) that received poultry litter and on which cotton, corn, and soybean were grown in rotation in 2010–2014

Fertility treatment	28 Apr. 2010[a]	31 Oct. 2011	7 Nov. 2012	25 Oct. 2013	30 Apr. 2015
UTC[c]	5.46	5.78a[b]	5.51a	5.19b	6.05ab
P5L	5.46	5.78a	5.60a	5.20b	5.97ab
N5L	5.46	5.83a	5.73a	5.48a	6.23a
N2L	5.46	5.92a	5.83a	5.36ab	6.01ab
Std	5.46	5.81a	5.58a	5.15b	5.85b
Pr > F	—	.806	.122	.077	.087

Note. Each value in the table is an average across four replications and four rotation treatments as there was no treatment by rotation interaction.
[a]Background nutrient levels based on samples taken prior to imposing treatments.
[b]Means followed by the same letter within a column are not significantly different at the $P = .05$ level.
[c]UTC, unfertilized control.

TABLE 6 Concentration of Mehlich 3–extractable mineral elements from soil (0 to 15-cm depth) on which cotton, corn, and soybean were grown in rotation from 2010 to 2014

Rotation treatment	pH	P	K	Mg	Ca	Zn	Cu	Fe	Mn
	mg kg^{-1}								
28 Apr. 2010[a]	5.46	58	230	80	2,070	2.91	0.92	262	85
31 Oct. 2011									
C**C**CCC	5.70b[b]	48.1b	295a	70.9b	1,634b	2.70a	1.12b	308a	106a
C**C**MMB	5.63b	47.5b	265a	75.2b	1,587b	2.90a	1.14b	298a	110a
C**M**BBM	5.97a	64.6a	307a	85.8a	1,793a	3.22a	1.29a	318a	110a
C**M**CBM	6.00a	50.2b	300a	72.7b	1,718ab	2.90a	1.18ab	299a	115a
Pr > F	.003	.051	.103	<.001	.05	.144	.089	.121	.525
7 Nov. 2012									
CC**C**CC	5.70a	73.2b	187b	80.5b	1,876a	3.44bc	1.40b	304b	119a
CC**M**MB	5.65a	58.9c	186b	82.3b	1,799a	3.29c	1.40b	292b	123a
CM**B**BM	5.66a	89.7a	212a	94.7a	1,912a	4.12a	1.59a	326a	128a
CM**C**BM	5.58a	77.4ab	204ab	85.7b	1,964a	3.85ab	1.60a	306b	132a
Pr > F	.788	<.001	.035	.002	.243	.001	.003	.004	.11
25 Oct. 2013									
CCC**C**C	5.35a	68.6ab	178a	86.2b	1,944bc	3.49b	1.63a	327b	110b
CCM**M**B	5.29a	60.5b	192a	86.8ab	1,828c	3.62b	1.54a	317b	120ab
CMB**B**M	5.12a	82.2a	175a	94.4a	2,024ab	4.02a	1.70a	347a	118ab
CMC**B**M	5.35a	71.8ab	180a	85.4b	2,077a	3.71ab	1.64a	329ab	127a
Pr > F	.158	.024	.384	.083	.001	.066	.164	.017	.039
30 Apr. 2015									
CCCC**C**	6.03a	62.9a	105a	57.9a	1,314a	2.33a	1.11a	186a	73a
CCMM**B**	5.86a	44.8b	88b	55.9a	1,200b	2.05a	1.02a	177a	75a
CMBB**M**	6.10a	55.0ab	90b	61.9a	1,337a	2.98a	1.18a	184a	75a
CMCB**M**	6.10a	46.4b	87b	54.2a	1,332a	1.93a	1.04a	178a	82a
Pr > F	.161	.04	.011	.237	.004	.111	.125	.727	.457

Note. The soil samples were taken after harvest each year starting in 2011. Each value in the table is an average across four replications and five fertility treatments as there was no fertility treatment × rotation interaction. The letters in bold font in the first column (rotation treatments) represent the last crop that was harvested before taking the soil samples for which data are given within each year. For example, the "B" in the CMCBM rotation on 25 Oct. 2013 shows the data in 2013 were for soil samples taken after growing and harvesting soybean. The previous crops in that rotation scheme were cotton, corn, and cotton in 2010, 2011, and 2012, respectively.
[a]Background nutrient levels based on samples taken prior to imposing treatments.
[b]Means followed by the same letter within a column and sampling date are not significantly different at the $P = .05$ level.

any of the treatments in any of the 4 yr (Figure 2). It is likely M3Mn levels, as M3Fe levels, were affected more by the soil chemistry (soil pH, for example) than by external supply of the element. Mehlich 3–extractable Mn, as M3Fe, for all treatments was lowest on the last day of sampling (Figure 2) when the soil pH was highest (Table 5). PL application did not clearly lead to a clear accumulation of M3Mn at any of the sampling dates. This is somewhat not consistent with results from a recent study in which PL was applied in surface or subsurface bands. In that study, a relatively low rate of PL (6.1 Mg ha^{-1}) applied for three consecutive years reduced extractable soil Mn by 20% and cotton tissue Mn by as much as 40% relative to fertilization with synthetic fertilizers (Tewolde et al., 2018). Although we did not find the reduction in M3Mn as in Tewolde et al. (2018), our results suggest elevation of extractable soil Mn due to repeated PL applications should not be a concern in this soil. Our results further suggest that PL application strategies that are effective for managing the accumulation of the macronutrients would also be effective for managing the levels of extractable Fe and Mn and possibly Zn and Cu.

3.2 | Rotating crops is not as effective as rotating fertilizers for poultry litter management

Crop rotation affected extractable soil elements and soil pH but the effects were small and inconsistent (Table 6). Mehlich 3–extractable P was affected by rotation in all 4 yr with an overall tendency of lower M3P when corn was included in the rotation. For example, in 2013, the CCMMB treatment (with 60.5 mg kg^{-1}) had the lowest M3P among the four rotation treatments. After harvesting the 5th-year crop, the continuous cotton treatment (CCCCC) had slightly more M3P and M3K than any other rotation treatment that included corn or soybean. Such accumulations due to continuous cotton, however, were not evident in the other years (2011–2013). Rotation did not affect extractable Mg or any of the micronutrients after 5 yr. Rotation affected soil pH in 2011 only. After growing and harvesting two crops in 2011, soil pH seemed to be lower when cotton followed cotton (average of 5.7) than when corn followed cotton (average of 6.0), but this soil pH lowering effect of continuous cotton was not apparent in subsequent years. Other rotation treatments did not significantly affect soil pH in 2012 or later.

The lack of clear and consistent effect of rotation on residual soil nutrients is contrary to our expectation and contrary to nutrient removal characteristics of the three crops included in this study. Nutrient removal from the soil in the harvested plant parts of the three crops selected for this study is known to vary substantially. For example, with yields typical for the southeastern United States, cotton removes 15–19 kg ha^{-1} P in harvested seedcotton, an amount that is less than half that is removed in harvested corn grain (40 kg ha^{-1}) (He et al., 2013; Heckman et al., 2003; Nathan et al., 2006; Rochester, 2007; Tewolde et al., 2007, 2010,; 2019). Soybean removes about 18.0 kg ha^{-1} P in harvested seed. Therefore, growing continuous cotton or soybean fertilized with poultry litter as the primary fertilizer should result in a greater buildup of PL-derived P. Growing cotton in rotation with corn, however, should reduce the level of residual P below that of continuous cotton. In 2015, the three rotation treatments that included corn had an average of 17% less M3P than the continuous cotton (Table 6). In 2013 and earlier, however, there was no such reduction due to the inclusion of corn and soybean in the rotation. These results suggest that crop rotation alone may not be an effective strategy to prevent the buildup of P and other mineral elements in the soil due to repeated PL applications.

4 | CONCLUSION

The results of this study show that when excess nutrients accumulate in the soil because of repeated PL applications, rotating fertilizers where the application of PL is suspended for 2–3 yr during which only synthetic N fertilizers are applied would return the soil nutrient status to near the initial levels. Applying the PL based on the P need of the crop, which is the most commonly recommended PL management, can also be used with about the same outcome. However, the new strategy where PL is applied at relatively high rates for a few years and the application is suspended for 2–3 subsequent yr may offer a more efficient management strategy for farmers who desire to reduce cost of production. There may also be yield-increasing advantages with this strategy. Rotating crops may help reduce the buildup of P and K but may not be as effective as rotating PL with synthetic fertilizers to manage nutrient buildup emanating from repeated poultry litter applications.

AUTHOR CONTRIBUTIONS

Haile Tewolde, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Writing-original draft, Writing-review & editing; Normie Buehring, Conceptualization, Investigation, Methodology, Resources, Supervision; Gary Feng, Investigation, Methodology, Resources; Tom Way, Methodology, Resources, Writing-review & editing.

CONFLICT OF INTEREST

Authors declare no conflicts of interest.

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