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Yield and nutrient removal of cotton–corn–soybean rotation systems fertilized with poultry litter

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Abstract

Exporting excess mineral nutrients from soils that receive repeated poultry litter (PL) applications may be enhanced by rotating crops and fertilizers that increase crop yield. This study determined the magnitude of yield enhancement and mineral nutrient removal at harvest by cotton–corn–soybean rotation systems and by PL-synthetic fertilizer rotations. Cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.] were grown in rotation for 5 yr with five fertility treatments which included an unfertilized control (UTC), a standard fertilization with synthetic fertilizers yearly, phosphorus-based poultry litter application every year for 5 yr (P5L), nitrogen-based poultry litter application for 5 yr (N5L), and nitrogen-based poultry litter application for 2 yr followed by synthetic nitrogen fertilization for 3 yr (N2L). The results showed that the N2L treatment, an alternative to the P-based PL management, increased the yield of all three crops and enhanced nutrient mining and removal. All three treatments that involved PL fertilization increased soybean yield by as much as 12% over the Std. Rotation did not affect the yield of any of the three crops, but continuous cotton removed the least amount of nutrients. Rotations that included two soybean crops in the 5 yr removed the most amount of nutrients. The best strategy of managing PL where the three crops are grown in rotation is to fertilize cotton with PL to supply 100% of its N need followed by growing soybean without applying any fertilization in the subsequent 2 or 3 yr.

1 | INTRODUCTION

Poultry litter (PL), a byproduct of the poultry industry, has increasingly been used as a fertilizer for row crop production in the southeastern United States where much of the industry in the United States is concentrated. Traditionally, PL has been used on pasture and forage fields not far from poultry houses. Row crop producers, however, are discovering its value and are expanding its use to new fields far from its point of generation.

Research has shown that P and other mineral elements accumulate in the soil when PL is applied repeatedly to the same soil for as few as 2–5 yr (Adeli et al., 2008; Gascho & Hubbard, 2006; Mitchell & Tu, 2006; Schomberg et al., 2009; Tewolde et al., 2007a). This accumulation can reach unsustainably high levels and become of environmental concern, such as eutrophication of surface water bodies, if the applications that exceed crop needs are continued for longer than 5 yr (Sharpley et al., 2004). Research has also shown that

Abbreviations: ICP-OES, inductively coupled plasma–optical emissions spectroscopy; NUE, nitrogen use efficiency; PAN, plant available nitrogen; PL, poultry Litter; UAN, urea-ammonium nitrate.

applying just enough PL to meet the P need of the crop, often referred to as P-based application, is the best PL application strategy to prevent P and other nutrients from accumulating in the soil (Eghball & Power, 1999; Maguire et al., 2008). However, operationally, this approach may not always be the most efficient strategy because of the inadequacy of the P-based PL application rate to meet all nutrient requirements of a crop. The nutrient profile of a typical PL is not balanced relative to the requirements of many crops. When applied to meet a crop's N need, PL often supplies P in excess of the crop's need. When PL is applied to meet the crop's P need, the rate is often inadequate to meet other nutrient needs including N and K. As a result, the P-based PL application must be supplemented with synthetic fertilizers which is a practice that leads to increased cost of production due to additional operations. The southeastern U.S. region, which generates much of the PL in the United States, needs PL management strategies that are cost-effective, sustainable, and compatible with current crop production systems as alternatives to the P-based PL management.

Core Ideas

- Fertilization with synthetic N after stopping poultry litter applications enhances yield and nutrient removal.
- Cotton among the three crops removed the least amount of nutrients and soybean removed the most.
- Rotations that included two soybean crops in 5 yr removed the greatest amount of nutrients.
- Growing soybean with residual nutrients from previous poultry litter applications may be most economical.
- Approximately 35% of total poultry litter N becomes available for corn during the same season.

One such strategy may be rotating crops with known differences in nutrient removal. Diversified crop rotations using cover crops, to provide a variety of ecosystem functions, and inserting legumes, such as soybean [*Glycine max* (L.) Merr.], which require a constant supply of P and K and which have greater potential for utilizing Cu and S, could maximize nutrient utilization, maintain yields, and balance nutrients in the soil (Hairston et al., 1990). In the southeastern United States, cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), and soybean are the most commonly grown row crops in several rotational schemes depending on agronomic and economic factors. The amount of minerals these crops remove with their respective harvested products vary greatly. For example, corn removes more than two times P in harvested grain (approximately 40 kg ha^{-1}) than cotton (approximately 15 kg ha^{-1}) or soybean (approximately 18 kg ha^{-1}) (Bender et al., 2015; Heckman et al., 2003; Rochester, 2007; Tewolde et al., 2007b). Thus, applying PL as the primary fertilizer to continuous cotton, which is not uncommon in the region, can result in the accumulation of PL-derived elements in the soil as has been reported by some (Adeli et al., 2008; Tewolde et al., 2018). Rotating cotton with either corn or soybean or both likely would reduce such nutrient accumulations but has not been thoroughly studied.

Another strategy for sustainable management of PL as a fertilizer in row cropping systems is rotating fertilizers. In this strategy, PL would be applied consecutively for a few years to meet the nutrient requirement of the target crop including N, P, K, and other mineral elements. In subsequent years, the level of PL-derived nutrients accumulated in the soil (He et al., 2019; Tewolde et al., 2007b) may be reduced following the cessation of further PL applications and replacement with other suitable fertilizers. Typically, only N from synthetic sources is needed when a crop is grown after a few years of PL applications (Tewolde, Sistani et al., 2016). The need for nutrients such as P, K, and other mineral elements would be met from residual elements from previous PL applications. These residual elements are then removed from the soil with the harvested products during years the crop is fertilized with synthetic N fertilizers. The cycling of fertilizers resumes by returning to PL fertilization after ensuring the elevated levels of soil P and other excess elements return to the initial normal levels.

The effectiveness of rotating crops or fertilizers to mine and remove soil mineral nutrients may be enhanced if either or both strategies also enhance the yield or the nutrient concentration in the harvested product. Since the amount of nutrient removal is the direct function of both the biomass amount and nutrient concentration of the harvested product, increasing one or both of these two parameters can increase the total amount of the removed nutrient. Past research has shown yield enhancements after stopping PL application and returning to synthetic N fertilization (Tewolde, Sistani et al., 2016). This implies the mining of residual nutrients could be enhanced when fertilizer rotation is used as a strategy for managing sustainable PL application.

Crop rotation has commonly been pushed as an effective strategy to increase crop yield and soil health relative to monocropping (Ohno et al., 2009). This also implies nutrient removal would be enhanced if the grain nutrient concentration is increased or remains the same. Whether the yield of any of the rotational crops is affected by fertilizer or crop rotation and whether nutrient removal is enhanced by these strategies is not known. The objective of this study was to determine the impact of fertilizer and crop rotation as a strategy of preventing PL-derived nutrient buildup in the soil on cotton, corn, and soybean yield and on the amount of mineral nutrients removed with harvested biomass. This work was part of a larger study in which the sustainability of land-applied PL was investigated and complements work reported in a companion article which addressed residual nutrients following repeated PL applications (Tewolde et al., 2021).

2 | MATERIALS AND METHODS

A field study was conducted in 2010–2014 at the Mississippi Agricultural and Forestry Experiment Station of Mississippi State University at Verona, MS, in a Leeper fine sandy loam soil (fine, smectitic, nonacid, thermic Vertic Epiaquept). The soil initially had approximately 2.0% organic matter, 58 mg kg^{-1} Mehlich 3-extractable P, 230 mg kg^{-1} Mehlich 3-extractable K, and pH of 5.46 (Tewolde et al., 2021).

2.1 | Experimental setup

The study consisted of four crop rotation treatments in a factorial combination with five fertility treatments. The crop rotation treatments were CCCCC, CCMMB, CMBBM, and CMCBM where each letter represents cotton (C), corn (M), soybean (B) planted in 2010, 2011, 2012, 2013, and 2014, respectively. The five fertility treatments included an unfertilized control (UTC), a standard fertilization with conventional synthetic fertilizers to meet yearly crop nutrient requirements (Std), and fertilization with PL which included three 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 for 2 yr and synthetic N application at the same rate as the Std in the last 3 yr (N2L). The N2L treatment represents a new strategy of PL management as a replacement for P-based poultry litter management (P5L). All fertilized treatments received equivalent plant available N (PAN) regardless of the source based on local recommendations for each crop for optimal yield. The N recommendation for the area was approximately 100 kg ha^{-1} for cotton and 224 kg ha^{-1} for corn. The N5L treatment received PL based on cotton N requirement for a target lint yield of approximately 1,200 kg ha^{-1} regardless of whether planted with cotton, corn, or soybean. The P-based treatment received PL that supplied enough P to replace expected P removed by cotton at harvest. Based on these criteria, the P5L treatment (P-based PL treatment) received a 5-yr average of 2.4 Mg ha^{-1} yr^{-1} PL and the N5L and N2L treatment (N-based PL treatments) received an average of 7.9 Mg ha^{-1} yr^{-1} PL (Table 1). When planted with corn, the P-based (P5L) and N-based (N5L and N2L) treatments received the same PL rates as for cotton (2.4 and 7.9 Mg ha^{-1} yr^{-1}, respectively). However, additional synthetic N was applied to meet the corn N need for optimal corn yield since the PL applied for cotton does not satisfy the N need for corn. The target N rate for corn was 224 kg ha^{-1} according to local recommendations. No synthetic N was applied to soybean. 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 subplots. Each subplot consisted of four 30.5-m long rows spaced 0.97 m apart.

2.2 | Field management

In 2010, the field was prepared by conventional tillage which included field cultivation, chisel harrowing, bedding, and a one-pass field preparation using a PrepMaster bed conditioner implement (Bigham Brothers). The plots in subsequent years were maintained as minimum tillage which included reshaping the beds without breaking them and preparing the plots using the PrepMaster prior to PL application and planting.

Poultry litter procured from local broiler chicken operations was applied each spring before planting corn, the earliest of the three crops. The litter was applied by broadcasting on the soil surface using a commercial manure spreader and incorporated into the soil within 1 d. The incorporation was accomplished by running a Do-All seedbed conditioner implement which lightly disturbed the surface soil with a harrowing action. The actual applied litter amount was determined by recording the PL weight in the spreader (equipped with load cells) before and after applying to each plot. The actual PL amount deviated from the target rate because the application was based on calibration of the spreader (Table 1). Additional details on the chemical properties of the PL and background soil are provided by Tewolde et al. (2021).

Nitrogen in the form of urea-ammonium nitrate solution (UAN, 32% N) in 2010 to 2013 and NH_4NO_3 in 2014 was applied to treatments according to the treatment design. The UAN in 2010–2013 was applied by injection into slits opened by serrated coulters about 15 cm to one side of the corn or cotton row to a depth of about 8–10 cm. A weighed amount of NH_4NO_3 was broadcast-applied by hand to each plot in 2014. The synthetic N was applied for cotton around the pin-head square stage and for corn at the six-leaf (V6) stage or earlier. Based on soil test results, 20 kg P ha^{-1} in the form of triple superphosphate and 28 kg K ha^{-1} in the form of KCl were broadcast-applied by hand on 13 May 2014 to the Std plots under cotton and soybean. Phosphorus and K fertilizers were not recommended for this treatment in other years.

Each spring, the three crops were planted according to regional practices as shown in Table 2. Cotton varieties

TABLE 1 Average amount and selected chemical properties of poultry litter (PL) used in a study that investigated the sustainability of poultry litter fertilization in a cotton-corn-soybean crop rotation system

Fertility treatment	Application date 29 Apr. 2010	9 May 2011	29 Mar. 2012	16 May 2013	24 Apr. 2014
	PL application rate, Mg ha^{-1}				
UTC	0	0	0	0	0
P5L	2.4	2.4	2.2	2.9	2.5
N5L	7.8	7.7	9.6	6.7	7.9
N2L	7.8	7.8	0	0	0
Std[a]	0	0	0	0	0
Element	Concentration, g kg^{-1}				
Moisture	274	220	373	220	261
N	26.9	27.6	26.8	33.1	23.3
C	226	230.4	211.7	234.8	202.2
P	18.1	15.6	11.8	21.5	10.5
K	28.4	30.5	23.2	23.8	22
Mg	6.32	6.54	5.75	6.22	5.56
Ca	29.2	22.7	17.9	31.7	18.7
	Concentration, mg kg^{-1}				
Cu	95	298	251	104	227
Fe	702	1872	759	853	1182
Mn	483	699	499	454	526
Zn	434	448	334	420	347

Note. UTC = unfertilized control, Std = fertilization with synthetic fertilizers, P5L = phosphorus-based poultry litter application every year for 5 yr, N5L = nitrogen-based poultry litter application for 5 yr, N2L = nitrogen-based poultry litter application for 2 yr followed by synthetic nitrogen fertilization for 3 yr.
[a]The Std treatment received synthetic fertilizers based on soil test results.

TABLE 2 Dates of fertilizer application and crop planting and harvest at Mississippi Agricultural & Forestry Experiment Station at Verona, MS where the sustainability of poultry litter (PL) application was investigated

Operation	Crop	2010	2011	2012	2013	2014
PL applied	All	29 Apr.	9 May	29 Mar.	16 May	24 Apr.
Synthetic N applied	Cotton	12 July	21 June	18 June	26 June	25 June
	Corn	–[a]	2 June	27 Apr.	13 June	7 May
Planting	Cotton	8 June	10 May	17 May	28 May	21 May
	Corn	–	10 May	29 Mar.	16 May	24 Apr.
	Soybean	–	–	24 Apr.	16 May	6 May
Harvesting	Cotton	18 Oct.	27 Sept.	17 Oct.	21 Oct.	7 Oct.
	Corn	–	9 Aug.	23 Aug.	19 Sept.	4 Sept.
	Soybean	–	–	23 Sept.	3 Oct.	18Sept.

[a]Corn or soybean was not part of the rotation system during these years.

planted were ‘PHY 485 WRF’ in 2010 and ‘PHY 499 WRF’ in 2011 to 2014 (PhytoGen Seed Company, Dow AgroSciences LLC) planted at 139,000 seeds ha^{-1}. The corn variety ‘DKC 64-69′ (DeKalb Genetics Corporation) was planted in all 4 yr corn was included in the rotation at 69,000 seeds ha^{-1}. Soybean varieties included ‘Pioneer P94Y90’ in 2012 (Pioneer Hi-Bred International, Inc.), ‘Armor DK 4744’ in 2013 (Armor Seed), and ‘Pioneer P49TR80’ in 2014 and all were planted at 337,000 seeds ha^{-1}. The plots received irrigation by furrow on 10 July 2013, 18 July 2013, and 7 Aug. 2013 with about 35–45 mm each day. No irrigation was needed in any of the other 4 yr. Local recommended practices were followed for pest control and other crop management needs.

2.3 | Data collection

At the end of each of the five seasons, cotton lint yield and corn and soybean grain yields were determined by harvesting the entire length of the middle two rows of each subplot. Table 2 lists the harvest dates for each crop in each year. Cotton was harvested with a two-row plot picker (Case-IH 1822) retrofitted with a self-weighing and dumping system. About 800 g of seedcotton subsamples from each plot were collected at the time of harvest for determining gin turnout and converting harvested seedcotton to lint yield. The subsamples were ginned on a 10-saw benchtop gin, the lint captured was weighed, the gin turnout determined as a percentage of the subsample fed to the gin, and lint yield per plot was calculated as the product of gin turnout and seedcotton weight. Corn and soybean were harvested with a two-row plot combine that also recorded grain moisture (Kincaid Seed Research Equipment Company). The reported corn yield was adjusted to 15.5% moisture and soybean yield was adjusted to 13% moisture content. Plant height of cotton and soybean was measured after picking for cotton and before harvest for soybean. The height measurements were made on the mainstem of 10 cotton plants and 20 soybean plants from the soil surface to the topmost visible node.

Nutrient removal from the soil with the harvested products was determined based on the yield and nutrient concentration in each harvested product. The products that were removed from the field were seed or grain for soybean and corn and seedcotton for cotton. The calculation of the amount of nutrients removed with harvest for corn and soybean was a straightforward product of yield in kg ha^{-1} and grain nutrient concentration. The calculation of the amount of nutrients removed with harvested cotton also was a straightforward product of yield in kg ha^{-1} and nutrient concentration in the seed. However, the yield of economic importance for cotton is lint not the seed. So, lint yield is reported for cotton but, since the nutrient concentration in cotton fibers is negligible, seed yield (not reported) was used for nutrient removal calculations.

Seeds of all three crops were analyzed for total P, K, Mg, Ca, Cu, Mn, Fe, and Zn content using inductively coupled plasma-optical emission spectroscopy (ICP-OES; Varian, Vista Pro; Varian Analytical Instruments). Briefly, soybean and corn grain and delinted cotton seed from harvest were ground to pass a 1-mm sieve and 0.2 g of this ground sample was ashed in a muffle furnace at 500 ˚C for 4 h. The ashed samples were then digested in 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. This digest was then analyzed by the ICP-OES. Total N content of the seeds was analyzed by an automated dry combustion method using an Elementar Vario MAX CN analyzer (Elementar Instrument). Nutrient content of the fresh PL was also analyzed by the same methods as the seed samples.

2.4 | Statistical analysis

All data were subjected to analysis of variance using the PROC MIXED procedure of the Statistical Analysis System (SAS 9.4). The yield data for each crop were analyzed separately. Year was included in the model 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 et al., 2002). Models with different covariance structures of the repeated measures were used to choose a covariance structure most effective (least value) 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

3.1 | Yield and plant height response

Fertility treatments affected the yield of all three crops and plant height of cotton and soybean (Table 3). The interaction between fertility and rotation was significant for soybean yield but not for cotton or corn. As a result, cotton and corn yield data and cotton and soybean plant height data are presented as fertility main effects and rotation main effects. The rotation × year interactions were significant for cotton yield and plant height which means these data as affected by rotation treatments should be presented for each year. The rotation × year interaction for corn, however, was not significant and therefore corn yield data for rotation are presented after pooling across years. The fertility × year interactions were significant for both cotton and corn yield and cotton plant height and therefore the fertility data for both cotton and corn are presented by year.

3.1.1 | Fertility effect

Cotton

The UTC treatment produced less lint yield than any other treatment in all years showing that this soil is responsive to

TABLE 3 Test of significance of the effect of crop rotation and fertilization treatments on yield and plant height of cotton, corn, and soybean over a 5-yr period

Effect	Yield			Plant height[a]	
	Cotton	Corn	Soybean	Cotton	Soybean
	P > *F*				
Rotation (R)	.915	.333	.174	.398	.007
Fertility (F)	<.001	<.001	<.001	<.001	.001
R × F	.790	.281	.016	.985	.169
Year (Y)	<.001	<.001	.053	<.001	.713
Y × R	.056	.654	–[b]	<.001	–
Y × F	<.001	<.001	.361	<.001	.106
Y × R × F	.366	.638	–	.041	–

[a]Corn plant height was not measured.
[b]Not applicable.

fertilization (Table 4). Among the four fertilized treatments, cotton that received the litter-only treatment (N5L) produced lint yield equivalent to the Std treatment in 3 of the 5 yr. In the other 2 yr, the N5L treatment produced nearly 11% less lint in 2010 and 24% less lint in 2013 than the Std treatment. These responses were also reflected in the end-of-season plant height. Plants that received the N5L treatment were 4.8 and 16.7% shorter than plants that received the Std treatment in 2010 and 2013, respectively. The N5L plants were as tall as or taller than the Std plants in the other 3 yr.

Each of the 5 yr, PL was applied to the N5L treatment to supply the full N requirement for lint yield equivalent to the Std treatment. The lint yield and plant height data, however, indicate that cotton did not seem to have received the intended N fertilization when fertilized with the full PL rate in at least 2 of the 5 yr (Table 4). The Std treatment received a 5-yr average of 103 kg ha^{-1} yr^{-1} of synthetic N. In 2013, the N5L treatment received 24% more calculated PAN from PL than the Std treatment's synthetic N (129 vs. 104 kg ha^{-1}) (Table 5) but produced nearly 24% less lint and had 17% shorter plants. In 2010, the N5L treatment produced 14% less lint yield than the Std treatment although the treatment received a calculated 105 kg ha^{-1} PL-derived PAN compared with the 101 kg ha^{-1} synthetic N applied to the Std treatment.

The basis for the inconsistent performance of the N5L treatment relative to the Std during the 5 yr may be attributed to several factors. Our main suspicion is N mineralization and availability from PL as affected by the seasons. Poultry litter was applied assuming 50% of the PL-derived total N mineralizes and becomes available for cotton uptake during the growing season (Tewolde et al., 2010). Calculating N mineralization and availability for the N5L treatment using yield equivalency to the Std treatment resulted in the PL N availability of 41.3, 47.0, 47.1, 30.6, and 57.6% in 2010, 2011, 2012, 2013, and 2014, respectively. The 30.6% PL-N availability factor in 2013 is unusually low considering this was the 4th year PL was applied to the same plots and some residual N was expected to increase yield (Tewolde, Sistani et al., 2016). We believe an unusually dry condition in 2013 slowed the mineralization of PL-derived organic N and therefore reduced the amount of mineral N the cotton received from the N5L treatment. Only 53 mm of rain was received during a nearly 2-mo period between 11 June 2013 and 9 Aug. 2013 (Table 6), while the pan evaporation was 421 mm (data not shown). We were able to irrigate three times on 10 July, 18 July, and 7 Aug. 2013 with about 35–45 mm of irrigation each time, but this may not have been early enough for expected PL-derived N mineralization.

The 41.3% PL-N availability factor in 2010 vs. the expected 50% was also considered low. But the reason for the estimated low N availability likely was due to loss of mineralized N, not due to lack of mineralization. The PL in 2010 was applied on 29 Apr. 2010 while cotton was planted 40 d later on 8 June 2010 (Table 2). The field received 253 mm rainfall during this period (Table 6) which caused a delay in planting but also likely caused loss of mineralized N during this period. The loss of mineralized N to leaching most likely continued beyond the 40-d absence of cotton into the early stages of cotton plant growth until plants grew large enough to uptake mineralized N which is known to peak around the flowering stage about 60 d after planting.

The 57.6% PL N availability in 2014 is high but that is not surprising, because N residual from the previous four applications is expected to contribute to the yield in 2014 (Tewolde, Sistani et al., 2016). Residual N from 2013 during which mineralization likely was incomplete may have contributed to the high PL N availability in 2014. In the other 2 yr (2011 and 2012) during which the N5L treatment produced as much lint yield as the Std, the PL-N availability factor of 47% approached the estimated 50%. Overall, the results show that care is needed when using PL as a fertilizer. While the 50% available factor for cotton is applicable in normal seasons, it

TABLE 4 Lint yield and plant height of cotton grown with selected fertility treatments that included synthetic N fertilizers and poultry litter (PL). Each value is an average across four replications and crop rotation treatments

Fertility treatment	Year 2010	2011	2012	2013	2014
	Lint yield, kg ha^{-1}				
UTC	892d[a]	1,145b	1,335c	760c	887b
P5L	1,150b	1,962a	1,856b	1,857a	1,494a
N5L	1,092bc	1,799a	1,905b	1,402b	1,426a
N2L	1,054c	1,783a	2,112a	1,982a	1,529a
Std	1,272a	1,885a	1,845b	1,842a	1,514a
ANOVA	$P > F$				
Rotation (R)		.534	.68	.	.
Fertility (F)	<.001	<.001	<.001	<.001	.034
R × F		.996	.208	.	.
	Plant height, cm				
UTC	103.9c	–[b]	86.2d	61c	65.8c
P5L	121.8ab	–	106.5bc	103.1a	100.2ab
N5L	119.4b	–	116.8a	84.1b	95b
N2L	119.5b	–	113.6ab	105.7a	103.9a
Std	125.4a	–	104.6c	100.9a	96.5b
ANOVA	$P > F$				
Rotation (R)	–[c]		.133	–	–
Fertility (F)	<.001		<.001	<.001	<.001
R × F	–		.382	–	–

Note. UTC = unfertilized control, Std = fertilization with synthetic fertilizers, P5L = phosphorus-based poultry litter application every year for 5 yr, N5L = nitrogen-based poultry litter application for 5 yr, N2L = nitrogen-based poultry litter application for 2 yr followed by synthetic nitrogen fertilization for 3 yr.

[a]Means followed by the same letter within a column are not significantly different at $P < .05$.

[b]Plant height measurements were not taken in 2011.

[c]Not applicable.

may not be applicable in unusually dry years. The results also show that the timing of PL application should be as close to cotton planting date as possible for the 50% PL-N availability to be applicable in the same cotton season. When feasible, applying the PL shortly after planting before or after emergence may be a preferred practice to applying weeks before planting (Tewolde et al., 2009).

The N2L treatment, which represents the new PL application strategy as an alternative to P-based application, resulted in yield increases of 15% in 2012 and 7.5% in 2013, statistically significant in 2012 but not 2013 when it was dry (Table 4). The N2L treatment also resulted in taller plants than the Std in all 3 yr by 5–9%. During these 3 yr, both the Std and the N2L treatments received the same amount of synthetic N fertilization. The difference between these two treatments was in the previous 2 yr (2010 and 2011), when the N2L treatment received 7.9 Mg ha^{-1} yr^{-1} PL while the Std received the full rate of synthetic N fertilization. Thus, the yield and growth advantage of the N2L over the Std in 2012–2014 may be attributed to the residual effect of the PL applied in 2010 and 2011. Such yield advantages due to the history of PL fertilization are consistent with other reports (Tewolde, Sistani et al., 2016).

The P5L treatment, which represents P-based PL application, resulted in similar lint yield as the Std in 4 of the 5 yr and in reduced yield in 1 yr (Table 4). Lint yield of the P5L treatment was essentially the same as that of the Std in 2011–2014. In 2010, lint yield of the P5L treatment was less than that of the Std by nearly 10%. This yield reduction is attributable to the early PL application and associated loss of mineralized N to leaching. Every year, the P5L treatment received an average of 2.5 Mg ha^{-1} litter plus enough synthetic N so that its total PAN was equivalent to that of the Std.

Corn

Corn grain yield, as cotton lint yield, was also affected by the fertility treatments (Table 3). The UTC, as expected, resulted in the least grain yield among the five fertility treatments. Yield reduction by the UTC relative to the Std was greater in corn than in cotton (78% corn vs. 40% cotton) which may indicate the difference in the resilience of these two crops under N insufficiency.

TABLE 5 Total N from poultry litter (PL) and synthetic fertilizers and total plant available nitrogen (PAN) (sum of N from synthetic and PL) applied yearly to cotton and corn in a study that investigated the sustainability of poultry litter fertilization in a cotton–corn–soybean crop rotation system

Fertility treatment	Cotton					Corn			
	2010	2011	2012	2013	2014	2011	2012	2013	2014
	Applied synthetic N, kg ha^{-1}								
UTC	0	0	0	0	0	0	0	0	0
P5L	65	71	70	69	69	203	197	178	195
N5L	0	0	0	0	0	133	121	139	132
N2L	0	0	114	104	99	133	242	227	224
Std	101	95	114	104	99	220	242	227	224
	Applied total N from PL, kg ha^{-1}								
UTC	0	0	0	0	0	0	0	0	0
P5L	64	76	49	96	49	56	65	141	64
N5L	210	193	250	259	162	230	266	217	166
N2L	209	216	0	0	0	216	0	0	0
Std	0	0	0	0	0	0	0	0	0
	Applied total plant available N (PAN)[a], kg ha^{-1}								
UTC	0	0	0	0	0	0	0	0	0
P5L	98	120	94	117	94	224	219	227	218
N5L	104	110	125	129	81	215	214	215	191
N2L	107	119	114	104	99	215	242	227	224
Std	101	95	114	104	99	220	242	227	224

Note. UTC = unfertilized control, Std = fertilization with synthetic fertilizers, P5L = phosphorus-based poultry litter application every year for 5 yr, N5L = nitrogen-based poultry litter application for 5 yr, N2L = nitrogen-based poultry litter application for 2 yr followed by synthetic nitrogen fertilization for 3 yr.

[a]The PAN from poultry litter was calculated at 35% of the total N if applied to corn or 50% if applied to cotton. All of the N applied as synthetic fertilizer is considered plant available.

TABLE 6 Monthly total rainfall at the Mississippi Agricultural and Forestry Experiment Station at Verona, MS where the sustainability of poultry litter application was investigated

Month	2010	2011	2012	2013	2014
	mm				
Jan.	122	132	145	261	59
Feb.	86	74	119	108	60
Mar.	103	150	194	137	86
Apr.	52	281	66	128	182
May	244	100	98	140	106
June	106	159	42	78	260
July	170	84	155	40	145
Aug.	73	79	101	46	41
Sept.	18	160	120	103	49
Oct.	86	30	142	17	261
Nov.	147	111	26	124	106
Dec.	50	172	183	141	121

TABLE 7 Grain yield (adjusted to 15.5% moisture) of corn grown with selected fertility treatments that included synthetic N fertilizers and poultry litter (PL). Each value is an average of four replications and crop rotation treatments

Fertility treatment	Corn grain yield 2011	2012	2013	2014
	kg ha^{-1}			
UTC	2,612b[a]	1,960c	1,558b	2,983d
P5L	9,537a	10,653a	8,558a	12,382c
N5L	9,340a	9,867b	8,199a	12,697bc
N2L	9,355a	11,218a	8,652a	13,702a
Std	9,741a	10,843a	8,381a	13,269ab
ANOVA	$P > F$			
Rotation (R)	.907	–[b]	–	.940
Fertility (F)	<.001	<.001	<.001	<.001
R × F	.794	–	–	.462

Note: UTC = unfertilized control, Std = fertilization with synthetic fertilizers, P5L = phosphorus-based poultry litter application every year for 5 yr, N5L = nitrogen-based poultry litter application for 5 yr, N2L = nitrogen-based poultry litter application for 2 yr followed by synthetic nitrogen fertilization for 3 yr.
[a]Means followed by the same letter within a column are not significantly different at $P < .05$.
[b]Not applicable.

Among the other four fertility treatments, the N5L was one of the lowest-yielding treatments in the four seasons corn was included in the rotation (Table 7). The four treatments did not significantly differ in grain yield in the 2 yr (2011 and 2013) when the Std produced <10.0 Mg ha^{-1} grain. The four treatments significantly differed when the Std produced >10.0 Mg ha^{-1} grain in the other 2 yr (2012 and 2014). These yield responses suggest that grain production of the Std in 2011 and 2013 probably was suppressed and thus the yield differences between the Std and the other three treatments were narrowed by factors other than N supply. This was reflected in the nitrogen use efficiency (NUE) calculated by dividing grain yield by PAN which shows, among the 4 yr, NUE of the Std treatment was lowest in 2013 (37 kg grain kg^{-1} applied PAN in 2013 vs. > 44 kg grain kg^{-1} applied PAN in the other 3 yr). Nitrogen use efficiency of all treatments among all years was also lowest in 2013 (avg. of approximately 38 kg grain kg^{-1} applied PAN), probably a reflection of the unusual season: wet early in the season that delayed planting and dry during the growing season (Table 6). The 2014 season had the highest NUE (avg. across all treatments) of 61 kg grain kg^{-1} applied PAN.

The N5L treatment produced less grain yield than the Std in all 4 yr (2.2–9.0% less) but this was significant only in 2012. The lower grain yield of the N5L treatment than the Std seems to be related to the PAN it received. All treatments other than the UTC received N from one or both of the two fertilizers used in this study (synthetic N and PL) to supply a target PAN of 224 kg ha^{-1}. While the N from synthetic sources was considered to be 100% plant available, PL in this study was applied following the then well-accepted assumption that 50% of its total N would become available to corn during the growing season (Warren et al., 2006). This assumption led to underapplying PAN to the N5L treatment because, today, we know that the N availability factor for PL should not have exceeded approximately 35% (Tewolde et al., 2013). When the PAN is recalculated with 35% PL-derived total N availability, the N5L treatment received 3% less PAN in 2011 and 5% less PAN in 2013 than the Std treatment (Table 5). In the 2 yr in which yield was significantly reduced relative to the Std, the N5L treatment received 11% less PAN in 2012 and 15% less in 2014 than the Std treatment. Thus, we believe the lower corn yield of the N5L treatment is attributed to the PL, and thereby PAN, underapplication relative to the Std.

The N2L treatment produced grain yield that exceeded that of the Std by about 3% every year in the last 3 yr (2012–2014) although not statistically significant (Table 7). Both treatments received the same amount of synthetic N in 2012–2014 (Table 5). The difference between these two treatments is that the N2L treatment received 7.9 Mg ha^{-1} yr^{-1} PL in 2010 and 2011 while the Std received only synthetic N. So, the yield difference between these two treatments in 2012–2014 is the residual effect of the PL applied in 2010 and 2011. This effect although not statistically significant is similar to the effect on cotton yield (Table 4). In 2011 when some of the PAN was derived from PL, the N2L treatment produced about 4% less grain yield than the Std (not statistically significant).

The grain yield of the P5L treatment was much more similar to that of the Std than to the other two PL treatments in all 4 yr. The grain yield of the P5L treatment in 2011–2013 was within ±2% of the yield of the Std treatment (Table 7). Only in 2014 did the P5L treatment produce nearly 7% less yield than the Std although not statistically significant. The increases or decrease in corn grain yield relative to the Std (although statistically not significant) were due to the amount of applied PAN. The results overall show that corn can be

TABLE 8 Seed yield (adjusted to 13% moisture) and plant height of soybean grown with selected fertility treatments that included synthetic N fertilizers and poultry litter (PL). Each value is an average across four replications and crop rotation treatments

Fertility treatment[a]	Soybean seed yield 2012	2013	2014	Plant height 2012	2013
	kg ha^{-1}			cm	
UTC	4,094c[a]	4,374c	4,383bc	85.6b	94.4b
P5L	4,362ab	4,600ab	4,605b	95.3a	97b
N5L	4,567a	4,805a	4,874a	96.1a	101.6a
N2L	4,498ab	4,736a	4,570bc	97.2a	97.9ab
Std	4,329b	4,457bc	4,344c	96.8a	96b
ANOVA	$P > F$				
Rotation (R)	–[b]	.338	–	–	.015
Fertility (F)	.004	.002	.003	.035	.007
R × F	–	.056	–	–	.067

Note. UTC = unfertilized control, Std = fertilization with synthetic fertilizers, P5L = phosphorus-based poultry litter application every year for 5 yr, N5L = nitrogen-based poultry litter application for 5 yr, N2L = nitrogen-based poultry litter application for 2 yr followed by synthetic nitrogen fertilization for 3 yr.
[a]Means followed by the same letter within a column are not significantly different at $P < .05$.
[b]Not applicable.

fertilized with PL assuming 35% of the total N from PL is available for corn in the same season and supplying the balance N from synthetic sources. Many growers in the southeastern United States have been fertilizing corn by applying the full synthetic N rate (approximately 200 kg ha^{-1}) after applying about 4.5 Mg ha^{-1} PL as a source of P. This practice ignores the N from PL and results in excess N fertilization. Part of the reason for this practice is lack of correct guidance on the PL N availability. So instead of taking the risk of underapplying N, farmers choose to err on the side of supplying excess N. Our results show that fertilizing corn with PL assuming about 35% of the total PL-derived N will be available for corn during the same season and applying the balance of the N from synthetic N sources results in yield as good as fertilizing with 100% synthetic N.

Soybean

Just as in cotton and corn, the fertility treatments affected soybean seed yield each of the 3 yr soybean was included in the rotation (Table 3). The Std and UTC did not differ because these two treatments were similar in terms of applied fertilizers for soybean with an exception in the last year (2014). Based on soil test, the Std planted to soybean received 20 kg P ha^{-1} and 28 kg K ha^{-1} on 13 May 2014. Phosphorus and K fertilization was not recommended in the other 2 yr.

Unlike cotton and corn, soybean that received the N5L treatment (7.9 Mg ha^{-1} yr^{-1} PL) produced the most seed yield among the five fertility treatments in each of the 3 yr (Table 8). Relative to the Std, the N5L treatment increased soybean yield by 5.5, 7.8, and 12.2% (238, 348, and 530 kg ha^{-1}) in 2012, 2013, and 2014, respectively. The other PL treatment (P5L, which received 2.5 Mg ha^{-1} yr^{-1}) also increased soybean yield each year, although this increase was significant only in 2014. The N2L treatment which received the higher PL rate of 7.9 Mg ha^{-1} in 2010 and 2011 (when no soybean was planted) increased yield, relative to the Std, in 2012–2014 during which soybean was grown without applying PL or any other fertilizer. Although these increases were not statistically significant, the consistency of the increases across years indicates that residuals from the first 2 yr PL applications benefitted soybean yield in subsequent years in a similar way as in cotton and corn.

These results show that PL increases soybean yield in the same season it is applied, but whether such applications are practical or economical is questionable. For example, the higher PL rate of 7.9 Mg ha^{-1} led to 238 kg ha^{-1} yield advantage in the 1st year of growing soybean. The revenue gain from fertilizing soybean with 7.9 Mg ha^{-1} PL would be approximately US$83.00 ha^{-1} at a soybean price of $0.35 kg^{-1}. Fertilizing with 7.9 Mg ha^{-1} would cost approximately $332 ha^{-1} at $42.00 Mg^{-1} PL (H. Tewolde, personal communication, 2020). Subtracting the cost for the 20 kg ha^{-1} P ($42 ha^{-1} at $2.10 kg^{-1} P) and 28 kg ha^{-1} K ($24.60 ha^{-1} at $0.88 kg^{-1} K) applied to the Std leads to $265 ha^{-1} cost due to the 7.9 Mg ha^{-1} PL use. So, even without performing a deeper economic analysis, the use of such PL rate would lead to economic losses ($83–$265 = –$183 ha^{-1}). The lower rate of 2.5 Mg ha^{-1}, however, may be a better choice for soybean as this rate increased yield at least in the later part of the study. This PL rate would cost $105 ha^{-1} compared with the $67 ha^{-1} for the inorganic P and K fertilizers required in this soil, but this difference in cost would be offset in the early years and lead to some profit in later years by the yield increases. These benefits would be greater in soils that require higher rates of P and K and possibly other nutrients that PL supplies. So, the use of PL applied at rates that supply the P need of the crop may lead to a sustainable soybean production in such soils but a deeper economic analysis that specifies conditions that led to economic benefits may be necessary.

The alternative application method in which PL is applied at rates that meet the N need of cotton (7.9 Mg ha^{-1} yr^{-1}) in the first 2 yr may also be economical when soybean follows cotton. This is so because, in the first 2 yr, the 7.9 Mg ha^{-1} PL meets all nutrient needs for cotton including N which has already been shown to be economical (Tewolde et al., 2010; Tewolde, McLaughlin et al., 2016). In the subsequent 3 yr, soybean can be grown without additional PL, P, or K fertilization and yet this soybean produced more seed yield than the Std. We feel this alternative PL application strategy is even more sustainable than the P-based PL application because it is more profitable than the P-based application when cotton and soybeans are included in a rotation system.

This study was conducted to test the viability and sustainability of a new PL application strategy as represented by the N2L treatment as an alternative to P-based PL application as represented by the P5L treatment. The effectiveness of the N2L treatment to drawdown excess nutrient levels to the initial in a similar way as the P5L treatment was shown previously (Tewolde et al., 2021). In this study, we show that the yield of all crops is either maintained as the Std or the P5L treatment or increased above the Std. This suggests, in addition to the operational advantages explained by Tewolde et al. (2021), adopting this strategy may enhance the yield of all three crops. This is particularly true with soybean.

3.1.2 | Rotation effect

Rotation did not affect the yield of any of the three crops (Table 3). Yield comparisons of rotations were possible in 2012 for cotton, in 2014 for corn, and in 2013 for soybean. The lint yield difference between the CC**C** and CM**C** in 2012 was only 27 kg ha^{-1} (1,797 vs. 1,824 kg ha^{-1}, respectively) which shows that growing corn in the 2nd year did not increase cotton yield in the 3rd year. Cotton plants in the CM**C** rotation were about 5.8% taller than plants in the CC**C** rotation (109 vs 102 cm, respectively), but this difference was not statistically significant. Difference in corn grain yield between the CMBB**M** and CMCB**M** in 2014 were also very small and not statistically significant (10,994 vs. 11,019 kg ha^{-1}, respectively). The difference between these two rotation treatments is the crop in 2012: cotton in CMCB**M** and soybean in CMBBM. The difference in soybean yield in 2013 between the CMB**B** and CMC**B** rotation treatments was also small and not statistically significant (4,671 vs. 4,518 kg ha^{-1}, respectively). Only soybean plant height was affected by rotation in 2013. Soybean plants in the CMC**B** rotation in 2013 were 9 cm taller than plants in the CMB**B** rotation (102 vs. 93 cm, respectively). These results suggest yield benefits from rotating these three crops should not be expected on a short-term basis.

3.2 | Nutrients removed at harvest

3.2.1 | Rotation effect

Among the four rotation treatments, the 5-yr continuous cotton (CCCCC) removed much less nutrients than any of the other three rotations that included corn or soybean when averaged across years and the fertility treatments (Table 9). The rotation treatment that included two soybean crops in the 5 yr removed the most amount of nutrients. The CMBBM rotation removed a 5 yr average of 66, 6.1, and 24.2 kg ha^{-1} (or 90, 39, and 103%) more N, P, and K, respectively, than the CCCCC rotation. The two rotation treatments that included two cotton crops in the 5-yr rotations (CCMMB and CMCBM) had nutrient removal intermediate between the CCCCC and the CMBBM rotations.

These results show that growing cotton does not deplete soil nutrients as much as growing soybean or corn. On the other hand, growing soybean in a rotation may lead to soil nutrient depletion even more than corn which produced much more harvested biomass than soybean (Tables 7 and 8). This property of the crops is shown in the yearly uptake data by crop in Table 9. As expected, cotton among the three crops removed the least amount of any of the nutrients with harvested seed and soybean removed the most. When averaged across years and the fertility treatments, soybean removed more than threefold N and K than cotton and more than twofold N and K than corn. Soybean removed 224 kg ha^{-1} N and 79 kg ha^{-1} K compared with 73 kg ha^{-1} N and 24 kg ha^{-1} K for cotton and 91 kg ha^{-1} N and 30 kg ha^{-1} K for corn. Soybean removed 49% more P than cotton and only 7% less P than corn. Soybean also removed greater amounts of microelements than cotton and corn. Soybean removed more than fourfold the amount of Fe, Cu, and Mn removed by cotton and more than twofold the amount of Fe and Cu removed by corn. While much of the N removed by soybean likely is derived from its own N_2 fixation, the other nutrients removed at harvest by soybean are mined from the soil. This shows that including soybean in a rotation would mine these elements from the soil and help in the management of PL application as a fertilizer. The ability of soybean to remove a large amount of K and, to some extent, P is well known (Bender et al., 2015; Mallarino et al., 2011; Salvagiotti et al., 2021). Mallarino et al. (2011) showed that soil test P and K declines across years when corn and soybean are grown in rotation without applying P and K fertilizers. The ability of soybean to remove the other nutrients, however, is not as well established as for P and K.

TABLE 9 Total nutrient removed from the soil with harvested seed after growing and harvesting cotton (C), corn (M), and soybean (B) in rotation in 2010–2014. Each value is an average across five fertility treatments and three or four replications in 2010–2014

Rotation[a]	N	P	K	Mg	Ca	Fe	Mn	Cu	Zn
	kg ha^{-1}					g ha^{-1}			
2010									
CCCCC	63a[b]	13.6a	21a	6.8a	3.1a	82a	31a	13.1a	91a
CCMMB	66a	14.2a	22a	7.1a	3.2a	86a	32a	13.6a	95a
CMBBM	61a	13.1a	20a	6.5a	2.9a	79a	30a	12.6a	88a
CMCBM	63a	13.7a	21a	6.8a	3.1a	83a	31a	13.1a	91a
2011									
CCCCC	74b	16.5b	25ab	8.2a	3.7a	100b	38b	15.8b	110b
CCMMB	68b	15.5b	24b	7.7a	3.5a	94b	35b	14.9b	104b
CMBBM	82a	21.7a	28a	6.6b	1.1b	207a	48a	26a	173a
CMCBM	81a	21.6a	27a	6.5b	1.1b	206a	48a	25.9a	173a
2012									
CCCCC	89b	18c	29b	9a	4.3b	118c	42c	21.6c	126c
CCMMB	90b	23.7a	30b	7.1b	1.2c	228b	53b	28.7b	189b
CMBBM	216a	21.4b	73a	9.5a	14.3a	372a	150a	66.6a	218a
CMCBM	87b	18.6c	30b	9.3a	4.2b	133c	46bc	19.6c	126c
2013									
CCCCC	71b	16.6b	25b	7.9b	3.5b	81c	39b	14.1b	95b
CCMMB	71b	20.7a	26b	6.8b	1.9c	239b	44b	36.2b	173ab
CMBBM	225a	23.3a	82a	10.6a	14.8a	428a	156a	91.4a	236a
CMCBM	218a	22.3a	78a	9.9a	14.1a	481a	158a	73.1a	282a
2014									
CCCCC	69c	12.9c	18c	6.7c	2.7b	76b	26c	9.5c	96c
CCMMB	237a	21.8b	70a	9.4a	16a	259a	157a	46.3a	172b
CMBBM	111b	28.4a	36b	8.1b	0.7c	233a	64b	21.3bc	226a
CMCBM	113b	27.6a	35b	7.9b	0.7c	236a	63b	27.6b	208ab

[a]The letters in bold font in the first column (rotation treatments) represent the crop for which nutrient removal data are given in that year. For example, the "B" in the CMCBM rotation in 2013 shows the data in 2013 were for soybean seed. The previous crops in that rotation scheme were cotton (C), corn (M), and cotton (C) in 2010, 2011, and 2012, respectively.

[b]Values followed by the same letter within a column and year are not significantly different from each other at $P < .05$ level.

3.2.2 | Fertility effect

The fertility treatments affected both the concentration of each element in the harvested product and the amount of nutrient removed at harvest. Concentration of most elements in cotton seed were affected by fertility treatments (Table 10). Cotton seeds from the unfertilized treatment (UTC) had greater concentration of the macro elements P, K, Mg, and Ca than the four optimally or near optimally fertilized treatments. This is consistent with other findings. For example, the seed P concentration of unfertilized cotton or cotton fertilized with suboptimal N at two locations in Mississippi was greater than cotton that was optimally fertilized (Tewolde et al., 2007a). He et al. (2013) reported that fertilization with sufficient PL or synthetic fertilizers reduced cotton seed Ca concentration. While Ca is an essential nutrient of cotton biomass (He et al., 2017), oversupply of Ca could inhibit cotton fiber elongation and maturity, reducing the fiber quality (Gamble, 2009; Guo et al., 2017). Fiber quality was not measured in our study but should be explored in future studies to ascertain that PL does not negatively affect lint quality. Among the four microelements, fertility affected only seed Mn concentration. The Std treatment elevated cotton seed Mn concentration. Unlike cotton, the fertility treatments did not affect nutrient concentration in soybean or corn grain.

Despite the lack of differences of grain nutrient concentration in corn and soybean, the fertility treatments differed in the amount of nutrients removed at harvest averaged across the three crops. Not surprisingly, the UTC removed the least amount of all measured nutrient elements each of the 5 yr

TABLE 10 Nutrient concentration in harvested seed/grain of cotton, corn, and soybean grown with selected fertility treatments that included synthetic N fertilizers and poultry litter (PL). Each value is an average of four rotation treatments, three or four replications, and 3–5 yr

Fertility treatment	N	K	P	Mg	Ca	Cu	Fe	Mn	Zn
	g kg^{-1}					mg kg^{-1}			
Cotton									
UTC	35.1c[a]	13.38a	9.53a	4.66a	2.2a	7.68a	47.2a	19b	52.9a
P5L	38.3b	12.7b	8.46b	4.2bc	1.93b	7.24a	49.9a	20.3ab	56.1a
N5L	37.6b	13.11ab	9.02a	4.33b	1.9b	7.88a	52.4a	18.6b	61.6a
N2L	39.2ab	13.18ab	8.41b	4.22bc	1.87b	8.17a	55.1a	19.2b	52.5a
Std	40.5a	12.59b	7.95b	4.01c	1.82b	7.77a	49.9a	21.7a	54.5a
ANOVA	*P* > *F*								
Year (Y)	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Treatment (T)	<.001	.076	<.001	<.001	<.001	.847	.352	.018	.467
Y × T	<.001	.518	.476	.368	.012	.881	.569	.032	.036
Corn									
UTC	10.6b	4.39a	3.46a	1.23a	0.22a	3.89a	31.9a	7a	28.8a
P5L	12a	4.15a	3.27a	0.99b	0.19a	4.37a	31.8a	7a	25.3a
N5L	11.7a	4.12a	3.3a	1b	0.2a	3.99a	29.9a	7.3a	27.6a
N2L	12a	4.09a	3.22a	0.98b	0.2a	5.17a	37a	7.2a	26.6a
Std	12.1a	3.97a	3.08a	0.97b	0.2a	4.19a	31.9a	6.9a	24.4a
ANOVA	*P* > *F*								
Year (Y)	.631	.013	.015	.003	<.001	.035	.063	.263	.091
Treatment (T)	.031	.268	.337	.010	.222	.612	.540	.951	.427
Y × T	.840	.624	.947	.812	.810	.663	.540	.994	.888
Soybean									
UTC	58.3a	18.42c	5.44a	2.4ab	3.88a	15.5a	83.8a	37a	45.8a
P5L	57.8a	18.8abc	5.63a	2.51a	3.82a	15.2a	85.5a	38.8a	48a
N5L	57a	19.28ab	5.71a	2.51ab	3.64a	14.9a	85.8a	37.5a	47.9a
N2L	57.1a	19.4a	5.66a	2.5ab	3.95a	18.3a	87.1a	42.3a	47a
Std	58.1a	18.64bc	5.54a	2.39b	3.88a	16.4a	87.1a	42.5a	46.7a
ANOVA	*P* > *F*								
Year (Y)	.003	.076	.152	.04	.038	.060	.003	.823	.045
Fertility (F)	.375	.061	.264	.100	.131	.783	.972	.275	.637
Y × F	.553	.410	.869	.089	.065	.733	.906	.824	.239

Note. UTC = unfertilized control, Std = fertilization with synthetic fertilizers, P5L = phosphorus-based poultry litter application every year for 5 yr, N5L = nitrogen-based poultry litter application for 5 yr, N2L = nitrogen-based poultry litter application for 2 yr followed by synthetic nitrogen fertilization for 3 yr.
[a]Values followed by the same letter within a column and crop are not significantly different from each other at $P < .05$ level.

(Table 11). The other four treatments which received optimal or near optimal fertilization also differed from each other although the differences were small. For example, the Std treatment removed a 5-yr average of 20.3 kg ha^{-1} P compared with 21.3 kg ha^{-1} for the N5L treatment, an increase of only 5%.

The differences in nutrient removal among the treatments was dependent largely on their yield differences. The N2L treatment which produced one of the largest yields also removed one of the largest amounts of all nutrients. In the first 2 yr when PL was applied, the nutrient removal by the N2L treatment was similar to the other three optimally fertilized treatments (Table 11). When PL application was stopped in 2012–2014 and the treatment was fertilized with synthetic N only, the N2L treatment removed the highest or one of the highest amounts of the macronutrients N, P, K, Mg, and Ca and the micronutrients Fe, Cu, and Mn. This enhanced nutrient removal of the N2L treatment suggests that the PL management strategy represented by this treatment is a viable alternative to P-based PL management. As discussed earlier, this treatment improved yield of the three crops and should be economically viable.

TABLE 11 Amount of nutrients removed from the soil with harvested seed after growing and harvesting cotton, corn, and soybean grown with selected fertility treatments that included synthetic N fertilizers and poultry litter (PL). Each value is an average of four rotation treatments and three or four replications

Fertility treatment	N	P	K	Mg	Ca	Fe	Mn	Cu	Zn
	kg ha^{-1}					g ha^{-1}			
2010									
UTC	47d[a]	12.1b	17c	5.9c	2.7c	62c	23d	10.4c	70c
P5L	69b	14.7a	22ab	7.4a	3.2ab	89ab	35b	13.3b	95b
N5L	62c	14.3a	21ab	6.9ab	3bc	84b	28c	13.4b	95b
N2L	63c	12.6b	20b	6.4bc	2.8c	81b	31c	13b	86b
Std	76a	14.6a	23a	7.4a	3.5a	96a	39a	15.3a	110a
2011									
UTC	35c	9.5d	13b	4.1c	1.5b	61d	19d	8.7d	64c
P5L	91a	21.9a	30a	8.4a	2.6a	178b	49ab	24.6a	157ab
N5L	83b	21.6ab	29a	8ab	2.5a	158c	46c	20.9c	166a
N2L	83b	20.4c	29a	7.7b	2.4a	187a	47bc	25.7a	155b
Std	90a	20.6bc	29a	8ab	2.6a	175b	50a	23.2b	157ab
2012									
UTC	83c	13.4d	29d	6.2d	5c	158c	50c	23.3c	96d
P5L	126b	21.7bc	42bc	9.1bc	6b	216b	76b	35.4b	158c
N5L	124b	22.6ab	44b	9.4b	6b	216b	73b	33.7b	209a
N2L	140a	23.7a	47a	10.2a	6.8a	251a	85a	43a	186b
Std	129b	20.8c	41c	8.8c	6.1b	223b	81a	35.2b	175b
2013									
UTC	117b	13.8c	42c	6.2c	7.6c	293a	80b	39.9b	116b
P5L	155a	23a	55b	9.6ab	8.6b	299a	100a	50.4b	185ab
N5L	150a	22.1ab	55b	9.1b	8.4b	303a	98a	53.5ab	280a
N2L	157a	23.3a	59a	10a	9.6a	335a	111a	70.8a	190ab
Std	153a	21.4b	54b	9.1b	8.8b	307a	106a	53.9ab	211ab
2014									
UTC	79c	10.8c	24d	4.4c	4.4c	98c	45b	15.6b	81b
P5L	143b	25.1ab	43bc	8.9ab	5.3a	233ab	83a	32.2a	190a
N5L	144ab	26.1ab	45ab	9ab	5.3ab	202b	84a	23.9ab	214a
N2L	153a	27.2a	46a	9.4a	5.2ab	257a	91a	31.3a	205a
Std	143b	24.3b	42c	8.5b	4.9b	216ab	85a	27.8a	186a

Note. UTC = unfertilized control, Std = fertilization with synthetic fertilizers, P5L = phosphorus-based poultry litter application every year for 5 yr, N5L = nitrogen-based poultry litter application for 5 yr, N2L = nitrogen-based poultry litter application for 2 yr followed by synthetic nitrogen fertilization for 3 yr.

[a]Values followed by the same letter within a column and year are not significantly different from each other at $P < .05$ level.

4 | SUMMARY AND CONCLUSION

Repeating PL application to the same soil as a fertilizer for as few as 5 yr has been shown to lead to soil accumulation of P and other elements that can be of environmental concern. Phosphorus-based application has been the only and most accepted PL management strategy; but, operationally, this approach may not always be the most efficient strategy. This study explored whether rotating fertilizers and crops or a combination of the two can be used to increase yield, enhance the export of mineral nutrients, and prevent PL-derived nutrient buildup in the soil when PL is repeatedly applied as a fertilizer. The study has identified a new strategy as a viable alternative to P-based PL management. This new strategy involves applying PL at a relatively high rate for 2 yr to meet the N need of cotton followed by a cessation of PL application for 2 or 3 yr during which only synthetic N is applied. Not only did this strategy lower the residual soil nutrients to be equivalent to the P-based application, it also improved the economic yield of all three crops in the study. The new strategy removed a greater amount of all mineral elements than the P-based PL management strategy and, therefore, should serve as a remediation strategy to reduce the level of residual elements from repeated PL applications. We believe this alternative PL application strategy is even more sustainable than the P-based PL application because it likely is more profitable than the P-based application. Regardless of the strategy, this study revealed that, although the well-accepted assumption that 50% of the total N from PL will become available to cotton during the growing season still is applicable during normal seasons, care must be exercised with this assumption during dry seasons and when the PL is applied several weeks before planting. With corn, the results confirm that PL should be applied assuming 35% (not 50% as is the common assumption) of the total N will be available for the corn crop during the same season and the balance of the N need should be met from synthetic sources. This study has shown that PL increases soybean yield during the same year it is applied, but this increase may not be economical at high rates. The best strategy of managing PL where the three crops are grown in rotation is to fertilize cotton or corn with PL to supply 100% of cotton's N need followed by growing soybean without applying any fertilization in the subsequent 2 or 3 yr.

AUTHOR CONTRIBUTIONS

Haile Tewolde, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Writing-original draft, Writing-review & editing; Normie Buehring, Methodology, Resources, Investigation; Thomas R. Way, Investigation, Methodology, Writing-review & editing; Gary Feng, Investigation, Writing-review & editing; Zhongqi He, Investigation, Writing-review & editing; Karamat Sistani, Investigation, Writing-review & editing; Johnie N. Jenkins, Supervision, Resources, Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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