# *Miscanthus* Production on a Coastal Plain Soil: Nitrogen Fertilization and Poultry Litter

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**ABSTRACT:** There has been limited study on the performance of miscanthus (*Miscanthus* × *giganteus*) on Coastal Plain soils in the Mid-South United States and use of poultry litter (PL) with miscanthus. This study examined the response of miscanthus growing on a low-fertility soil to N and PL, including effects of PL on water quality. A randomized complete block experiment on Ruston soil (fine-loamy, siliceous, semiactive, thermic Typic Paleudults) compared five fertilizer treatments: 0, 80, and 160 kg N $ha^{-1}$ $y^{-1}$ as urea or PL, applied 2010 through 2013, and native vegetation (NV). Data included yields, tissue nutrients, and runoff from subplots of NV, 0, and PL, 2010 to 2014; fertility parameters in surface (0–15 cm) soil, 2009 to 2015; organic C (OC) and oxalate-extractable Al, Fe, and P with depth, 2010; and fertility parameters (including OC, total N, and total and inorganic P) with depth, 2015. Yields exhibited a 3-year lag before a maximum of 18 Mg $ha^{-1}$ in 2014 and were not increased by N fertilization. Nutrient removal was low, leading to increased P with PL in 0- to 15-cm soil but no evidence of P leaching below 30 cm. Runoff P was increased by PL at the higher rate (0.40 kg P $ha^{-1}$ $y^{-1}$ greater than no PL). Although use of PL alone to replenish nutrients would lead to high P loss, supplementing a reduced PL rate with non-P fertilizer might be sustainable. *Miscanthus* did not increase soil OC or affect water quality compared with NV.

**Key Words:** low-fertility soil, *Miscanthus* × *giganteus*, nitrogen fertilization, phosphorus, poultry litter, runoff water quality

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Miscanthus (MIS; *Miscanthus* × *giganteus*) has been studied for more than three decades as a potential biomass crop, first in Europe where highest yields averaged about 20 Mg $ha^{-1}$ (Lewandowski et al., 2000) and then in the United States Midwest where potential yields are even greater (Heaton et al., 2008; Kiniry et al., 2013). Although studies on MIS productivity have commonly used fertile agricultural soils, a few have examined yields on more-weathered, less-fertile Ultisols, including examples from the Coastal Plain (Fedenko et al., 2013; Palmer et al., 2014). The major land uses of the Coastal Plain are forestry and pasture (USDA-NRCS, 2006), the latter often supporting cattle-poultry production in which poultry litter (PL; a mix of bedding material, spilt feed and excreta) is used as pasture fertilizer. However, long-term application of PL results in high concentrations of soil P (Sharpley et al., 1993; Kingery et al., 1994) and increased loss of P in surface runoff (Schroeder et al., 2004a) and internal drainage (Sims et al., 1998) that may enrich water bodies with P and affect their ecology (Correll, 1998). Therefore, to the extent PL might be diverted from pasture fertilization to beneficial use with MIS on low-fertility soil, off-site loss of P may be reduced.

The feasibility of producing a perennial biomass grass crop depends in large part on lower nutrient requirements than for agronomic crops. It is presumed, therefore, that low-fertility soil such as abandoned cropland would be suitable for such crops (Campbell et al., 2008). However, requirements for MIS are not fully established, even for agricultural soils. For example, although Arundale et al. (2014) found that N fertilization up to 200 kg $ha^{-1}$ may be needed for maximum yields, others found either inconsistent (Davis et al., 2015; Dierking et al., 2016) or no response to N (Kering et al., 2012; Maughan et al., 2012; Palmer et al. 2014). Requirements for other nutrients appear modest based on harvest removal data, <80 kg $ha^{-1}$ K, <30 kg $ha^{-1}$ Ca, <20 kg $ha^{-1}$ Mg, and <10 kg $ha^{-1}$ P and S (Propheter and Staggenborg, 2010; Kering et al., 2012; Palmer et al., 2014; Masters et al., 2016), indicating that low rates of application are sufficient to maintain fertility. However, ratios of P to other nutrients removed in MIS harvest are low compared with these ratios for the average composition of PL (broiler; Bolan et al., 2010). Therefore, use of PL alone to supply N or replenish other nutrients would increase soil P.

On the other hand, nutrient imbalances might be corrected with supplemental inorganic fertilizer so that build-up of soil P is minimized. Even so, short-term extraction of P from the surface-applied PL into runoff would occur. Although there are no studies on P runoff from surface-applied PL with MIS, runoff losses might be comparable to those under pasture grasses on initially low P soil (Vervoort et al., 1998; Pierson et al., 2001; Harmel et al., 2004).

This report describes the performance of MIS on a low-fertility Coastal Plain soil in Louisiana, including responses to N fertilization, nutrient dynamics with PL, and effects of land conversion from fallow. Objectives were to determine the effects of N fertilizer source (urea or PL) and rates with MIS on (1) short- to intermediate-term yields, (2) nutrient removals in harvest, and (3) soil fertility; (4) effects of PL on runoff water quality; and (5) effects of MIS on soil fertility and runoff water quality.

## MATERIALS AND METHODS

### Field Experiment

The experiment was conducted at the Louisiana State University Agricultural Center (LSU AgCenter) Calhoun Research Station in Calhoun, Louisiana, on a long-term fallow (rotary-mowed only),

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8% grade hillside site (32.51769ºN, −92.34949°E) of Ruston series soil (fine-loamy, siliceous, semiactive, thermic Typic Paleudults). It was a randomized block design with three replicates of (1) MIS, unfertilized (0); MIS fertilized annually from March 2010 to March 2013 with (2) 80 kg N ha$^{-1}$ PL (80PL); (3) 160 kg N ha$^{-1}$ PL (160PL); (4) 80 kg N ha$^{-1}$ urea (80U); (5) 160 kg N ha$^{-1}$ urea (160U); and (6) native vegetation, unfertilized (NV). The latter was predominately a mixture of bahiagrass (*Paspalum notatum*) and bermudagrass (*Cynodon dactylon*) with some blackberry (*Rubus* species). The composition of PL is given in Table 1. Blocks of treatment plots (5.0 × 5.0 m, separated by 2.0 m) were oriented perpendicular to the slope, and blocks were separated by 6 m. Plots were rototilled to 10 cm and rhizomes (Illinois clone) planted on 1-m centers in spring 2009. Weeds were controlled by hand in 2009 and 2010, but negligible in later years. Runoff subplots were installed in all 0, 80PL, 160PL, and NV plots before treatment application in 2010. These subplots were stainless-steel frames (2.00 × 0.75 × 0.15 m; inserted to 0.07-m depth) with covered collection troughs from which runoff drained through PVC pipe into 20-L closed plastic buckets downslope.

### Yields and Tissue Concentration of Nutrients

Whole plots (original 25 m$^2$) were harvested in late fall to winter in all years with a sickle-bar mower to ~10-cm stubble. Dry matter yield was determined from wet mass and moisture content (60°C for 2 days). Ground subsamples were analyzed by the Soil Testing and Plant Analysis Laboratory, LSU AgCenter, for N (Leco CN analyzer; St. Joseph, MI) and P, K, Ca, Mg, and S ($HNO_3$ digestion and inductively coupled plasma spectroscopic analysis; SPECTRO ARCOS Model FH E12, Kleve, Germany).

### Soil Parameters

Samples of 0- to 15-cm surface soil were collected when rhizomes were planted in 2009, before treatment application in 2010 through 2013, and again in spring 2014 and 2015 for residual effects of treatments. Two 5-cm-diameter cores were taken to 1 m from the center of MIS plots before treatment application in 2010 and in spring 2015 and sectioned into 0- to 15-, 15- to 30-, 30- to 45-, 60- to 80-, and 80- to 100-cm depth increments. Surface soil samples were analyzed for pH (1:2 soil to water ratio), total N (TN) (Leco CN analyzer), Mehlich 3 extractable elements, organic C (OC) by wet digestion (Nelson and Sommers, 1982), and fluorescein diacetate (FDA) hydrolysis rate (Schnürer and Rosswall, 1982; corrected for background absorbance, Adam and Duncan, 2001). All soil core samples were analyzed for Mehlich 3 elements and OC, samples from the 0, 80PL, and 160PL plots in 2010 were analyzed for oxalate-extractable Al, Fe, and P ($Al_{ox}$, $Fe_{ox}$, and $P_{ox}$; Schoumans, 2009), and samples from 2015 were analyzed for TN and total P (TP), inorganic P (IP), and organic P (OP, by difference; Walker and Adams, 1958). Bulk density was estimated from the core increments.

### Runoff Water Quality

Following rainfall greater than 2 cm (NOAA station, Calhoun Research Station, LA), runoff volume was measured by net mass. If volume was ≥0.2 L, all or 0.5 L was taken to the laboratory for analysis of solids (by evaporation at 105°C; total, TS, and dissolved, DS, by 0.45-μm filtration, and suspended, SS, by difference); chemical oxygen demand (COD; dichromate oxidation; APHA, American Public Health Association, 1998); dissolved reactive P (DRP; Pote and Daniel, 2009); TP (persulfate-$H_2SO_4$ digestion; Pote et al., 2009); $NH_3$ + $NH_4^+$ (phenate method; APHA, American Public Health Association, 1998), $NO_3^-$ + $NO_2^-$ (nitrate reduction with $VaCl_3$; Miranda et al., 2001); and dissolved OC (DOC; Shimadzu TOC-V analyzer, Kyoto, Japan). The pH was also measured. Runoff collection began with the first event following treatment application in 2010 and continued for approximately 4 years until late winter 2014.

### Statistical Analyses

Multiyear plant, soil, and water data were analyzed as a randomized complete block with repeated measures in time using the MIXED procedure of SAS Institute (2012), with treatment, year, and treatment × year as fixed effects, and replicate and replicate × treatment as random effects. Means separations were performed with Tukey-Kramer at $\alpha = 0.05$. The MIXED procedure with treatment as the fixed effect was used for soil core parameters; the general linear models and *t* test procedures of SAS Institute (2012) were respectively used for regressions and change in soil OC.

## RESULTS AND DISCUSSION

### *Miscanthus* Yields, Tissue Concentrations, and Nutrient Removal

There was no effect of fertilizer treatment on MIS yields (Table 2), similar to Kering et al. (2012), Maughan et al. (2012), and Palmer et al. (2014). However, yearly average yields increased following a 3-year lag, being 79% greater in 2013 and 156% greater in 2014 than the average for 2010 through 2012. Yields were related to rainfall and temperature during the growing season only for the drier than average conditions in 2010 (36% less rain) and wetter and cooler conditions in 2014 (45% more rain and 2º C lower; Table 3). The average yield of 10.3 Mg ha$^{-1}$ was low compared with those from the Midwest, which may approach ~38 Mg ha$^{-1}$ (Illinois, Heaton et al., 2008; Missouri, Kiniry et al., 2013), but lower yields may be expected for warmer conditions (Kiniry et al., 2013). The average yield in this study was greater than that for Oklahoma (3–5 Mg ha$^{-1}$; Kering et al., 2012; Kiniry et al., 2013) and Texas (4–5 Mg ha$^{-1}$;

**TABLE 1.** Composition of Poultry Litter as Applied 2010–2013 and Cumulative Elemental Masses Applied in Four Annual Applications at a Rate of 160 kg N Ha$^{-1}$

| Year | N | C | P | K | Ca | Mg | S |
|---|---|---|---|---|---|---|---|
| | g kg$^{-1}$ | | | | | | |
| 2010 | 23.3 | 253 | 16.9 | 27.9 | 27.2 | 4.4 | 7.4 |
| 2011 | 29.6 | 231 | 16.2 | 27.1 | 26.4 | 5.1 | 7.1 |
| 2012 | 28.1 | 322 | 14.3 | 33.4 | 25.1 | 6.2 | 6.5 |
| 2013 | 27.7 | 369 | 13.5 | 26.1 | 19.6 | 4.8 | 5.7 |
| | | | | | | | |
| | kg ha$^{-1}$ | | | | | | |
| Total | 640 | 6951 | 363 | 679 | 586 | 121 | 159 |

Data from the LSU AgCenter Soil Testing and Plant Analysis Laboratory (Leco CN analyzer; $HNO_3$ digestion and inductively coupled plasma spectroscopic).

**TABLE 2.** Effects of Treatment (T), Year (Y), and T × Y on Average Yields, Tissue Concentrations and Harvest Removals of N, P, K, Ca, Mg, and S

| T | Yield | N | P | K | Ca | Mg | S | N | P | K | Ca | Mg | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mg ha$^{-1}$ | g kg$^{-1}$ | | | | | | kg ha$^{-1}$ | | | | | |
| 0 | 8.75 | 3.00 | 0.27 b[†] | 2.39 | 2.52 | 0.50 | 0.37 | 25.2 | 2.3 b | 23.4 bc | 19.5 | 3.9 | 2.8 |
| 80PL | 11.47 | 3.01 | 0.62 a | 2.81 | 2.13 | 0.49 | 0.35 | 32.8 | 7.5 a | 32.4 ab | 21.5 | 5.4 | 3.7 |
| 160PL | 11.54 | 3.26 | 0.81 a | 3.31 | 2.03 | 0.56 | 0.40 | 34.9 | 9.2 a | 37.7 a | 21.3 | 6.4 | 4.2 |
| 80U | 8.38 | 3.48 | 0.17 b | 2.22 | 2.29 | 0.47 | 0.39 | 24.6 | 1.2 b | 18.2 c | 17.3 | 3.6 | 2.6 |
| 160U | 11.59 | 3.18 | 0.11 b | 2.21 | 2.14 | 0.44 | 0.37 | 33.8 | 1.2 b | 25.2 bc | 22.4 | 4.8 | 3.7 |
| | | | | | | | | | | | | | |
| Y | Yield | N | P | K | Ca | Mg | S | N | P | K | Ca | Mg | S |
| | Mg ha$^{-1}$ | g kg$^{-1}$ | | | | | | kg ha$^{-1}$ | | | | | |
| 2010 | 6.55 c | 3.64 a | 0.23 b | 2.33 bc | 3.05 a | 0.73 a | 0.51 a | 22.6 d | 1.4 c | 15.1 c | 20.2 b | 4.6 b | 3.2 bc |
| 2011 | 7.26 c | 3.47 a | 0.26 b | 2.16 c | 1.80 b | 0.23 c | 0.37 b | 23.7 cd | 1.8 c | 15.0 c | 12.2 c | 1.8 c | 2.4 d |
| 2012 | 7.31 c | 3.70 a | 0.55 a | 2.92 ab | 3.55 a | 0.64 a | 0.49 a | 26.7 c | 4.0 b | 20.6 bc | 26.7 a | 4.4 b | 3.5 b |
| 2013 | 12.57 b | 2.45 b | 0.48 a | 2.04 c | 0.98 c | 0.36 c | 0.23 d | 31.0 b | 6.2 ab | 26.1 b | 12.5 c | 4.5 b | 2.9 cd |
| 2014 | 18.04 a | 2.66 b | 0.47 a | 3.48 a | 1.75 bc | 0.50 b | 0.29 c | 47.2 a | 8.0 a | 60.0 a | 30.5 a | 8.7 a | 5.0 a |
| | | | | | | | | | | | | | |
| Effect | Yield | N | P | K | Ca | Mg | S | N | P | K | Ca | Mg | S |
| T | NS[‡] | NS | *** | NS | NS | NS | NS | NS | *** | ** | NS | NS | NS |
| Y | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| T × Y | NS | NS | * | NS | NS | NS | NS | NS | * | NS | NS | NS | NS |

Treatments were no fertilization (0) or fertilization with 80 or 160 kg N ha$^{-1}$ annually in the spring from 2010 to 2013 with PL (80PL and 160PL) or urea (80U and 160U).

[†] Numbers within a column followed by different letters are significantly different; Tukey-Kramer, α = 0.05.

[‡] *, **, ***Significant at $P < 0.05$, 0.01 and 0.001, and NS = not significant.

**TABLE 3.** Rainfall and Average Temperature From March Through August, 2010–2014 and Historical Averages for Calhoun, LA

| Parameter | Year | | | | | Average |
|---|---|---|---|---|---|---|
| | 2010 | 2011 | 2012 | 2013 | 2014 | |
| Rainfall, cm | 43 | 62 | 78 | 60 | 97 | 67 |
| Temperature, °C | 23 | 24 | 24 | 21 | 21 | 23 |

Kiniry et al., 2013) and within ranges for Arkansas (6–20 Mg ha$^{-1}$; Burner et al., 2009; Kiniry et al., 2013) and Florida (8–28 Mg ha$^{-1}$; Fedenko et al., 2013). By 2014, the 18 Mg ha$^{-1}$ yield was comparable to that for cooler climates, including Kentucky (13–18 Mg ha$^{-1}$; Maughan et al., 2012; Davis et al., 2015; Dierking et al., 2016), North Carolina (18 Mg ha$^{-1}$; Palmer et al., 2014), and Virginia (13 Mg ha$^{-1}$; Davis et al., 2015). While maximum yields are common in the second year after establishment (Clifton-Brown et al., 2001), yields increased beyond a postestablishment plateau, 2010 to 2012. Since the study site was chosen as representative of marginal soil on the Coastal Plain of Louisiana, protracted establishment and no responses to N fertilization might be expected elsewhere in the region under similar conditions.

Fertilization with N had no effect on tissue concentrations or removal in harvest; however, concentration decreased, but removal increased with greater yield (Table 2). Similar results are common in previous studies (Kering et al., 2012; Dierking et al., 2016; Masters et al., 2016). Despite high content of Ca and K and appreciable Mg and S in PL (Table 1), the only significant effect of PL on tissue concentrations was higher P. However, the relatively high yields from PL plots did lead to significantly greater removal of K from the 160PL plots than non-PL plots and greater removal from the 80PL plots than from the 80U plots. Differences among years in tissue concentrations of K, Ca, Mg, and S generally oscillated 2010 > 2011 < 2012 > 2013 < 2014, which reflected date of harvest, midfall in 2010, 2012, and 2014 and midwinter in 2011 and 2013, thus continued translocation with further senescence. However, increasing soil P with continued PL application (discussed below) led to increasing tissue concentrations over time and a significant treatment × year interaction. Since numerical differences in yields among treatments were small each year, the same oscillatory pattern in harvest removal occurred with Ca, Mg, and S; however, continued fertilization with PL increased K and P removal over time. Compared with previous studies across ranges in experimental conditions and yields, all tissue concentration and uptake data for the non-PL treatments except for Ca were low (Propheter and Staggenborg, 2010; Kering, et al., 2012; Palmer et al., 2015; Dierking et al., 2016; Masters et al., 2016), in part likely reflecting low fertility of the soil. Despite higher tissue P concentration and P removal for the PL treatments, only an average of 17% and 10% of the P applied in the 80PL and 160PL treatments (Tables 1 and 2) was removed in harvest. Because there was no response to N and removal of other nutrients was less than applied in PL, a lower rate of application would replenish nutrients removed and slow the build-up of soil P.

## Soil Fertility Parameters in Surface and Subsurface Soil

The LSU AgCenter recommendation for warm-season grasses on coarse texture soil such as the Ruston and with low content of Mehlich 3 P and bases (Table 4) is 44 kg P and 167 kg K ha$^{-1}$, and dolomitic limestone. Therefore, four applications of the PL treatments (Table 1) greatly exceeded these recommendations, with the 160PL treatment adding Ca and Mg equal to the initial amounts and up to 19 times more P and S than in 2010. However, time-averaged (2011 through 2014) treatment effects in the surface 0- to 15-cm soil were modest: Mehlich 3 P was greater in the 160PL than other plots; K decreased 160PL > 80PL > other plots, and Mg was greater in the 160PL plots than in control and urea plots, but addition of Ca and S did not significantly increase concentrations compared with other plots (Table 5). Significance of effects generally paralleled the mass of nutrients applied relative to the mass of Mehlich 3 element initially present (Tables 1 and 4), least for Ca < Mg < K < P, except for S. The latter exists predominantly as soil organic S, and the increase in soil S due to fertilization is minimal in relatively coarse texture soil such as the Ruston (Wyngaard and Cabrera, 2015). Significant effects of year on P, K, and Mg reflected cumulative additions with PL, as did significant treatment × year interactions. The pH was greatest in the PL plots (Table 5) largely due to the net addition of bases compared with removal in harvest (Tables 1 and 2). It was lowest in the NV plots (the only difference with respect to unfertilized MIS) but likely reflected a persistent effect of spatial variability in initial conditions (data not shown). There was a significant effect of year on pH, but it reflected oscillations year to year, and there was no significant treatment × year interaction.

There was neither treatment effect on soil OC nor effect of N fertilization on soil TN (Table 5). Whereas conversion of agricultural land to MIS increases soil OC (Davis et al., 2015; Zang et al., 2018), conversion of perennial grassland to MIS has little (Kahle et al., 2001; Hansen et al., 2004; Zang et al., 2018) or no (Zatta et al., 2014) positive effect on soil OC content and may even decrease it (Davis et al., 2015). Application of no more than 160 kg N ha$^{-1}$ y$^{-1}$ for only 4 years, together with variability among plots, presumably accounts for no increase in soil TN. Glendining et al. (1996), for example, found that application of 144 kg N ha$^{-1}$ y$^{-1}$ for 135 years in wheat increased soil TN only 21% compared with no N fertilization, and Mazzoncini et al. (2011) observed an increase only where N had been applied for 15 years at $\geq$200 kg ha$^{-1}$ y$^{-1}$. Although TN did not increase over time (the significant year effect being 2013 > 2014), OC

**TABLE 4.** Average Profile Content of Mehlich 3 Macronutrients, Oxalate-Extractable Al and Fe (Al$_{ox}$ + Fe$_{ox}$), and Extent to Which Al$_{ox}$ + Fe$_{ox}$ Was Saturated With Oxalate-Extractable P Before Treatments Were Applied in 2010

| Depth | P | K | Ca | Mg | S | Al$_{ox}$ + Fe$_{ox}$ | P$_{sat}$ |
|---|---|---|---|---|---|---|---|
| cm | kg ha$^{-1}$ | | | | | kmol ha$^{-1}$ | % |
| 15 | 43 ± 19[†] | 148 ± 44 | 707 ± 229 | 77 ± 37 | 13 ± 5 | 30.4 ± 9.0 | 10.0 ± 2.2 |
| 30 | 16 ± 11 | 97 ± 57 | 189 ± 148 | 73 ± 40 | 12 ± 12 | 34.2 ± 10.0 | 3.2 ± 2.2 |
| 45 | 7 ± 6 | 140 ± 107 | 315 ± 253 | 101 ± 54 | 28 ± 32 | 42.1 ± 20.0 | 2.5 ± 1.0 |
| 60 | 9 ± 8 | 187 ± 143 | 420 ± 337 | 135 ± 71 | 37 ± 43 | 66.1 ± 33.0 | 1.3 ± 1.2 |
| 80[‡] | 5 ± 4 | 229 ± 173 | 560 ± 483 | 178 ± 123 | 55 ± 36 | 67.1 ± 21.6 | 0.7 ± 0.8 |

Masses are based on average bulk densities estimated from cores.

[†] SD.

[‡] Cores to 100 cm could not be taken from several plots in the low elevation block due to wetness.

**TABLE 5.** Effects of Treatment (T), Year (Y) and T × Y on Average Mehlich 3 Extractable Macronutrients, pH, OC, TN, and FDA Hydrolysis Rate in Surface 0- to 15-cm Soil, 2011 Through 2014

| T | P | K | Ca | Mg | S | pH | OC | TN | FDA |
|---|---|---|---|---|---|---|---|---|---|
| | mg $kg^{-1}$ | | | | | | g $kg^{-1}$ | | μmol $g^{-1}$ $h^{-1}$ |
| 0 | 23.4 b[†] | 90 c | 348 | 38 b | 7.3 | 5.77 b | 8.9 | 0.82 | 0.177 |
| 80PL | 29.8 b | 112 b | 446 | 62 ab | 6.7 | 6.03 a | 9.2 | 0.69 | 0.193 |
| 160PL | 58.8 a | 133 a | 496 | 74 a | 8.6 | 6.03 a | 9.2 | 0.91 | 0.179 |
| 80U | 22.9 b | 65 d | 300 | 33 b | 6.7 | 5.57 bc | 8.0 | 0.98 | 0.180 |
| 160U | 19.2 b | 70 d | 345 | 39 b | 5.8 | 5.63 b | 7.6 | 0.80 | 0.159 |
| NV | 16.4 b | 90 c | 435 | 53 ab | 7.8 | 5.40 c | 8.7 | 1.01 | 0.171 |
| | | | | | | | | | |
| **Effect** | **P** | **K** | **Ca** | **Mg** | **S** | **pH** | **OC** | **TN** | **FDA** |
| T | **[‡] | *** | NS | * | NS | *** | NS | NS | NS |
| Y | *** | *** | NS | *** | NS | *** | *** | * | *** |
| T × Y | *** | * | NS | ** | NS | NS | NS | NS | NS |

Treatments were miscanthus with no fertilization (0) or fertilization with 80 or 160 kg N $ha^{-1}$ annually in the spring from 2010 to 2013 with PL (80PL and 160PL) or urea (80U and 160U) and unfertilized NV.

[†] Numbers within a column followed by different letters are significantly different; Tukey-Kramer, α = 0.05.

[‡] *, **, ***Significant at $P < 0.05$, 0.01 and 0.001, and NS = not significant.

did. Including soil OC data from 2009, 2010, and 2015 suggests that OC in the rototilled MIS plots may have initially decreased and then increased above initial concentrations (Fig. 1), consistent with the modeling results of Anderson-Teixeira et al. (2009). Increases in OC for the MIS plots presumably reflect cumulative addition of unharvested biomass (up to two-thirds of the maximum aboveground biomass; Hansen et al., 2004) and PL. Leaving the NV plots undisturbed may also have led to increased soil OC, possibly due to increased biomass/deposition and species diversity (Steinbeiss et al., 2008), which were apparent but not measured. Furthermore, fluorescein diacetate hydrolysis rate significantly decreased over time (Table 5), so respiration and OC mineralization may have decreased (in part perhaps due to N fertilization; Ramirez et al., 2010), reinforcing the above effects on increasing soil OC. On the other hand, Zang et al. (2018) found parallel increases in soil OC under MIS and reference undisturbed grassland, and they attributed the effect to long-term, continuing OC accretion following conversion of agricultural land to perennial grass. However, the Calhoun study site had been in fallow for many years before MIS was planted (D. Cooper, personal communication).

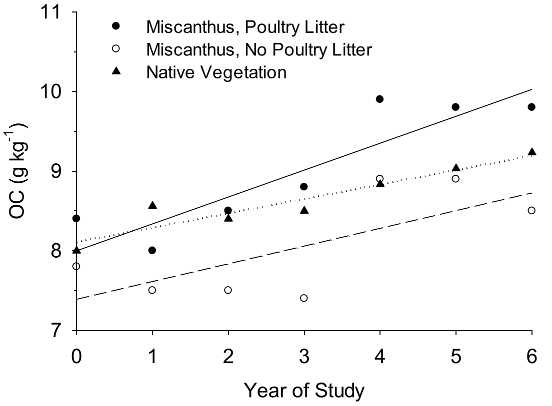

**FIGURE 1.** Average OC in surface 0- to 15-cm soil in miscanthus plots amended with PL (n = 6), not amended with PL (n = 9), and in NV plots (n = 3) from 2009 to 2015. The solid line is the linear regression for miscanthus plots with PL, $Y = 8.00 + 0.388X$ ($R^2 = 0.81$; $P < 0.001$); the dashed line is for miscanthus plots without PL, $Y = 7.39 + 0.223X$ ($R^2 = 0.81$; $P < 0.001$), and the dotted line is for NV plots, $Y = 8.11 + 0.181X$ ($R^2 = 0.86$; $P < 0.10$).

Conversion to MIS had no effect on OC in the subsoil (ΔOC, 2015–2010, below 15 cm was not significantly >0; *t* test, non-PL plots; data not shown). Poeplau and Don (2014) obtained a similar result in this regard; although conversion of an agricultural soil to MIS increased soil OC, the effect was limited to the topsoil. Residual effects of fertilizer treatments on fertility parameters 2 years after the last application (Table 6) were similar to average effects from 2011 to 2014 (Table 4) in the upper 15 cm except for higher Ca in the 160PL than non-PL plots. Four applications of PL, however, had not significantly increased the concentration Mehlich 3 P, K, Ca, or Mg or pH below 15 cm. Aside from the small increase in Mehlich 3 S in the 15- to 30-cm depth for the 160PL treatment, there were no significant treatment effects except greater IP in the 160PL than 0 and 160U plots (however, if relaxed to $P < 0.10$, TP and IP were greatest in the 160PL plots). Thus, there was no evidence of P leaching below 30 cm, reflecting the high P sorption capacity of the Ruston soil relative to the mass of P applied. The P sorption capacity estimated by P-unsaturated $Al_{ox} + Fe_{ox}$ ($[Al_{ox} + Fe_{ox}] \times (1 - P_{sat}/100) \times 30.97$ kg P $kmol^{-1}$ for the upper 30 cm; Table 4; Hooda et al., 2000) was 1,870 kg P $ha^{-1}$, but 363 kg P $ha^{-1}$ was applied at most (Table 1). On the other hand, slow downward migration of P from the surface, together with small harvest removal (Table 2), implies that the increased concentration in the surface soil is a long-term source of P loading into runoff.

## Effects of Poultry Litter on Runoff Water Quality

The only significant treatment effects were higher concentrations of DRP and TP from the 160PL than other plots (Table 7). These and concentrations of COD, DOC, $NH_4^+$-N, and $NO_3^-$-N were similar to or much lower than concentrations in runoff found in earlier studies with PL applied at similar P rates (Edwards and Daniel, 1994; Shreve et al., 1995; Sauer et al., 1999; Schroeder et al., 2004b). Compared with runoff data from small pastures amended with PL,

**TABLE 6.** Treatment (T) Effects on Average Mehlich 3 Extractable Macronutrients, pH, OC, TN, TP, IP, and OP in 0- to 15-cm and 15- to 30-cm Depth Soil in 2015

| T | Depth | P | K | Ca | Mg | S | pH | OC | TN | TP | IP | OP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | cm | mg kg$^{-1}$ | | | | | | g kg$^{-1}$ | | mg kg$^{-1}$ | | |
| 0 | 15 | 11.2 b[†‡] | 42 c | 327 b | 43 bc | 6.4 | 5.07 c | 8.4 | 1.14 | 101 b | 10 c | 91 |
| 80PL | | 41.8 b | 75 b | 343 ab | 64 b | 6.6 | 5.62 b | 10.2 | 1.18 | 136 ab | 49 b | 87 |
| 160PL | | 112.7 a | 102 a | 479 a | 91 a | 7.2 | 5.97 a | 9.6 | 1.08 | 171 a | 81 a | 90 |
| 80U | | 11.7 b | 46 c | 284 b | 45 bc | 7.0 | 5.04 c | 8.7 | 0.93 | 97 b | 13 c | 84 |
| 160U | | 12.6 b | 45 c | 283 b | 37 c | 7.0 | 4.95 c | 8.4 | 0.99 | 92 b | 11 c | 81 |
| | | | | | | | | | | | | |
| 0 | 30 | 6.7 | 57 | 73 | 15 | 5.1 b | 5.13 | 3.7 | 0.66 | 73 | 7 b | 66 |
| 80PL | | 10.4 | 61 | 101 | 21 | 4.9 b | 4.93 | 2.1 | 0.61 | 63 | 12 ab | 51 |
| 160PL | | 20.7 | 97 | 98 | 23 | 6.2 a | 5.15 | 2.5 | 0.65 | 106 | 39 a | 67 |
| 80U | | 6.3 | 42 | 62 | 12 | 5.1 b | 4.87 | 2.2 | 0.48 | 64 | 11 ab | 53 |
| 160U | | 5.7 | 56 | 90 | 22 | 4.5 b | 4.75 | 2.9 | 0.52 | 62 | 9 b | 53 |

There were no treatment effects below 30-cm depth. Treatments were miscanthus with no fertilization (0) or fertilization with 80 or 160 kg N ha$^{-1}$ annually in the spring from 2010 to 2013 with PL (80PL and 160PL) or urea (80U and 160U), and native vegetation with no fertilization (NV).

[†] Numbers within a column followed by different letters are significantly different; Tukey-Kramer, $\alpha = 0.05$.

[‡] $P < 0.05$ for IP in the 15- to 30-cm depth; $P < 0.01$ for Mehlich 3 P and Mg, and TP in the 0- to 15-cm depth; and $P < 0.001$ for all others.

TABLE 7. Effects of Treatment (T), Year (Y), and T × Y on Average Annual Volume-Weighted pH and Concentrations of TS, DS, and SS, DOC, COD, Ammonium, Nitrate, and TP and DRP in Runoff From NV and *Miscanthus* Plots With No Fertilization (0) or Fertilization With Poultry Litter at N Rates of 80 and 160 kg N $Ha^{-1}$ Annually (80PL and 160PL) From spring 2010 to 2014; and Corresponding Effects on Average Runoff Depth (RD) and Loads

| **T** | **pH** | **TS** | **DS** | **SS** | **DOC** | **COD** | **$NH_4^+$** | **$NO_3^-$** | **TP** | **DRP** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | mg $L^{-1}$ | | | | | | | | |
| NV | 6.22 | 117 | 95 | 23 | 30 | 68 | 0.68 | 1.61 | 0.51 b | 0.40 b |
| 0 | 6.23 | 131 | 89 | 45 | 23 | 59 | 0.77 | 1.15 | 0.66 b | 0.56 b |
| 80PL | 6.32 | 121 | 95 | 28 | 23 | 45 | 0.64 | 1.47 | 1.06 b | 0.93 b |
| 160PL | 6.39 | 110 | 99 | 13 | 27 | 56 | 1.13 | 1.38 | 1.88 a | 1.76 a |
| | | | | | | | | | | |
| **Effect** | **pH** | **TS** | **DS** | **SS** | **DOC** | **COD** | **$NH_4^+$** | **$NO_3^-$** | **TP** | **DRP** |
| T | NS | NS | NS | NS | NS | NS | NS | NS | * | * |
| Y | *** | NS | * | NS | NS | NS | * | *** | * | ** |
| T × Y | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| T | RD | TS | DS | SS | DOC | COD | $NH_4^+$ | $NO_3^-$ | TP | DRP |
| | cm | kg $ha^{-1}$ | | | | | | | | |
| NV | 6.0 | 59 | 44 | 14 | 15 a | 31 | 0.29 a | 0.64 | 0.21 b | 0.16 b |
| 0 | 3.0 | 39 | 25 | 14 | 7 b | 19 | 0.18 bc | 0.30 | 0.17 b | 0.15 b |
| 80PL | 2.6 | 29 | 20 | 9 | 5 b | 10 | 0.12 c | 0.34 | 0.31 b | 0.27 b |
| 160PL | 3.2 | 30 | 28 | 5 | 7 b | 15 | 0.23 ab | 0.52 | 0.58 a | 0.56 a |
| | | | | | | | | | | |
| **Effect** | **RD** | **TS** | **DS** | **SS** | **DOC** | **COD** | **$NH_4^+$** | **$NO_3^-$** | **TP** | **DRP** |
| T | NS | NS | NS | NS | * | NS | * | NS | ** | *** |
| Y | ** | * | *** | NS | *** | * | ** | *** | * | *** |
| T × Y | NS | NS | NS | NS | NS | NS | NS | NS | NS | NS |

[†] Numbers within a column followed by different letters are significantly different; Tukey-Kramer, $\alpha = 0.05$.

[‡] *,**,***Significant at $P < 0.05$, 0.01 and 0.001, and NS = not significant.

average concentration of $NH_4^+$-N was lower than that found by Pierson et al. (2001), but $NH_4^+$-N and $NO_3^-$-N concentrations were higher than those in Harmel et al. (2004). The DRP and TP concentrations were less than half those in Moore Jr. et al. (2000), and the DRP concentration was smaller than in Pierson et al. (2001) and similar to Vervoort et al. (1998) and Harmel et al. (2004). Runoff pH and $NH_4^+$-N concentration tended to decrease, and $NO_3^-$-N concentration increased with year, suggesting a possible increase in nitrification rate, but trends for each parameter were not steady, and soil TN did not increase (Table 5). Increases in concentrations of DS, DRP, and TP from 2010 through 2013 were also inconsistent year-to-year, as were increases in DRP and TP concentrations with year for either PL rate. However, DRP and TP concentrations were linearly related to Mehlich 3 P in surface 0- to 15-cm soil as shown in Fig. 2 for TP. Thus, as P concentration in the surface soil increased, the soil retained less of the P extracted from PL and/or released more P into runoff.

More DOC was lost from the NV than other plots, and more $NH_4^+$-N was lost from the NV than 0 and 80PL plots, presumably due to numerically greatest runoff from the NV plots (Table 7). However, greater loads of TP and DRP from the 160PL than other plots were the major treatment effects. Compared with losses from small pastures, DRP loads ranged from about 6 kg $ha^{-1}$ lower than in Pierson et al. (2001) to 0.5 kg $ha^{-1}$ higher than in Vervoort et al. (1998), and TP loads ranged from 3 to 0.3 kg $ha^{-1}$ lower than in Moore Jr. et al. (2000) and Harmel et al. (2004), respectively. However, because the ratio of runoff to rainfall decreases with increasing

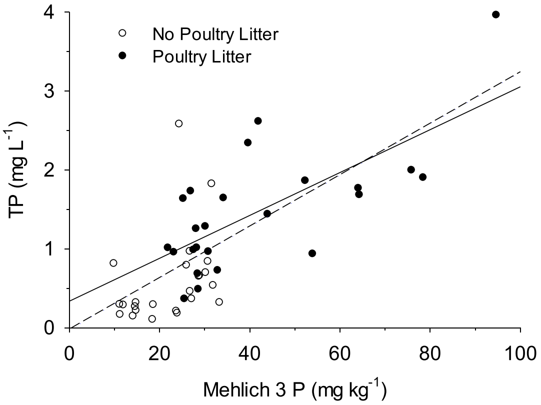

FIGURE 2. Linear relationships of the volume-averaged annual concentration of TP in runoff to concentration of Mehlich 3 P in the surface 0- to 15-cm soil. The solid line is for miscanthus plots that were amended with PL, $Y = 0.361 + 0.0253X$ ($R^2 = 0.47$; $P < 0.001$), and the dashed line is for plots without PL (miscanthus and NV), $Y = -0.051 + 0.0280X$ ($R^2 = 0.13$; $P < 0.10$). Linear regressions for the concentration of DRP were similar: amended with PL, $Y = 0.174 + 0.0280X$ ($R^2 = 0.49$; $P < 0.001$), and without, $Y = -0.058 + 0.0242X$ ($R^2 = 0.12$; $P < 0.10$).

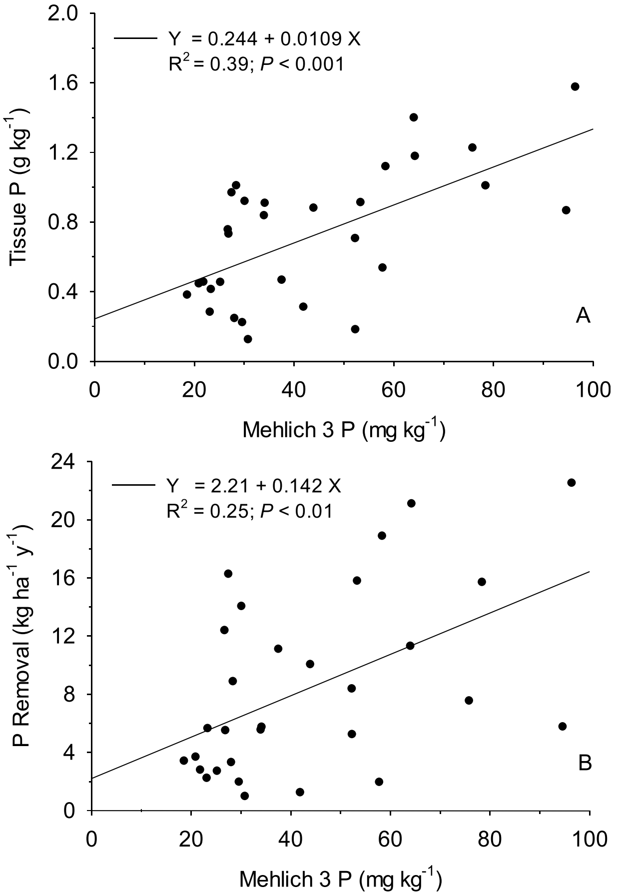

FIGURE 3. Linear dependence of (A) tissue P concentration and (B) P removal rate on Mehlich 3 P in the surface 0- to 15-cm soil for plots amended with PL.

runoff area (Delmas et al., 2012), the small plot data for P loads may overestimate losses for a field of MIS fertilized with PL. Bohl Bormann et al. (2012) have demonstrated this effect with P runoff data for small plots versus fields. As with concentrations, average $NH_4^+$ loads decreased, and $NO_3^-$, TP, and DRP loads increased with year, whereas other effects of year (TS, DS, DOC, and COD) largely reflect numerical differences in yearly runoff.

### Relationships of P Removal to Soil P and Effect on Runoff P

Tissue P concentration of MIS fertilized with PL was related to soil Mehlich 3 P in the surface 0- to 15-cm soil (Fig. 3A), but it was unrelated to yield ($P < 0.74$; data not shown). Therefore, the rate of P removal at any Mehlich 3 P value (within the range that occurred) might be estimated by concentration × assumed yield. Alternatively, P removal might be estimated from its relationship to Mehlich 3 P (Fig. 3B; although the data in part reflect relatively low yields and tissue P from 2010 through 2012; Table 2). Provided that the rate of P addition did not exceed the maximum rate of removal (unknown plateau value not reached in Figs. 3A and B), a steady state in surface 0- to 15-cm soil P (removal = addition − leaching and runoff losses) and runoff P might be approached. At this point, however, annual P loss would likely be high if PL alone was used to replenish nutrients. For example, K removal at 60 kg $ha^{-1}$ $y^{-1}$ (average rate in 2014; Table 2) would require offset by PL at a P rate of ~30 kg $ha^{-1}$ (Table 1), which would correspond to Mehlich 3 P >100 mg $kg^{-1}$ (from Fig. 3A at yield = 18 Mg $ha^{-1}$ or Fig. 3B) and runoff TP concentration beyond the range of data in Fig. 2. Thus, the potential for use of PL with MIS appears limited—only as a P-based supplement to non-P fertilizer and at a rate consistent with the low rate of nutrient removal (Table 2).

## SUMMARY AND CONCLUSIONS

The 5-year average yield of MIS on a low-fertility Coastal Plain soil in Louisiana was low compared with many data from elsewhere in the United States, but after a 3-year lag phase, it approached yields typical of the southeastern United States; however, N fertilization did not increase yields. Tissue concentrations of P were greater for the PL than other treatments and increased with year. Harvest removal of P and K was greatest with the 160PL treatment and increased with year. Averaged across all years, however, removal of P in harvest was only 17% and 10% of the amount annually applied in the 80PL and 160PL treatments. Thus, there was build-up of P in the surface soil with PL but slight leaching due to appreciable content of $Al_{ox} + Fe_{ox}$ and low initial P saturation. The 160PL treatment generated significantly greater DRP and TP runoff concentrations and loads compared with the 80PL, 0, and NV treatments. Positive relationships between concentration of soil and runoff P indicate increasing potential for P loss in runoff with further P additions to the soil. However, increasing P removal in harvest with increasing soil P concentration would set an upper limit to runoff P where PL was applied at a P rate equal to or smaller than the maximum rate of P removal. The limit may be environmentally sustainable at a low rate of PL application, but supplement with non-P fertilizer would be necessary to replenish nutrients removed in harvest. Thus, use of PL with MIS might reduce total off-site P loss to some extent because an equal mass of PL would be displaced from P-enriched pasture. Compared with NV at the site, MIS had no effect on soil OC and probably any other fertility parameter, and unfertilized MIS had no effect on runoff water quality.

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