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Flue gas desulfurization gypsum and grass buffer strip influence on runoff and nutrient loss from inorganically and organically fertilized corn on a US Coastal Plain soil

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Abstract: Broiler litter (BL) and flue gas desulfurization gypsum (FGDG), both readily available in the US Southeast, can potentially ameliorate soil constraints adversely affecting agricultural productivity and environmental quality in the region. However, benefits and risks must be evaluated prior to making recommendations to producers. The effectiveness of a combination of FGDG and grass buffer strips (GBS) to reduce edge-of-field nutrient losses from corn (*Zea mays* L.) production under inorganic (NPK) or organic (BL) fertilization was evaluated on Coastal Plain soils near Tifton, Georgia, from April of 2014 through January of 2017. Nine treatments were randomly established in each of three replications on plots instrumented to collect runoff. This was the first phase of a three-phase study. Treatments consisted of combinations of three fertilizer treatments (NPK, BL, and BL+FGDG) and three GBS treatments (no GBS [–GBS], GBS without FGDG [GBS–FGDG], and GBS with FGDG [GBS+FGDG]). A tenth treatment of NPK+FGDG without GBS was also included. Annual rates for BL and FGDG were 13.45 Mg ha^{-1} each. The BL rate was based on a high nitrogen (N) demand of corn and would represent a risky scenario for nutrient loss. Runoff and concentrations and loads of nitrate-nitrogen (NO_3-N), ammonium-nitrogen (NH_4-N), total Kjeldahl nitrogen (TKN), dissolved reactive phosphorus (DRP), and total P (TP) were determined in runoff from 29 storms from May of 2015, through January of 2017. Rainfall partitioned into runoff (percentage runoff) decreased by 50% to 70% under –GBS with BL or BL+FGDG compared with NPK fertilization, and under GBS–FGDG or GBS+FGDG compared with –GBS for NPK and BL fertilization. Under –GBS, concentration of DRP and TP increased by ~160% from BL compared with NPK fertilization, and by 150% for DRP and by 115% for TP from BL+FGDG compared with NPK fertilization. On the other hand, the combined BL+FGDG and GBS+FGDG treatment reduced nutrient concentration by 65% to 80% compared with BL with –GBS (a standard practice), and nutrient load by 40% to 70% compared with NPK with –GBS (another standard practice) or BL with –GBS. Results indicate the potential for FGDG to improve edge-of-field runoff water quality when applied to fields with BL and to edge-of-field GBS. In planned follow-up articles, results will be compared with phase-2 when BL and FGDG rates were reduced by a third and phase-3 when BL application was discontinued.

Key words: eutrophication—manure—phosphorus—poultry—soil amendment—water quality

Poultry production and coal-fired power generation both produce byproducts that can have beneficial uses in agricultural production systems. In 2017, 57.1% of the 8.91 billion broilers raised in the United States came from the southeastern states of Alabama, Arkansas, Georgia, Mississippi, and North Carolina (USDA NASS 2019). Using coefficients from Ritz and Merka (2013), 5.8 million Mg of broiler litter (BL; a mixture of total excrement, spilt feed and water, feathers, soil, and bedding material such as wood shavings, sawdust, wheat straw, peanut hulls, etc.) containing 185,000 Mg of total nitrogen (N), 68,000 Mg of elemental phosphorous (P), and 115,000 Mg of elemental potassium (K) are produced annually in the five states combined. Values could be 30% greater based on estimation approaches of Mitchell and Tu (2005) or Ashworth et al. (2019). Most plant macro- and micronutrients are present in BL depending on types of feed, supplement, and enzymes (Ashworth et al. 2019; Tewolde et al. 2005). Numerous studies indicate that soil amendment with organic materials such as BL could improve soil organic matter and consequently soil physical and chemical properties (Feng et al. 2019, 2021; Adeli et al. 2007, 2010; Eden et al. 2017; Edmeades 2003; Sistani et al. 2004; Watts et al. 2010).

Forages and crops normally require four- to eight-fold more N than P, while BL has 1:1 to 3:2 total N:phosphorus pentoxide (P_2O_5) ratio (Zhang et al. 2002; Ashworth et al. 2019). Hence, using BL to meet the N needs of forages and crops results in over-application of P and excessive P levels in soils (Schomberg et al. 2009; Kingery et al. 1994), which can cause nonpoint source pollution of surface waters (Sharpley et al. 2017; Carpenter et al. 1998; Moore et al. 1995). Heavy metals such as arsenic (As), cadmium (Cd), copper (Cu), and zinc (Zn), often present in BL, can contaminate soil and surface waters and reach toxic levels for certain crops (Hou et al. 2014; Endale et al. 2010; He et al. 2009). Pastures and hay lands near broiler production facilities typically receive repeated BL application, exacerbating buildup of potentially environmentally harmful nutrients.

Coal-fired power plants in the United States produced 421.44 Tg of flue gas desul-

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furization gypsum (FGDG; calcium sulfate dihydrate, $CaSO_4 \cdot 2H_2O$) from 2000 to 2018 (American Coal Ash Association 2021) as a byproduct of "scrubbing" sulfur dioxide (SO_2) from flue gases to meet air quality regulations (EPRI 2006; Kairies et al. 2006). The FGDG currently produced is of high purity with low levels of toxic components (Schomberg et al. 2018; Chen and Dick 2011; EPRI 2011; Koralegedara et al. 2019). Average FGDG production from 2014 to 2018 was 29.8 Tg y^{-1} (Good and VanBriesen 2019; Southern Company 2017, 2018). From 2000 to 2018, 51.1% of the FGDG produced was used in construction industries for wallboard, concrete and cement mixes, structural fill in embankments, and mining, while only about 2.3% was used in agriculture as a soil amendment. The remaining 196.4 Tg of FGDG was placed in landfills near production facilities.

Although gypsum has been used as a soil amendment for a long time, availability, quality, and industrial demand has limited its widespread use in agriculture (Chen and Dick 2011; Crocker 1922). The literature indicates agronomic, soil health, and water quality benefits of gypsum in many but not all soils and production systems (Shainberg et al. 1989). As a moderately soluble source of calcium (Ca) and sulfur (S), gypsum application is beneficial to a variety of crops (Chen and Dick 2011; Miller et al. 1998; Stout et al. 1998; Wallace 1994). Gypsum has been shown to improve soil aggregation, flocculation, and structural stability; reduce surface sealing and crusting; improve water infiltration and percolation; and reduce runoff and soil erosion (Norton and Dontsova 1998; Stout et al. 1998; Shainberg et al. 1989; Miller 1988). Several studies point to reduction of water-soluble P in runoff resulting from gypsum application (King et al. 2016; Endale et al. 2014b; Torbert and Watts 2014; Watts and Torbert 2009, 2016; Norton 2008; Stout et al. 1998).

Grass buffer strips (GBS) reduce nutrient (N and P) transport from agricultural fields and are identified as best management practices by USDA Natural Resources Conservation Service (USDA NRCS 1999; Dillaha et al. 1989; Magette et al. 1989). However, site-specific conditions, such as cropping system, hydrology, climate, soil, type, and buffer width, determine effectiveness of GBS (Habibiandehkordi et al. 2019; Valkama et al. 2019; Stutter et al. 2012; Dorioz et al. 2006). Data indicating increased effectiveness of GBS through FGDG amendment are limited. In one study, Watts and Torbert (2009) found that a 1.52 m wide GBS reduced soluble P concentrations in surface runoff from plots fertilized with BL by 32% to 40% and 18%, with and without FGDG amendment, respectively. Their study applied concentrated flow (124 mm h^{-1} producing 30-minute runoff event) to tall fescue (*Schedonorus arundinaceus*) established on a sandy loam soil in the Appalachian Plateau region of northeast Alabama. Effectiveness of FGDG amendment to reduce nutrient loss with GBS on Coastal Plain soils of the US Southeast is unknown.

Ultisols and Alfisols are the predominant soil groups in the Southern Coastal Plain (West et al. 1997). Coastal Plain surface soils are mostly sandy, have low organic matter, are prone to surface crusting, have low water holding capacity, and are highly erodible. Intense spring and summer storms often result in runoff and loss of nutrients. Twenty years (1998 to 2019) of research at Tifton, Georgia, showed that surface runoff was 1.7-fold and mean annual total sediment loss was 7.7-fold greater from conventional tillage (CT) than strip tillage (ST); carbon (C) and N losses from ST were less than from CT in part because of sediment-bound C and N; and surface runoff was the primary avenue for loss of P, K, Zn, iron (Fe), and manganese (Mn), while subsurface flow was the primary avenue for loss of Ca, magnesium (Mg), and S (Pisani et al. 2020; Strickland et al. 2015; Endale et al. 2014a; Bosch et al. 2012). Results from this long-term study for the period from 2004 to 2008 determined that subsurface flow was the primary hydrologic pathway for losses of dissolved N and chloride (Cl) in both tillage systems (Bosch et al. 2015). The total five-year load for N was equivalent to 8.3% and 18.4% of the applied to CT and ST, respectively.

Our project was designed to evaluate the effectiveness of FGDG in reducing edge-of-field losses of nutrients from inorganic (NPK) or BL fertilization to corn (*Zea mays* L.) on Coastal Plain soils. In this evaluation, FGDG was applied on cropped areas and on bermudagrass (*Cynodon dactylon* L.) GBS located at the down slope field edge. Our hypothesis was that addition of FGDG to cropped areas will reduce nutrient losses significantly below that without FGDG and the effect would be greater for BL compared to NPK fertilization. We also hypothesized that application of FGDG to GBS would increase the effectiveness of the GBS. While the experiment was established in spring 2014, data for runoff quantity and quality were obtained beginning in 2015 to allow for complete establishment of the runoff collection system.

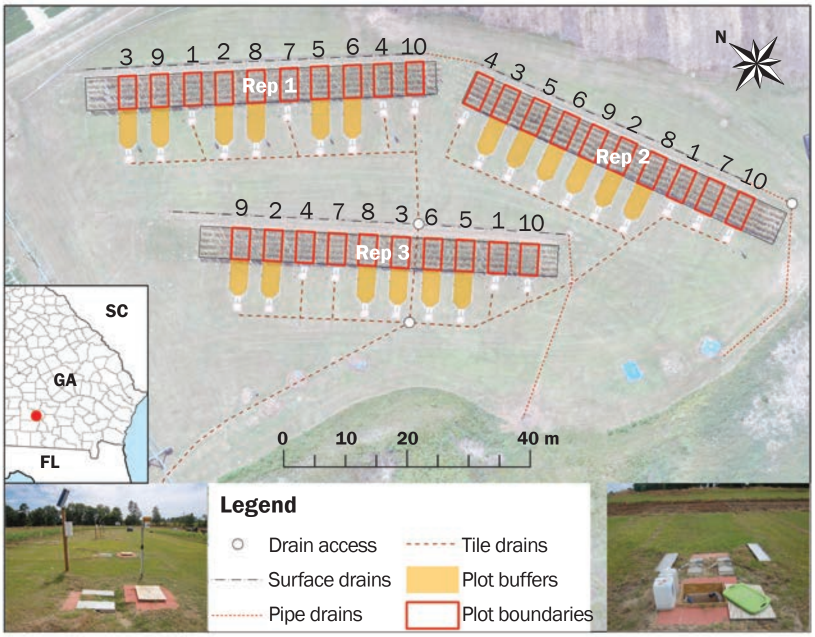
Materials and Methods

Site and Experimental Setup. The study has a nine-year duration divided into three phases of three years each. In phase-1 (the subject of this article), BL and FGDG were applied at 13.45 Mg ha^{-1} y^{-1}. In phase-2, rates are reduced to 4.48 Mg ha^{-1} y^{-1}. In phase-3, fertilization is all NPK (no BL) but FGDG rate continues at the same as that of phase-2. Thus, the study is designed to track the hysteresis of nutrient dynamics in the soil, runoff, and plants from residual sources of BL and FGDG through the three phases. Our rationale for the rate during phase-1 included (1) a previous study indicating effectiveness of FGDG in reducing P losses in runoff is dependent on soil P levels—since P level in our soil was low, we wanted to increase it quickly; (2) typical BL application in the area is based on crop N requirement assuming 50% mineralization during the cropping season; (3) because of transportation costs, BL tends to be applied frequently to nearby fields leading to a buildup of soil P; and (4) Ritz and Merka (2013) list maximum yearly BL application rate of 14.6 Mg ha^{-1} for corn. These typical BL management approaches were used in determining our BL application rate during phase-1.

Plots were established in early spring of 2014 at the University of Georgia Gibbs Farm located in Tift County, Georgia (31°26′08″ N, 83°35′20″ W; figure 1). The climate is humid subtropical, summers are hot and humid, and winters are cool with few hard freezes. Average monthly temperatures range from 11°C in January to 27°C in July and August with a mean annual temperature of 18.7°C. The 50-year mean annual rainfall is 1,200 mm, with mean monthly distribution from 70 mm in May and October to 130 mm in March, June, and July (Bosch et al. 2020). However, regular periods of below average rainfall occur with negative impact on water availability and agricultural productivity.

The mean daily temperature and cumulative rainfall for 2014 through 2017 are shown in figure 2. Mean daily temperature

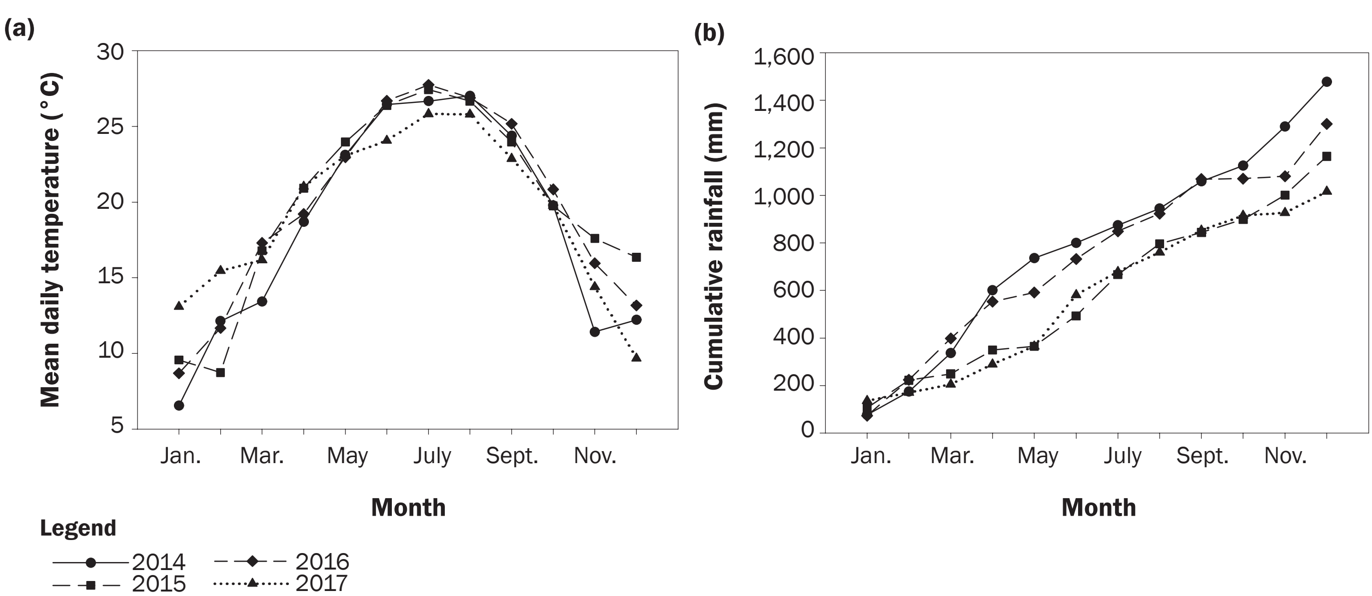
Figure 1
Layout of replication, plots, grass buffer strips, and runoff collection system. Numbers on the upper end of plot boundaries indicate corresponding treatment numbers (see table 1). Small surface ditches separate plots conveying plot runoff toward collecting systems.



each month steadily rose from below 13°C in January to a peak of 24°C to 28°C in the summer months, then steadily declined to below 15°C in December. Cumulative rainfall at the end of each month from the start of the year was similar between 2014 and 2016 and between 2015 and 2017 except in November and December, where it diverged. Total yearly cumulative rainfall in millimeters was 1,478 in 2014, 1,300 in 2016, 1,165 in 2015, and 1,016 in 2017 (figure 2). Whenever a drought risk was thought to occur, 25 mm of irrigation at a time was applied using a travelling gun to avoid crop loss. This occurred four to six times during a corn season. The runoff amount and quality data for what is reported here came from 29 storms over a 21-month period from May of 2015 through January of 2017. Seventeen occurred in 2015 and 11 in 2016. Storms per month varied from one to six. Mean storm amount was 30 mm (range 7 to 91 mm) and the prerunoff five-day antecedent storm amount that likely influenced runoff generation was 23 mm (range 0 to 73 mm).

The site was previously an established bermudagrass field managed over the past decade with frequent mowing but limited fertilization. The experimental design included nine treatments randomly assigned to plots in each of three replications. Two replications were assigned to the upper and one to the lower landscape positions due to field dimensions (figure 1). Treatments consisted of three nutrient sources (NPK, BL, and BL+FGDG) applied to the cropped areas and three GBS treatments (no GBS [–GBS], GBS without FGDG [GBS–FGDG], and GBS with FGDG [GBS+FGDG]) (table

Figure 2
(a) Mean daily temperature per month and (b) cumulative rainfall from start of a year to end of a month from 2014 through 2017.



1). The field physiography precluded the inclusion of a fourth nutrient source treatment (NPK+FGDG) with and without GBS. However, in May of 2014, we determined we could add NPK+FGDG without GBS. This gave us an additional treatment to evaluate effectiveness of FGDG applied with NPK in the field. Application methods and rates for BL and FGDG are described below.

Cropped plots were 3.05 m across slope by 5.49 m downslope, with a 2.13 m alley between plots. The GBS area, placed immediately downslope of plots, was 6.1 m long with the same width as cropped plots and was bounded on three sides by 10 to 15 cm wide and high berms (see below) created with soil from a nearby field. Mean cropped plot slope was 3.9% in replication 1 (plot mean 2.8% to 6.2%), 5.5% in replication 2 (plot mean 3.6% to 6.3%), and 3.7% in replication 3 (plot mean 2.7% to 4.5%). Equivalent values for mean GBS slopes were 5.8% (5.5% to 6.3%), 7.1% (6.4% to 8.0%), and 4.2% (3.3% to 4.8%), respectively. Surface ditches, approximately 0.50 m deep and 0.6 m wide at the top, were established along the upper end of each replication to divert surface water away from the plots.

Soil Sampling. The dominant soil series in the field is Carnegie sandy loam (fine, kaolinitic, thermic Plinthic Kandiudults) (USDA NRCS 2021). The surface 15 cm horizon is a brown sandy loam overlaying a dominantly sandy clay argillic subsoil. The series is strongly to very strongly acidic unless modified through liming. Soil cores, approximately 120 cm deep and 6.4 cm diameter, were collected with a tractor mounted hydraulic sampler (Giddings Machine Company, Windsor, Colorad0) from cropped and GBS areas prior to corn planting in early April of 2014 to establish baseline soil characteristics. Core holes were backfilled with a 50-50 sand and kaolin mixture. Based on these samples, mean sand and clay content was 80.6% and 8.7%, respectively, in the 0 to 8 cm depth (loamy sand) and 74.3% and 15.4%, respectively, in the 8 to 15 cm depth (sandy loam). Mean soil pH varied between 5.2 and 5.4 across plots. Before and after each corn season, additional soil samples were collected by hand from the 0 to 8 cm and 8 to 15 cm depths to determine fertilizer requirements and evaluate nutrient stratification.

Soil samples were sent to the Agricultural and Environmental Services Laboratories, University of Georgia (UGA) in Athens, Georgia, for analysis. Mean Mehlich-1 extracted soil P in the 0 to 15 cm depth on samples taken on March 21, 2014, was 21.4, 17.7, and 20.2 mg kg^{-1} in NPK, BL, and BL+FGDG fertilized plots, respectively. A year later (March 4, 2015), values were 18.9, 43.2, and 55.1 mg kg^{-1}, respectively. Two years later (April 14, 2016), equivalent values were 17.1, 50.7, and 74.1 mg kg^{-1}. By March 17, 2017, levels had increased to 37.8, 57.7, and 70.1 mg kg^{-1}, respectively. Thus, in the 0 to 15 cm depth, Mehlich-1 extracted soil P increased in three years by 2- to 3- and 2- to 4-fold in BL and BL+FGDG fertilized plots compared with those of NPK fertilization, respectively. The higher values in the BL+FGDG fertilized plot suggest possible complexion and retention in soil of P from BL with Ca and possibly S from gypsum. The UGA recommendations classify soil test P values generally as low when Mehlich-1 P value ≤20 mg kg^{-1}, medium when between 20 and 35 mg kg^{-1}, high when between 35 and 55 mg kg^{-1}, and very high when >55 mg kg^{-1}.

Agronomic Practices. The Georgia Corn Production Manual (Lee 2012) was used for management decisions, outside of those specific to the 10 treatments, including managing the rye (*Secale cereale*) Austrian winter pea (*Pisum arvense*) cover crop mixture planted in October and terminated in April each year. Tillage prior to corn planting consisted of disking to approximately 20 cm deep with several passes of a 4.6 m disk harrow (Athens Plow Company Inc., Athens, Tennessee), followed by a four row KMC ripper bedder with attached subsoiler (KMC, Kelly Manufacturing Co., Tifton, Georgia), and finally a KMC 3.7 m field conditioner.

In April of 2015 and 2016, the cover crop mixture was rolled and sprayed with glyphosate prior to tillage as above. Similar tillage was performed prior to planting the cover crop mixture in the fall following rolling of corn stover. Corn (Pioneer P1690YHR) was planted in spring (April 24, 2014; May 14, 2015; May 13, 2016) to the full area of each replication at 91.4 cm spaced rows (six rows per plot), and 18 to 20 cm between plants in each row. Target planting density was 8,700 plants ha^{-1}. Corn was hand harvested in September (September 4, 2014; September 14, 2015; September 19, 2016). The cover crop mixture was planted on October 28, 2014, October 5, 2015, and October 14, 2016. Weed control was performed once or twice each season using glyphosate applied before corn reached V4 stage and immediately after planting the cover crop mixture.

Small ditches, which served as plot boundaries as well as for conveying plot runoff to collectors (see below), were established prior to applying fertilizer and FGDG by hand in the week following corn planting. The BL was from a local producer near Ashburn, Georgia, who cleans out the broiler houses annually after producing five to six flocks. Each year, the FGDG source was Southern Company's Bowen Plant near Cartersville, Georgia. Once delivered, both BL and FGDG were kept under cover near the research site until applied on the plots—less than three weeks. Table 2 summarizes nutrient content of FGDG and BL used from 2014 to 2016 as determined at UGA after site delivery but

Table 1
Treatment details by plot fertilization and buffer arrangement and amendment.

	Plot*		Buffer†		
Treatment #	Fertilizer	Gypsum	Buffer	Gypsum	Buffer designation
1	NPK	None	No buffer	None	–GBS
2	NPK	None	Buffer	None	GBS–FGDG
3	NPK	None	Buffer	FGDG	GBS+FGDG
4	BL	None	No buffer	None	–GBS
5	BL	None	Buffer	None	GBS–FGDG
6	BL	None	Buffer	FGDG	GBS+FGDG
7	BL	FGDG	No buffer	None	–GBS
8	BL	FGDG	Buffer	None	GBS–FGDG
9	BL	FGDG	Buffer	FGDG	GBS+FGDG
10	NPK	FGDG	No buffer	None	–GBS

*NPK = inorganic fertilizer with N equivalent of 224 kg ha^{-1} and P and K equivalent to that from BL. BL = broiler litter at rate of 13.45 Mg ha^{-1} and N equivalent of 224 kg ha^{-1} assuming ~57% mineralization. FGDG = flue gas desulfurization gypsum at rate of 13.45 Mg ha^{-1}.

†Buffer FGDG at a rate of 13.45 Mg ha^{-1}. GBS = grass buffer strip.

Table 2
Nutrient content of applied flue gas desulfurization gypsum (FGDG) and broiler litter (BL) for 2014 to 2016.

	FGDG (kg Mg^{-1})				BL (kg Mg^{-1})			
Nutrient*	2014	2015	2016	Average	2014	2015	2016	Average
Aluminum (Al)	0.33	0.09	0.06	0.16	0.69	1.20	2.09	1.33
Boron (B)	NG	NG	0.03	0.03	0.24	0.20	0.17	0.20
Calcium (Ca)	236.23	216.07	256.48	236.26	19.95	18.20	19.23	19.13
Copper (Cu)	0.01	NG	NG	0.01	0.31	0.27	0.21	0.26
Iron (Fe)	0.49	0.31	0.22	0.34	0.49	0.93	1.10	0.84
Lead (Pb)	NG	0.07	0.07	0.07	ND	ND	ND	ND
Magnesium (Mg)	0.14	0.05	0.12	0.10	5.87	6.50	5.04	5.80
Phosphorus (P)	0.05	NG	0.02	0.04	12.46	12.74	10.14	11.78
Potassium (K)	1.56	NG	NG	1.56	26.10	30.61	27.89	28.20
Silicon (Si)	0.51	0.60	0.36	0.49	ND	ND	ND	ND
Sodium (Na)	0.11	NG	NG	0.11	8.34	7.32	7.08	7.58
Sulfur (S)	187.42	181.42	188.44	185.76	7.12	7.70	6.22	7.01
Zinc (Zn)	0.01	NG	NG	0.01	0.34	0.40	0.32	0.35
Total carbon (DC)	2.50	2.70	2.83	2.68	ND	ND	ND	ND
Total nitrogen (DC)	0.90	0.30	0.20	0.47	28.70	30.14	29.30	29.38
FGD gypsum purity (%)	ND	92.95	97.03	94.99	NA	NA	NA	NA
FGD gypsum Ca (%)	23.62	21.63	25.65	23.63	NA	NA	NA	NA
FGD gypsum S (%)	18.74	18.17	18.84	18.58	NA	NA	NA	NA

Notes: Analyses done at the Agricultural and Environmental Services Laboratories of the University of Georgia, Athens, Georgia. Values for each year are averages of three samples analyzed that year. DC = dry combustion. NG = negligible amount. ND = not determined. NA = not applicable.

*All in elemental form.

before plot application. The target N rate for all treatments was 224 kg N ha^{-1}. The amount of BL applied was estimated based on a ~57% N mineralization rate (Ritz and Merka [2013] and our own experience). Urea (46:0:0) was the primary source of N for NPK treatments while P, K, and S, based on amounts equivalent to those in the BL, were from mono-ammonium phosphate (MAP; 50% P_2O_5 and 10% N), muriate of potash (MOP; 60% K_2O), and a 90% pure S product all purchased from a local supplier. As shown in table 2, the average N, P, K, and S content in kilograms per megagram of the applied BL during 2014 to 2016 was 29.4, 11.8, 28.2, and 7.0, respectively, which translates to application rates of 224, 157, 378, and 94 kg ha^{-1}, respectively, based on the 13.45 Mg ha^{-1} litter application rate and 57% mineralization for N.

Water Sample Collection and Analyses. Ditches, 15 to 20 cm deep and ~15 cm wide along the southern end of plots and established prior to corn planting, served as plot boundaries, and directed runoff to the measuring and collecting systems. The flume collection system, a modification of that of Franklin et al. (2001), was designed to direct a fifth of the total runoff volume into collection vessels. Two 15 L plastic jugs for runoff collection were placed inside a 60 × 40 × 45 cm plastic tote placed in a pit containing a plywood box with a cover to protect the vessels from sunlight and rain. Controlled laboratory and field tests of the modified collector system consistently gave very close to 20% (one-fifth) capture of water released upslope. To eliminate problems from perched water pushing the totes and jugs above runoff collection points (which occurred in 2014), a system of 10 cm diameter primary tile drains was installed below the collection pits to convey water to a central 15 cm diameter secondary tile drain. The latter tile drains conveyed water to a natural ditch at the northwest corner of the field (figure 1).

Runoff measurement and sample collection began in May of 2015 after establishment of the field tile drains. Collection jugs were checked within 24 hours, except for weekends, of significant rainfall events. When runoff occurred, the volume in each jug was measured and two 1 L composite subsamples were saved in acid-washed Nalgene bottles. Samples were taken to the laboratory and kept in coolers (4°C) pending processing. One of the two samples was partitioned into filtered (0.45 micron filter) and unfiltered fractions, which were kept in coolers or freezers. The second sample was acidified and kept in a freezer as a backup. Subsamples from each of the filtered and unfiltered fractions were transferred into 20 mL vials and placed on ice (or frozen) for transfer to the Analytical Services Laboratories at the University of Florida (UF) in Gainesville, Florida. There, filtered samples were analyzed for ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), and dissolved reactive phosporus (DRP), and unfiltered samples were analyzed for total Kjeldahl N (TKN) and total P (TP) using standard US Environmental Protection Agency (USEPA) methods with appropriate quality assurance protocols (UF-IFAS Analytical Services Laboratories 2016).

Data Processing and Analyses. Measured runoff was multiplied by a factor of 5 due to the splitter arrangement on the runoff collector to estimate total runoff from catchment areas (cropped plot or cropped plot and GBS) for each event. Total runoff was used to estimate nutrient load by multiplying the event volume by the event concentration. The runoff volume was normalized by the catchment area and expressed in millimeters, which allowed comparison among treatments of the percentage rainfall partitioned into runoff.

Although there were 29 storms that led to runoff events in some plots, variability among replications and plots in runoff response per event was large. For an event, there might be no runoff in plots of one replication while the other two replications would have several plots with runoff. Similarly, within a replication, runoff might occur in as few as one or up to all plots. While some runoff was measured for all 29 events, samples for nutrient analysis were not collected for all events because of cost considerations, especially if events occurred within a few days of each other. Typical intervals between two consecutive runoff events varied from 1 to 13 days.

Runoff, concentration, and load data were normalized by converting to natural logs prior to statistical analysis. Concentration values expressed originally as milligrams per liter were multiplied by 1,000 giving micrograms per liter and 1 was added to these values before converting to natural logs. Load in kilograms per hectare were similarly converted to grams per hectare and 1 was added to these values before converting to natural logs. These steps were applied to ensure values were greater than one prior to conversion. Concentration and load data were back transformed for presentation in tables and figures using appropriate conversion factors.

Because more data were collected for runoff events than for nutrient analyses, statistical analyses for runoff, nutrient concentration, and load were conducted separately. For statistical analyses, values were set to missing and not included to avoid negatively biasing results where runoff volume or nutrient concentration (or load) were zero or missing. In other words, we avoided the use of zero values in the data sets.

The statistical analyses were conducted using SAS Enterprise Guide version 7.15 (SAS Institute Inc. 2017) and the SAS/STAT 15.1 (SAS Institute Inc. 2016) MIXED procedure to determine treatment effects on runoff, nutrient concentration, and load. Treatments were assigned values from 1 to 10 (table 1) to simplify the analyses and were considered fixed effects. A set of a priori determined contrasts were used to evaluate specific treatment contrasts using LSMESTIMATE statement. Several additional factors were included in the model as covariate effects to account for plot differences, time since fertilizer application, and antecedent soil moisture conditions. These included plot percentage slope (PSLP), days after planting (DAP) to runoff event, rainfall plus irrigation amount during the five days prior to a runoff event (RN_5D), and rainfall plus irrigation amount during the previous 24 hours (RN_1D) prior to a runoff event. Covariates were included in the model as continuous fixed effects. A REPEATED statement was used to account for any autocorrelation among runoff events within a year using an autoregressive first order covariance structure, AR(1). Random effects in the model were replication, year, and event, where event represents rainfall events identified sequentially within each year. Significant treatment effects were identified at the $p <$ 0.05 level for percentage runoff, concentrations of NO_3-N, DRP, and TP, and loads of NH_4-N, NO_3-N, DRP, and TP using log normal-transformed data. Percentage differences between paired treatments were calculated based on back transformed least square means.

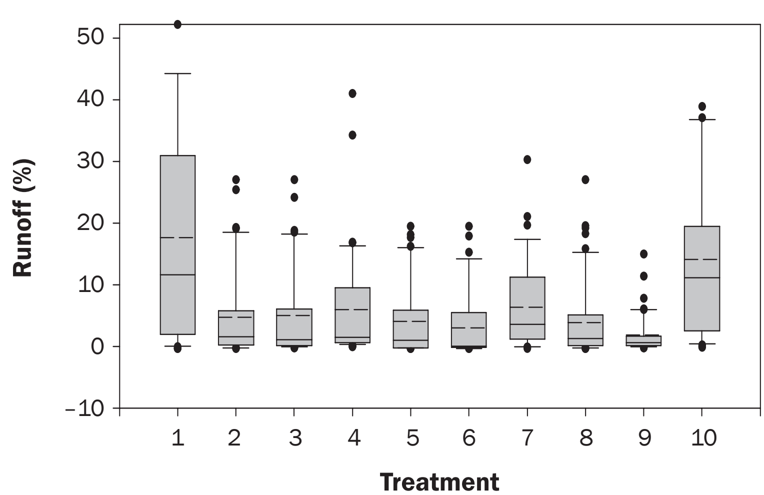
To assess effect of fertilizer source on runoff and nutrient concentration and load, our contrasts compared BL versus NPK, BL+FGD versus NPK, and BL+FGD versus BL. For GBS effect, we compared GBS–FGDG versus –GBS, GBS+FGDG versus –GBS, and GBS+FGDG versus GBS–FGDG. The NPK and –GBS combination versus that of NPK+FGDG and –GBS comparison indicates the influence of adding FGDG to inorganically fertilized plots in the absence of GBS.

Results and Discussion

Runoff. Twenty-nine storm events from May of 2015 through January of 2017 produced runoff. Irrigation had been applied immediately prior to only two of these events. If all plots had produced runoff for each event we would expect (29 × 3) 87 observations per treatment. Because this was not the case, there were 35 to 52 observations per treatment identified as being appropriate for use in the statistical analyses. The mean rainfall amount that led to runoff was 30 mm (range 7 to 92 mm) while the mean prerunoff five-day antecedent rainfall and irrigation was 23 mm (range 0 to 73 mm). Figure 3 shows variability within and across treatments for

Figure 3

Box plots showing variability of percentage runoff by treatment based on the original nontransformed data. Boxes enclose data within the 25th and 75th percentiles. Dotted and sold lines within boxes represent means and medians, respectively. Whiskers represent data at 90th percentile. Treatment details: 1 = NPK and (–GBS); 2 = NPK and (GBS–FGDG); 3 = NPK and (GBS+FGDG); 4 = BL and (–GBS); 5 = BL and (GBS–FGDG); 6 = BL and (GBS+FGDG); 7 = (BL+FGDG) and (–GBS); 8 = (BL+FGDG) and (GBS–FGDG); 9 = (BL+FGDG) and (GBS+FGDG); 10 = (NPK+FGDG) and (–GBS). NPK = inorganic fertilizer; BL = broiler litter; FGDG = flue gas desulfurization gypsum. *Y*-axis is truncated. Values not shown are 60.5 and 72.5 for treatment 1 and 59.8 for treatment 9.



percentage runoff using the original untransformed data. The box plots of treatments 2 through 9 show lower percentage runoff and variability than treatments 1 (NPK and –GBS) and 10 (NPK+FGDG and –GBS), indicative of the effects of BL, BL+FGDG, and GBS with or without FGDG amendment in reducing runoff. A GBS effect is indicated by the general downward trend of box depth (25th to 75th percentile) within each fertilizer treatment group (1,2, and 3; 4,5, and 6; 7,8, and 9) and lower mean and median values. This is particularly evident for treatments 7 to 9 (BL+FGDG fertilization). Treatment 9, where BL was applied to the field and both the field and GBS received FGDG, had the least observed percentage runoff with the least variability.

Results from analysis of variance regarding runoff are shown in table 3. Treatment, plot slope, the prerunoff five-day antecedent rainfall + irrigation, and the interval between planting and runoff dates had significant effects on percentage runoff. Table 4 shows back-transformed least square means (LS-means) and significance of difference between LS-means of paired treatments based on analysis of LN-transformed data. Under NPK fertilization (treatment 1, 2, and 3), percentage runoff was reduced by ~ 67% for GBS–FGDG and GBS+FGDG compared with –GBS. Percentage runoff was not different between GBS–FGDG and GBS+FGDG. Under BL fertilization (treatment 4, 5, and 6), percentage runoff for GBS+FGDG decreased by 52% compared with –GBS and by 46% compared with GBS–FGDG. Percentage runoff was not different between GBS–FGDG and –GBS. Under BL+FGDG fertilization (treatment 7, 8, and 9), GBS had no significant effect on percentage runoff. Comparison among –GBS plots (treatments 1, 4, and 7) showed a ~56% reduction in percentage runoff for BL and BL+FGDG compared with NPK fertilization. There was no difference between BL+FGDG versus BL or between NPK+FGDG versus NPK fertilization. Comparison within GBS–FGDG or GBS+FGDG plots showed no fertilization source effect on percentage runoff. Percentage runoff was 72% less from treatment 9, the combined BL+FGDG and GBS+FGDG treatment, compared with treatment 1, NPK and –GBS, considered one

Table 3
Analysis of variance evaluating treatment, plot slope, the one-day rainfall + irrigation causing runoff, the prerunoff five-day antecedent rainfall + irrigation, and the number of days between corn planting and runoff event on nutrient concentration and load and rainfall + irrigation partitioned into runoff.

		Effect						
Variable	Statistics	TRT	PSLP	RN_1D	RN_1D × RN_1D	RN_5d	RN_5d × RN_5d	DAP
Runoff (%)*	FValue	5.77	7.25	1.9	1.26	17.17	24.95	20.32
	ProbF	**0.0008**	**0.0132**	0.1747	0.2676	**0.0001**	**<0.0001**	**<0.0001**
Concentration (μg L^{-1})								
NH_4-N	FValue	1.75	2.11	0.07	0.18	0.08	1.16	4.39
	ProbF	0.1545	0.1636	0.7935	0.6699	0.7768	0.2872	**0.0423**
NO_3-N	FValue	2.58	0.03	5.3	5.53	0.2	0.36	11.41
	ProbF	**0.0471**	0.8713	**0.0258**	**0.0231**	0.657	0.5491	**0.0016**
TKN	FValue	1.93	0.54	1.09	1.86	1.24	2.39	1.85
	ProbF	0.1178	0.4731	0.3025	0.1799	0.271	0.1301	0.1813
DRP	FValue	5.07	2.4	2.35	1.11	0.47	1.03	12.52
	ProbF	**0.0015**	0.1347	0.1325	0.298	0.497	0.3154	**0.001**
TP	FValue	4.68	2.58	1.75	1.32	0.25	1.21	11.07
	ProbF	**0.0024**	0.1221	0.1934	0.2581	0.6197	0.2777	**0.0019**
Load (g ha^{-1})								
NH_4-N	FValue	4.32	0.02	2.61	1.72	7.48	5.93	1.99
	ProbF	**<0.0001**	0.8979	0.113	0.1964	**0.0091**	**0.0194**	0.1658
NO_3-N	FValue	5.05	5.59	0.13	0.61	12.01	19.28	0.02
	ProbF	**0.0021**	**0.0297**	0.7208	0.4372	**0.0012**	<0.0001	0.8858
TKN	FValue	2.48	4.4	3.95	2.75	11.66	14.38	17.02
	ProbF	0.0562	0.0516	0.0525	0.1041	**0.0014**	**0.0005**	**0.0002**
DRP	FValue	3.09	3.71	2.59	0.45	16.51	19.82	6.38
	ProbF	**0.0025**	0.0581	0.1144	0.5062	**0.0002**	**<0.0001**	**0.0154**
TP	FValue	3.3	4.35	2.08	0.68	15.52	17.51	6.86
	ProbF	**0.018**	0.0531	0.1559	0.415	**0.0003**	**0.0001**	**0.0123**

Notes: Bolded numbers imply effect is statistically significant. NH_4-N = ammonium-nitrogen. NO_3-N = nitrate-N. TKN = total Kjeldhal N. DRP = dissolved reactive phosphorus. TP = total P. TRT = treatment. PSLP = plot slope (%). RN_1D = one day rainfall + irrigation that led to runoff (mm). RN_5D = prerunoff five-day antecedent rainfall + irrigation (mm). DAP = days after planting up to runoff event.

*Percentage runoff = percentage of rainfall + irrigation that is partitioned into runoff.

Table 4

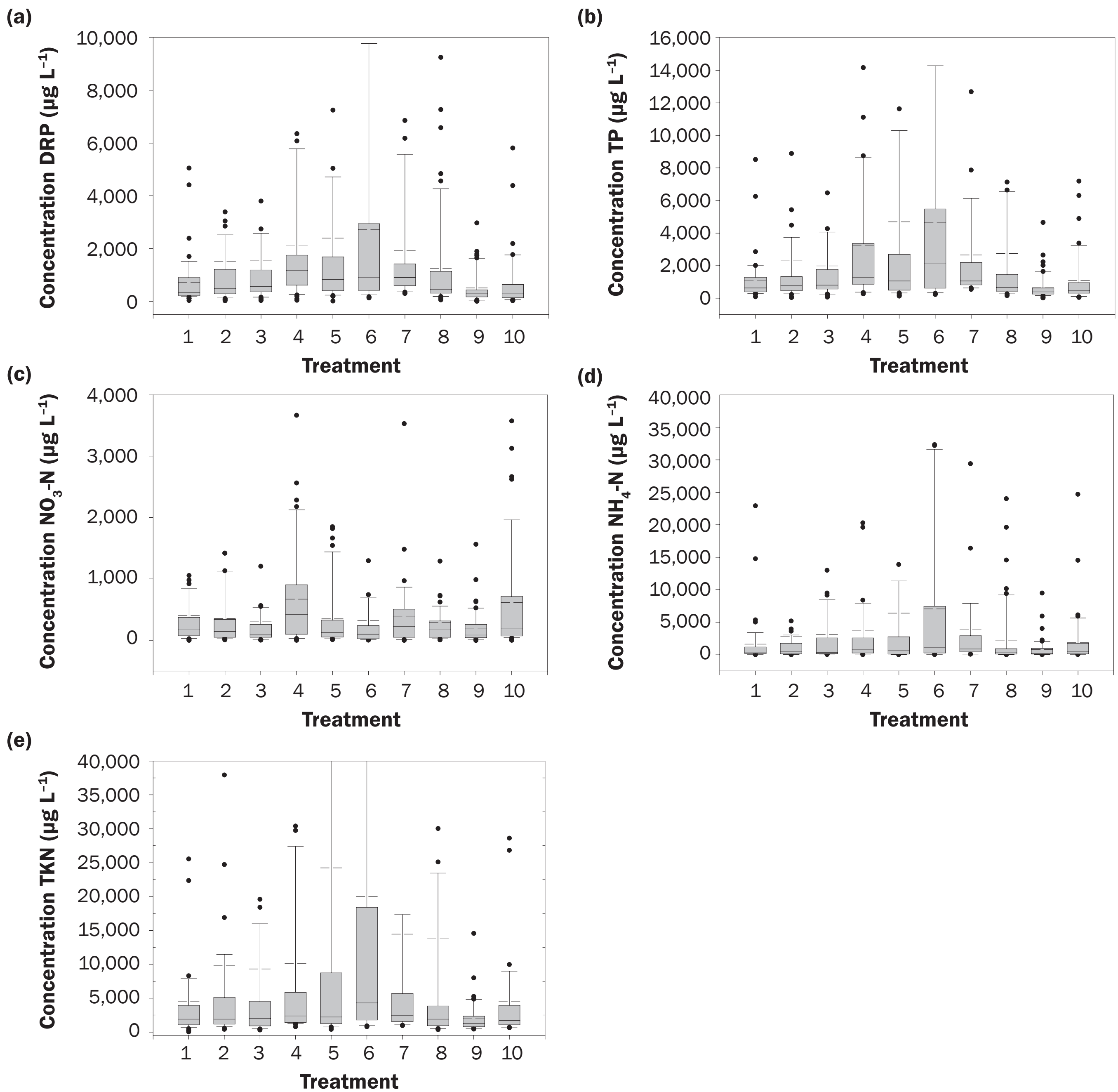
Back-transformed least square means (LS-means), significance of difference between LS-means of paired treatments based on analysis of LN-transformed data (SoD), and ([LS-means – standard error] to [LS-means + standard error]) for nutrient concentration and load for ammonium N (NH_4-N), nitrate-N (NO_3-N), total Kjeldahl N (TKN), dissolved reactive phosphorus (DRP), and total phosphorus (TP).

		Treatment									
Variable	Statistics	1	2	3	4	5	6	7	8	9	10
Runoff	LS-means	10.3	3.7	3.2	4.3	3.8	2.1	4.8	3.4	2.9	7.6
(%)*	SoD	a	cd	cd	bc	c	d	bc	cd	cd	ab
	LS-means ∓ SE	(8.5 to 12.6)	(3.0 to 4.5)	(2.6 to 3.9)	(3.5 to 5.3)	(3.1 to 4.8)	(1.7 to 2.6)	(3.9 to 5.9)	(2.8 to 4.2)	(2.4 to 3.6)	(6.1 to 9.4)
Concentration (μg L^{-1})											
NH_4-N	LS-means	464	425	766	821	507	1,324	1,062	405	238	715
	SoD	abc	abc	abc	ab	abc	a	ab	bc	c	abc
	LS-means ∓ SE	(297 to 725)	(272 to 664)	485 to 1,210)	(522 to 1,292)	(311 to 826)	(831 to 2,110)	(671 to 1,680)	(261 to 629)	(152 to 374)	(442 to 156)
NO_3-N	LS-means	171	152	105	315	147	97	177	134	94	208
	SoD	abc	bc	c	a	bc	c	abc	bc	c	ab
	LS-means ∓ SE	(133 to 220)	(118 to 195)	(81 to 135)	(243 to 408)	(112 to 193)	(74 to 127)	(136 to 230)	(105 to 171)	(73 to 120)	(159 to 22)
TKN	LS-means	2,037	2,552	2,663	3,701	3,376	6,166	3,699	2,633	1,350	2,464
	SoD	bc	abc	abc	ab	ab	a	ab	abc	c	abc
	LS-means ∓ SE	(1,455 to 2,850)	(1,826 to 3,568)	(1,889 to 3,753)	(2,631 to 5,205)	(2,338 to 4,874)	(4,335 to 8,771)	(2,617 to 5,227)	(1,894 to 3,659)	(963 to 1,891)	(1,714 to 3,543)
DRP	LS-means	433	550	742	1,147	819	1,367	1,086	615	251	367
	SoD	de	cd	abcd	ab	abcd	a	abc	bcd	e	de
	LS-means ∓ SE	(338 to 554)	(429 to 704)	(576 to 955)	(889 to 1,478)	(627 to 1,071)	(1,052 to 1,778)	(839 to 1,405)	(482 to 784)	(196 to 322)	(282 to 478)
TP	LS-means	695	847	1,095	1,808	1,214	2,187	1,491	926	362	646
	SoD	de	cd	abcd	ab	abcd	a	abc	bcd	e	de
	LS-means ∓ SE	(540 to 894)	(659 to 1,088)	(848 to 1,414)	(1,399 to 2,338)	(926 to 1,591)	(1,675 to 2,855)	(1,148 to 1,934)	(724 to 1,185)	(282 to 465)	(495 to 844)
Load (g ha^{-1})											
NH_4-N	LS-means	7.2	4.3	5.8	5.3	5.1	5.2	6.9	4.3	2.8	8.1
	SoD	a	b	ab	ab	ab	ab	a	b	c	a
	LS-means ∓ SE	(5.7 to 90)	(3.4 to 5.4)	(4.6 to 7.2)	(4.3 to 6.7)	(4.0 to 6.5)	(4.1 to 6.6)	(5.5 to 8.7)	(3.5 to 5.4)	(2.2 to 3.5)	(6.4 to 10.3)
NO_3-N	LS-means	4.1	2.5	1.9	3.2	2.4	1.4	2.4	2.2	1.9	3.6
	SoD	a	bcd	de	abc	bcd	e	bcd	cd	de	ab
	LS-means ∓ SE	(3.5 to 4.7)	(2.1 to 2.9)	(1.6 to 2.2)	(2.8 to 3.8)	(2.0 to 2.9)	(1.2 to 1.7)	(2.1 to 2.8)	(1.9 to 2.6)	(1.6 to 2.2)	(3.1 to 4.3)
TKN	LS-means	24.8	16.9	14.8	16.5	21.0	13.3	18.4	15.6	7.8	20.2
	SoD	a	a	ab	a	a	ab	a	a	b	a
	LS-means ∓ SE	(18.8 to 32.7)	(12.8 to 22.3)	(11.2 to 19.6)	(12.4 to 21.8)	(15.6 to 28.2)	(9.9 to 17.8)	(13.8 to 24.5)	(11.9 to 20.5)	(5.9 to 10.3)	(15.2 to 27.0)
DRP	LS-means	6.8	5.1	5.5	6.9	6.3	4.7	7.0	5.1	3.0	4.7
	SoD	a	a	a	a	a	ab	a	a	b	ab
	LS-means ∓ SE	(5.7 to 8.0)	(4.3 to 6.0)	(4.6 to 6.5)	(5.8 to 8.3)	(5.2 to 7.6)	(3.9 to 5.7)	(5.9 to 8.4)	(4.3 to 6.0)	(2.6 to 3.6)	(3.9 to 5.7)
TP	LS-means	9.7	7.1	7.0	9.6	8.8	6.2	8.9	6.8	3.6	7.1
	SoD	a	a	a	a	a	a	a	a	b	a
	LS-means ∓ SE	(8.0 to 1 1.8)	(5.8 to 8.6)	(5.8 to 8.5)	(7.9 to 11.7)	(7.2 to 10.9)	(5.0 to 7.6)	(7.3 to 10.9)	(5.6 to 8.1)	2.9 to 4.3)	(5.7 to 8.7)

Notes: SE = standard error. LS-means of paired treatments with the same letter for each nutrient are not significantly different at alpha = 0.05.

*Percentage runoff = percentage of rainfall + irrigation that is partitioned into runoff.

Figure 4
Box plots showing variability of nutrient concentration for (a) dissolved reactive phosphorus (DRP), (b) total phosphorus (TP), (c) nitrate-nitrogen (NO_3-N), (d) ammonium-nitrogen (NH_4-N), and (e) total Kjeldahl nitrogen (TKN) by treatment based on the original nontransformed data. Boxes enclose data within the 25th and75th percentiles. Dotted and sold lines within boxes represent means and medians, respectively. Whiskers represent data at 90th percentile. Treatment details: 1 = NPK and (–GBS); 2 = NPK and (GBS–FGDG); 3 = NPK and (GBS+FGDG); 4 = BL and (–GBS); 5 = BL and (GBS–FGDG); 6 = BL and (GBS+FGDG); 7 = (BL+FGDG) and (–GBS); 8 = (BL+FGDG) and (GBS–FGDG); 9 = (BL+FGDG) and (GBS+FGDG); 10 = (NPK+FGDG) and (–GBS). NPK = inorganic fertilizer; BL = broiler litter; FGDG = flue gas desulfurization gypsum. *Y*-axis is truncated. Values not shown in (a) are 10,840 to 33,814 for treatments 2 to 7; in (b), 17,800 to 50,417 for treatments 3 to 8; in (c), 4,372 to 6,625 for treatments 1 to 3; in (d), 47,773 to 104,851 for treatments 2 to 7; and in (e), 51,047 for treatment 1.



of two standard practices, the other being treatment 4, BL–GBS.

Nutrient Concentration. Figure 4 shows variability within and across treatments for nutrient concentration using the original untransformed data. The box plots generally show a slightly greater range in treatments 4, 5, and 6 (BL) compared with treatments

1, 2, and 3 (NPK). The GBS effect appears evident for DRP, TP, and TKN under BL+FGDG (treatment 7, 8, and 9), and for NO_3-N under BL and BL+FGDG. Overall, the box plots for treatment 9 (BL+FGDG and GBS+FGDG) show that additions of FGDG to both the cropped and GBS areas consistently led to lower nutrient concentrations with the least variance.

Considering extreme values, those within the 4th quartile (represented by dots in figure 4), BL fertilization (treatment 4, 5, and 6) had a greater number for all nutrients (except for NO_3-N) than NPK or BL+FGDG fertilization (Note the *y*-axis in figure 4 is truncated—not all 4th quartile data are shown). Across all treatments, mean concentration in the 4th quartile compared with the 2nd and 3rd quartile combined was 14-fold greater for NH_4-N and TKN, and 5- to 8-fold greater for the remaining nutrients (for untransformed data). This is in line with what is generally reported in the literature, such as Langdale et al. (1992) and Endale et al. (2014a), that a few extreme storm events contribute the larger portion of nutrient losses in a season.

Table 3 shows results from analysis of variance for nutrient concentration while table 4 shows back-transformed LS-means and significance of difference between LS-means of paired treatments based on analysis of LN-transformed data. None of the variables shown in table 3 had effect on TKN concentration while only the interval between planting and runoff dates had significant effects on concentration of NH_4-N. On the other hand, treatments and the interval between planting and runoff dates had significant effects on concentration of NO_3-N, DRP, and TP. Concentration of NO_3-N was also significantly affected by the one-day rainfall + irrigation causing runoff.

Nutrient Concentration under Different Fertilization Treatments. Under NPK fertilization (treatments 1, 2, and 3), GBS had no significant effect on the concentration of any nutrient (table 4). Under BL fertilization (treatments 4, 5, and 6), the only GBS effect observed was the reduction in NO_3-N concentration by 53% and 69% for GBS–FGDG and GBD+FGDG, respectively, compared with –GBS. Under BL+FGDG fertilization (treatments 7, 8, and 9), GBS–FGDG had no effect on concentration of any nutrient compared with –GBS. However, GBS+FGDG decreased concentrations of NH_4-N, TKN, DRP, and TP by 65% to 80% compared with –GBS. Concentrations of DRP and TP decreased by ~60% each for GBS+FGDG compared with GBS–FGDG.

Nutrient Concentration under Different Grass Buffer Strips Treatments. In –GBS plots, concentration of DRP and TP increased by 160% to 165% for BL compared with NPK, and concentration of DRP and TP increased by 150% and 115%, respectively, for BL+FGDG compared with NPK (table 4). There were no differences in nutrient concentrations between BL and BL+FGDG or between NPK and NPK+FGDG. In GBS–FGDG plots, nutrient concentration was not different among the three fertilizer treatments. In GBS+FGDG plots, BL fertilization did not affect nutrient concentration compared with NPK. However, BL+FGDG compared with NPK decreased DRP and TP concentrations by 67% each. Similarly, BL+FGDG compared with BL decreased concentrations of TKN, DRP, and TP by 75% to 85%. Nutrient concentrations were similar between treatment 1 (NPK and –GBS; a standard practice) and treatment 9 (BL+FGDG and GBS+FGDG). However, nutrient concentration was 65% to 80% less from treatment 9 compared with treatment 4 (BL and –GBS; another standard practice).

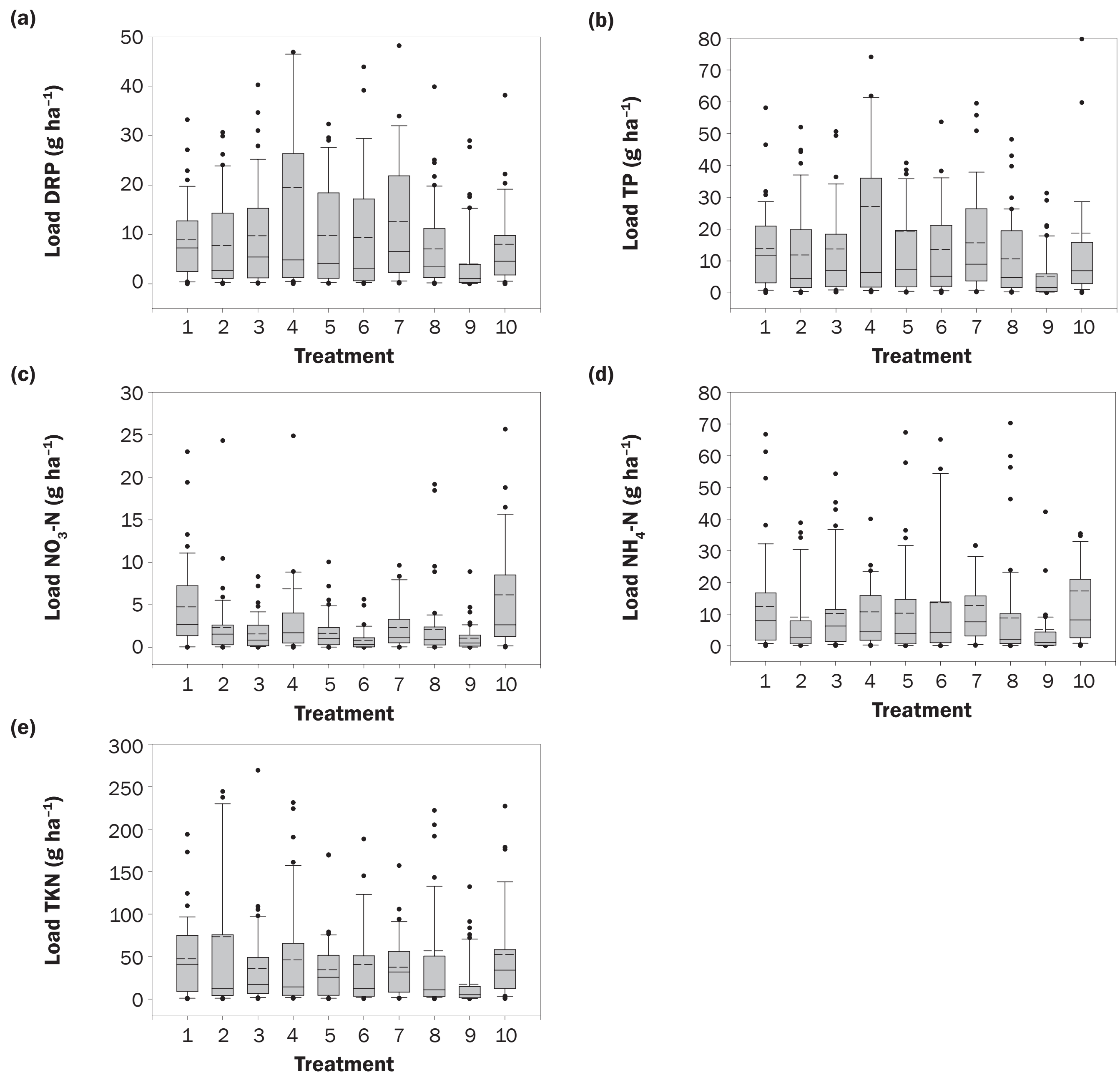
Nutrient Load. Figure 5 shows variability within and across treatments for nutrient loads using the original untransformed data. The box plots suggest stronger GBS than fertilizer effects, especially for DRP, TP, and TKN, although a BL (treatments 4, 5, and 6) effect is apparent for DRP and TP when compared with NPK (treatments 1, 2, and 3). As in the case of concentration, the box plots for treatment 9 (BL+FGDG plus GBS+FGDG) show that additions of FGDG to both the cropped and GBS areas consistently led to lower loads with the least variance. Nutrient load values within the 4th quartile for BL (treatments 4, 5, and 6) were in greater proportion than those for NPK or BL+FGDG but in this case for only DRP and TP load (note the y-axis in figure 4 is truncated—not all 4th quartile data are shown). Across all treatments, mean nutrient load in the 4th quartile was 5- to 6-fold greater compared with that in the 2nd and 3rd quartile combined (for untransformed data).

Table 3 shows results from analysis of variance for nutrient load while table 4 shows back-transformed LS-means and significance of difference between LS-means of paired treatments based on analysis of LN-transformed data. Treatment had significant effects on loads of NO_3-N, DRP, and TP while plot slope had significant effect on load of NO_3-N only. The prerunoff five-day antecedent rainfall + irrigation had significant effect on all nutrient loads. The interval between planting and runoff dates had significant effects on loads of TKN, DRP, and TP only.

Nutrient Load under Different Fertilization Treatments. In treatments fertilized with NPK (treatments 1, 2, and 3), GBS–FGDG compared with –GBS decreased loads for NO_3-N and NH_4-N by ~40% (table 4). GBS+FGDG decreased NO_3-N load by 54% compared with –GBS. There was no difference for any nutrient load between GBS–FGDG and GBS+FGDG. In treatments fertilized with BL (treatments 4, 5, and 6), GBS–FGDG had no significant effect on nutrient load compared with –GBS. However, GBS+FGDG decreased load for NO_3-N by 56% compared with –GBS. Similarly, GBS+FGDG decreased load of NO_3-N by 41% compared with GBS–FGDG. In BL+FGDG plots (treatments 7, 8, and 9), GBS–FGDG decreased NH_4-N load by 38% compared with –GBS. GBS+FGDG decreased loads of NH_4-N, TKN, DRP, and TP by 55% to 60% compared with –GBS. GBS+FGDG compared with GBS–FGDG decreased loads of NH_4-N, TKN, DRP, and TP by 35% to 50%.

Nutrient Load under Different Grass Buffer Strips Treatments. In treatments without GBS (–GBS), BL compared with NPK fertilization had no significant effect on nutrient load (table 4). Fertilization with BL+FGDG reduced NO_3-N load by 40% compared with NPK. Nutrient loads were similar between BL+FGDG and BL fertilization. Adding FGDG to NPK or BL did not change nutrient loads. In the GBS–FGDG treatments, fertilizer source had no effect on nutrient load. In the GBS+FGDG treatments, nutrient load was similar between BL and NPK fertilization. In contrast, BL+FGDG decreased loads of NH_4-N, DRP, and TP 45% to 50% compared with NPK fertilization for the GBS+FGDG treatments. Similarly, BL+FGDG compared with BL fertilization decreased loads of NH_4-N and TP by 40% to 50% for the GBS+FGDG treatments. Nutrient load from treatment 9 (combined BL+FGDG and GBS+FGDG) was 50% to 70% less compared with treatment 1 (NPK

Figure 5
Box plots showing variability of nutrient load for (a) dissolved reactive phosphorus (DRP), (b) total phosphorus (TP), (c) nitrate-nitrogen (NO_3-N), (d) ammonium-nitrogen (NH_4-N), and (e) total Kjeldahl nitrogen (TKN) by treatment based on the original nontransformed data. Boxes enclose data within the 25th and75th percentiles. Dotted and sold lines within boxes represent means and medians, respectively. Whiskers represent data at 90th percentile. Treatment details: 1 = NPK and (–GBS); 2 = NPK and (GBS–FGDG); 3 = NPK and (GBS+FGDG); 4 = BL and (–GBS); 5 = BL and (GBS–FGDG); 6 = BL and (GBS+FGDG); 7 = (BL+FGDG) and (–GBS); 8 = (BL+FGDG) and (GBS–FGDG); 9 = (BL+FGDG) and (GBS+FGDG); 10 = (NPK+FGDG) and (–GBS). NPK = inorganic fertilizer; BL = broiler litter; FGDG = flue gas desulfurization gypsum. *Y*-axis is truncated. Values not shown in (a) are 51 to 260 for treatments 4 to 6 and 10; in (b), 101 to 358 for treatments 3 to 7 and 10; in (c), 54 for treatment 10; in (d), 82 to 235 for all treatments but 1, 3, 5, and 8; and in (e), 464 to 1,312 for treatments 2, 8, and 10.



and –GBS) and 40% to 65% less compared with treatment 4 (BL and –GBS).

Correlation between Dissolved Reactive Phosphorus and Total Phosphorus. Table 5 shows slope parameters for linear regressions between DRP as the dependent and TP as the independent variables (with the intercept set at zero) for concentration and load of the various treatments. Across all treatments, DRP accounted for 56% of TP concentration and 70% of TP load. There was some variation by treatment. For NPK

Table 5

Parameters for linear regression for concentration and load between dissolved reactive phosphorus (DRP as dependent variable) and total P (TP as independent variable) by treatment.

Treatment #	Plot fertilizer	Buffer arrangement	Concentration ($\mu g\ L^{-1}$) r^2	Concentration Slope	Load ($g\ ha^{-1}$) r^2	Load Slope
1	NPK	No buffer (–GBS)	0.863	0.629	0.776	0.670
2	NPK	Buffer no gypsum (GBS–FGDG)	0.978	0.689	0.904	0.626
3	NPK	Buffer with gypsum (GBS+FGDG)	0.982	0.843	0.927	0.757
4	BL	No buffer (–GBS)	0.713	0.631	0.897	0.790
5	BL	Buffer no gypsum (GBS–FGDG)	0.892	0.467	0.923	0.748
6	BL	Buffer with gypsum (GBS+FGDG)	0.945	0.573	0.838	0.620
7	BL	No buffer (–GBS)	0.967	0.691	0.900	0.799
8	BL	Buffer no gypsum (GBS–FGDG)	0.833	0.319	0.816	0.642
9	BL	Buffer with gypsum (GBS+FGDG)	0.732	0.711	0.938	0.854
10	NPK	No buffer (–GBS)	0.741	0.590	0.937	0.575
ALL	ALL	NA	0.862	0.558	0.872	0.696

Notes: NPK = inorganic fertilizer. BL = broiler litter. FGDG = flue gas desulfurization gypsum. GBS = grass buffer strip. NA = not applicable. All linear regression models were significant at alpha ≤ 0.05.

fertilization, DRP concentration and load constituted 62% to 84% and 62% to 76% of TP, respectively. For BL fertilization, DRP accounted for 46% to 63% of TP concentration, lowest in GBS–FGDG, and 62% to 79% of TP load. For BL+FGDG fertilization, DRP accounted for 31% to 71% of TP concentration, lowest in GBS–FGDG, and 64% to 85% of TP load.

The BL contribution to reductions in runoff likely arose from organic matter additions improving surface soil physical properties as highlighted in Feng et al. (2019, 2021) and studies cited therein, where organic amendments varied with rates as high as 17 Mg ha^{-1} y^{-1} in some cases. Feng et al. (2021) reported improved soil aggregate stability, infiltration rate, saturated hydraulic conductivity, and soil water retention and availability for a sandy loam soil under a cotton (*Gossypium hirsutum* L.)–corn–soybean (*Glycine max* [L.] Merr.) rotation following application of BL at 7.6 Mg ha^{-1} y^{-1} for five years. Similar results were reported for a fine sandy loam soil under cotton after four years of BL application at 6.7 Mg ha^{-1} y^{-1} (Feng et al. 2019). Total C content of BL is variable as shown by reports from Feng et al. (2021) (202 to 232 kg Mg^{-1}) and Sharpley et al. (2020) (mean of 253 kg Mg^{-1} from 289 samples in Arkansas). Taking an average total C content of 230 kg Mg^{-1}, at our annual BL application rate of 13.45 Mg ha^{-1}, we would have added annually approximately 3.4 Mg ha^{-1} of total C under BL.

Several factors contribute to the effectiveness of GBS in reducing nonpoint source pollution from agricultural fields (Proser et al. 2020; Valkama et al. 2019). Proser et al. (2020) list buffer width, ratio of source to buffer area, slope, rainfall and runoff intensity, soil composition and structure, plant community structure, interval from nutrient or pesticide application, and fate and transport properties of nutrients and pesticides as factors that come into play. Surface vegetation, root zone, and subsoil also play important roles in nutrient loss reduction efficacy. Optimizing combinations of the factors indicated above would be expected to provide the greatest benefit. Proser et al. (2020) found that in some instances, buffer widths < 5 m were similarly efficient as one with 60 m width. The magnitude and rate of rainfall and of runoff entering a vegetated buffer, along with nutrient concentrations, is an important factor determining GBS effectiveness. A region with lower total rainfall and/or less frequent intense rainfall may achieve the desired nutrient or pesticide reduction efficiency with a narrower width GBS. Habibiandehkordi et al. (2019) noted that GBSs reduce nutrient losses best under diffuse, shallow flow, rather than concentrated flow conditions, and could even be ineffective under the latter flow conditions.

In our case, slope, source area, and GBS width (where present) were similar among the various treatments. Also, the shallow slope and observed flow condition would have resulted in diffuse shallow flow favorable to increasing infiltration. Our treatments, fertilizer source, the presence or absence of GBS, and application of FGDG were the primary factors influencing GBS performance efficacy. Our GBS were well established from over a decade of bermudagrass production that stabilized and improved surface and subsurface physical and hydraulic properties conducive for soil water infiltration and nutrient capture. Tillage of the corn cropped area twice each year (preplanting of corn and rye) would be expected to increase the rate of SOM decomposition and disruption of physical properties favorable to infiltration. Habibiandehkordi et al. (2019) noted that even though GBSs are effective in reducing total and particulate P in runoff, their effectiveness in reducing dissolved P long term could be uncertain due to accumulation of legacy P, in which case GBS could become sources of dissolved P. This effect would not have been expected in our study due to the short three-year period of BL application. Overall, our results point to the strong advantage of including GBS ± FGDG downstream of cropped fields to reduce runoff and nutrient loss for soils in our region.

As indicated in the introduction, previous studies have documented reductions in soil soluble P after gypsum application. In addition to increased infiltration due to improved soil aggregation and flocculation under FGDG, decreased P concentrations observed in the current study were likely due to enhanced P sorption through the dissolution of the Ca in the applied FGDG and the precipitation of Ca-, Al-, and Fe-phosphates (Havlin et al. 1999; King et al. 2016; Callahan et al. 2002; Cox et al. 2005; Stout et al. 1998). In an incubation study with five contrasting soils, Murphy et al. (2010) compared P reduction potential of lime and gypsum assessed by water extraction. Gypsum application had greater effect decreasing molybdate-reactive P solubility by 14% to 56% and organic P by 10% to 53% across all soils. The authors note that although often neglected in studies of P losses, organic P can be an important fraction in soil solution and P loss. Organic P can become bio-available and contribute to eutrophication in receiving water bodies. Decreased organic P solubility with liming in two soils and with gypsum in all soils may be due to increased stability of organic matter complexes with increased Ca concentrations and ionic strength.

Concentrations for soluble P we observed were in the range recently reported from other studies involving BL and FGDG such as Endale et al. (2014b), Sheng et al. (2014), Torbert and Watts (2014), and Watts and Torbert (2009). These studies used rainfall simulations conducted immediately or within a few weeks of applying treatments. In one case (Torbert and Watts 2014), two natural rain events that produced runoff occurred before rainfall simulation. Treatments that received BL at ~9 or 13 Mg ha^{-1} had soluble P concentrations in the range 5 to 47 mg L^{-1}. Treatments that combined these BL rates with rates of 6 or 9 Mg ha^{-1} gypsum had soluble P concertation in the range 1 to 26 mg L^{-1}. In the one study that involved GBS with gypsum (Sheng et al. 2014), soluble P concentration was reduced by 40%. Concentrations were 9 mg L^{-1} in the rainfall simulation immediately after treatment application and 4 mg L^{-1} four weeks later.

Summary and Conclusions

We evaluated the potential for FGDG to reduce losses of nutrients at the field edge and from GBS located at the down slope field edge for Coastal Plain soils cropped to corn fertilized with NPK or BL. In this first part of a three-phase study, BL and FGDG were applied at rates of 13.45 Mg ha^{-1} each year. The three phases of the study will track hysteresis of nutrient dynamics in the soil, runoff, and plants from residual sources of BL and FGDG. Our BL rate during phase-1 would be considered excessive relative to P-Index application rates with a high probability of nutrient loss. The remaining two phases of the project are designed to evaluate legacy implications of the current rates as applications of BL and FGDG are reduced over time.

During phase-1 (this article), runoff quantity and quality data gathered from 29 storms over a 21-month period from May of 2015 through January of 2017, with 17 in 2015 and 11 in 2016, are used to assesses treatment impacts on percentage runoff and concentration and load of NH_4-N, NO_3-N, TKN, DRP, and TP. The results showed that edge-of-field runoff and nutrient concentration and load can be significantly reduced under the following conditions.

Runoff:

- In cases of –GBS, fertilizing with BL or BL+FGDG instead of NPK can reduce percentage runoff by 50% to 60%.
- When fertilizing with NPK, GBS–FGDG or GBS+FGDG can reduce percentage runoff by 60% to 70% compared with –GBS.
- When fertilizing with BL, GBS+FGDG can reduce percentage runoff by 40% to 60% compared with –GBS or GBS–FGDG.

Nutrient concentration:

- When fertilizing with NPK, GBS–FGDG or GBS+FGDG does not change nutrient concentration.
- When fertilizing with BL, adding GBS–FGDG or GBS+FGDG can reduce NO_3-N concentration by 50% to 70% compared with –GBS. In the –GBS, fertilizing with BL or BL+FGDG instead of NPK can increase concentration of DRP and TP by 110% to 165%.
- When fertilizing with BL+FGDG, GBS–FGDG does not affect nutrient concentration compared with –GBS but GBS+FGDG can reduce concentrations of NH_4-N, TKN, DRP, and TP by 65% to 80% compared with –GBS, and DRP and TP concentration about 60% compared with GBS–FGDG.
- When GBS+FGDG are added, fertilization with BL+FGDG instead of NPK can decrease concentrating of DRP or TP by 65% to 70%; fertilization with BL+FGDG instead of BL can decrease concentrating of NH_4-N, TKN, DRP, and TP by 75% to 85%.

Nutrient load:

- When fertilizing with NPK, GBS–FGDG or GBS+FGDG versus –GBS can reduce load of NO_3-N by 35% to 55% due to a reduction in runoff; NH_4-N load can decrease by 40% for GBS–FGDG versus –GBS.
- When fertilizing with BL only, GBS+FGDG versus –GBS or versus GBS–FGDG can reduce NO_3-N load 40% to 60% due to a reduction in runoff.
- When fertilizing with BL+FGDG, GBS+FGDG can reduce load of NH_4-N, TKN, DRP, and TP by ~ 60% compared with –GBS, and 35% to 50% compared with GBS–FGDG.
- When GBS+FGDG are included, fertilization with BL+FGDG instead of NPK can reduce loads of NH_4-N, DRP, and TP by 45% to 55%; fertilization with BL+FGDG instead of BL can reduce loads of NH_4-N and TP by 40% to 50%.

Consistently, combining BL+FGDG with GBS+FGDG was one of the most effective ways for reducing nutrient losses. This treatment reduced nutrient load by 50% to 70% compared with NPK fertilization and –GBS. BL+FGDG with GBS+FGDG also reduced nutrient concentration by 65% to 80% and nutrient load by 40% to 65% compared with BL fertilization and –GBS. Our results point to a simple approach to improving edge-of-field runoff quality in cropping systems of the US Southeast, especially where BL is used as fertilizer source. Further studies conducted at field and watershed scales would be needed to quantify landscape scale benefits of these practices.

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