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Bermudagrass growth in soil contaminated with hydraulic fracturing drilling fluid

*Douglas C. Wolf** and Kristofor R. Brye*[†]

ABSTRACT

Hydraulic fracturing is the process of injecting aqueous solutions at high pressure to break apart rock formations and increase the extraction of natural gas. The solutions are recovered and have been land-applied as one disposal technique. Excessive fluid application can result in increased soil salinity that can inhibit plant growth. The objective of this greenhouse study was to evaluate the effects of inorganic fertilizer, broiler litter, and Milorganite® and soil depth interval (0-15 cm or 0-30 cm) on the growth of bermudagrass [*Cynodon dactylon* (L.) Pers] in soil that was collected from a site that had been contaminated with fracturing fluid and was initially devoid of vegetation. Amendment rates were added to provide 60 mg of plant-available N/kg. Bermudagrass was sprigged and harvested after nine weeks and shoot, root, and total biomass were determined. Addition of inorganic fertilizer, broiler litter, or Milorganite® resulted in greater shoot biomass compared to unamended soil. Plants grown in 0-30-cm-depth soil had greater root biomass compared to the 0-15-cm soil depth. The addition of recommended plant nutrients and mixing of the contaminated surface soil with the subsurface soil enhanced bermudagrass growth.

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† Kristofor R. Brye is a faculty mentor and a professor in the Department of Crop, Soil, and Environmental Sciences.

MEET THE STUDENT-AUTHOR

Douglas Wolf

I graduated summa cum laude with a Bachelor of Science in the Crop, Soils, and Environmental Sciences Department and was a member of the Agricultural, Food, and Life Sciences Honors Program. I have had the opportunity to participate in study abroad programs in three countries—Belize, Scotland, and New Zealand —with funding from the Honors College, American Society of Agronomy Cross Cultural Experience Program Scholarship, and Phi Kappa Phi. In 2012, I was 2012 National Golden Opportunity Scholar with the Soil Science Society of America and also received an Arkansas State Undergraduate Research Fellowship, which was used to fund this study. I am also a recipient of a Morris K. Udall Fellowship Honorable Mention.

After completing my internship at the National Center for Toxicology Research this summer, I will be attending the University of California, Riverside Environmental Toxicology Doctoral Graduate Program. I will be funded by the University of California, Riverside Chancellor's Distinguished Fellowship and the National Science Foundation Graduate Research Fellowship.

I would like to express deep gratitude and appreciation to Dr. Kristofor Brye for his guidance and support throughout my academic career at the University of Arkansas as a mentor, advisor, and friend. I would also like to thank my committee members, Dr. Mary Savin, Dr. David Miller, and Dr. Curt Rom, for revisions on my thesis.

INTRODUCTION

Throughout the 21st century, the world has experienced an ever-increasing demand for petroleum to power an exponentially growing population (Cunningham and Cunningham, 2008). The United States' response to the depletion of petroleum is to explore other domestic energy sources such as natural gas. In 2011, natural gas consumption accounted for approximately 23% of the total United States energy use, which is expected to increase to 27% by 2040 (USEIA, 2013). In its 2013 Annual Energy Outlook, the U.S. Energy Information Administration (USEIA) estimated that natural gas consumption would increase from 6.91×10^{11} m^3 in 2011 to 8.35×10^{11} m^3 in 2040. The USEIA 2013 report also predicted that a 57% increase in natural gas production (1.02×10^{12} m^3) would occur by 2035. The increased production would be due primarily to the advancements in drilling technology and techniques such as a process called hydraulic fracturing that can extract natural gas in previously unconventional reservoirs.

Unconventional gas reservoirs typically contain concentrations of natural gas over large areas that have a lower permeability or porosity than conventional gas reservoirs, such as sandstone and carbonate reservoirs (Vidas and Hugman, 2008). An unconventional gas reservoir, called the Fayetteville Shale, is located in the Arkoma Basin of north-central Arkansas where approximately 5,357 natural gas producing wells have been constructed (AOGC, 2014a). The Fayetteville Shale contains approximately 6.5×10^4 km^2 of black, fissile, concretionary, dense clay shale that has very low permeability. However, extraction has recently become economically feasible due to advances in horizontal drilling and hydraulic fracturing (Kresse et al., 2012).

Hydraulic fracturing has been utilized in combination with horizontal drilling for multiple decades of shale gas extraction and is a stimulation technique to enhance the flow rate of natural gas wells by increasing the gas-bearing rock permeability (USEPA, 2004). The hydraulic fracturing process begins with the building of site infrastructure, such as well pads, holding ponds, and access roads, that generally encompasses 1 to 2 ha (USEPA, 2011). Production wells are then drilled to a depth of 2130 to 3040 m depending on gas-containing rock formations and can be vertical, horizontal, or S-shaped (Wang et al., 2014). Currently, horizontal wells are the most common well formation because horizontal wells provide more exposure to the rock containing natural gas compared to vertical wells. Horizontal drilling increases the recovery of natural gas and the cost effectiveness of the natural gas well in addition to allowing multiple wells drilled on a single well pad to access natural gas resources (Arthur et al., 2008).

After the hydraulic fracturing well is constructed, the gas-containing formation is hydraulically fractured in a series of stages by pumping fracturing fluid into the wellbore under high pressures that fill the voids in the geologic formation until the formation can no longer accommodate the fracking fluid, causing the rock to fracture and release natural gas to the well bore and surface (Wang et al., 2014). The fracturing fluids, comprised primarily of water mixed with chemical additives, are used throughout the natural gas operation to increase the performance and efficiency of extraction by creating fractures of ample width that maximize fluid injection rates. In addition to these optimized fractures, a proppant, typically sand, is also used to keep the induced hydraulic fractures from closing when the injection ceases (Arthur et al., 2008). Hydraulic fracturing operations in the Fayetteville Shale use an estimated 1.1×10^7 L per well (Satterfield et al., 2008). Because of the large volume of water used per well, large amounts of chemical additives are being disposed of as waste products.

After hydraulic fracturing and the gas extraction process is complete, the internal pressure of the geologic formation causes the drilling fluids to rise to the surface and is referred to as flowback or "produced" water (Wang et al., 2014). Rahm (2011) and Wang et al. (2014) reported that as much as 15% to 100% of the "produced" water may be returned to the surface and require disposal. Historically, flowback was disposed of by deep injection into underground injection control (UIC) class II wells or through land application. However, the controlled injection disposal of used fracking fluids has been associated with a 4.7-magnitude earthquake in central Arkansas in 2011 (Ellsworth, 2013). Although north-central Arkansas is partially located on the New Madrid seismic zone, 98% of 157 earthquakes occurred within 6 km of one of the three Arkansas UIC class II wells during flowback injection from 2010 to mid-2011(Horton, 2012; King, 2012). Because of this apparent correlation, the Arkansas Department of Environmental Quality (ADEQ) has closed all disposal wells and suspended any new disposal wells within the Fayetteville Shale (Arkansas Hydraulic Fracturing State Review, 2012).

The ADEQ also regulates the land application process of water-based drilling fluids based upon the physical landscape (i.e., slope, storage capacity, and weather), physical and chemical soil properties (i.e., electrical conductivity and pH), and the drilling waste characteristics (ADEQ, 2009). In addition to the chemical additives, the flowback also contains high concentrations of total dissolved solids and the potential for high concentrations of hydrocarbons and heavy metals (Wang et al., 2014). At some natural gas drilling sites, over-application of drilling fluid waste has resulted in contaminated soil that could not adequately support vegetation to meet ADEQ requirements for natural gas site closure. Site closure requires vegetative coverage of 75% or more, or equivalent to the surrounding landscape, whichever is less, within six months of site closure (AOGC, 2014b). Previous studies have been conducted concerning the impact of land application of hydraulic fracturing drilling fluid on vegetation (Nelson et al., 1984; Adams, 2011); however, no information regarding revegetation has been discussed.

Since little is known about the optimum approach to revegetate a site that has been contaminated by surface-applied hydraulic fracturing fluid, much benefit can be gained from the evaluation of potential inorganic and organic soil amendments to enhance plant establishment and growth. Therefore, the objective of this 9-wk greenhouse study was to evaluate the effects of inorganic fertilizer, broiler litter, and Milorganite® and soil depth interval (i.e., 0-15 cm or 0-30 cm) on the growth of bermudagrass [*Cynodon dactylon* (L.) Pers] in soil that was collected from a site that had been contaminated with hydraulic fracturing fluid and was initially devoid of vegetation. It was hypothesized that adding required plant nutrients through soil amendments in addition to a dilution effect created by mixing soil from a lower depth with highly contaminated topsoil would increase bermudagrass growth in soil contaminated with fracturing fluid.

MATERIALS AND METHODS

Initial Soil Collection and Analyses

Contaminated soil was collected using a shovel during December 2011 from the 0-15 cm (Ap horizon) and 0-30 cm (deep plow) depths from a 3-ha drilling-fluid-contaminated field near a natural gas drilling site located in the Fayetteville Shale in Branch, Ark. Soil collected from each of the two depths was air-dried for 5 days at approximately 22 °C, crushed, and sieved through a 2-mm, stainless steel mesh screen. Representative sub-samples of the soil were analyzed for soil physical and chemical properties (Table 1).

Soil particle-size distribution and textural classification were determined using the 12-hr hydrometer method (Gavlak et al., 2003). Soil electrical conductivity (EC) were determined potentiometrically in a 1:1 and 1:2 soil (m)-to-water (v) suspension (U.S. Salinity Laboratory Staff, 1954; Donohue, 1992). The initial EC values (μmhos/cm) were converted to saturated-paste values (EC_e) using the relationship described by Zhang et al. (2005). The soil pH was determined potentiometrically in a 1:2 soil (m)-to-water (v) suspension (Donohue,

Table 1. Initial soil physical and chemical properites of the two soil depth intervals used in the 9-wk study. Dry-weight means ± standard deviation are reported based on three replications.

	Soil Depth (cm)	
Soil Characertistic	**0-15**	**0-30**
Sand (%)	12 ± 0.9	9 ± 0.5
Silt (%)	59 ± 0.5	64 ± 2.3
Clay (%)	29 ± 0.4	27 ± 1.7
Electrical Conductivity (1:2) (dS/m)	4.23 ± 0.874	3.65 ± 0.125
Saturated Paste Extract (EC_e) (dS/m)	14.5 ± 0.42	14.1 ± 1.32
pH	7.99 ± 0.0170	8.00 ± 0.051
Mehlich-3 Extractable		
P (mg/kg)	6.0 ± 0.59	4.3 ± 0.18
K (mg/kg)	303 ± 4.39	276 ± 5.53
Na (mg/kg)	2994 ± 114.8	2550 ± 40.59
Ca (mg/kg)	2390 ± 72.64	2176 ± 31.59
Mg (mg/kg)	332 ± 6.33	285 ± 3.20
S (mg/kg)	161 ± 6.61	99 ± 2.7
Cu (mg/kg)	7.0 ± 0.03	5.7 ± 0.13
Zn (mg/kg)	10.1 ± 0.087	7.99 ± 0.102
Water-extractable Cl^- (mg/kg)	5603 ± 76.38	5020 ± 264.4
Total N (%)	0.1215 ± 0.0013	0.1081 ± 0.0046
Total C (%)	2.347 ± 0.0370	1.839 ± 0.0300
NO_3-N (mg/kg)	10.6 ± 0.351	6.9 ± 0.20
NH_4-N (mg/kg)	1.7 ± 0.30	2.1 ± 0.23

1992). Mehlich-3 extractable nutrients (i.e., P, K, Na, Ca, Mg, S, Cu, and Zn) were determined from a 1:10 soil (m)-to-extractant-solution (v) ratio (Tucker, 1992) using a SPECTRO ARCOS inductively coupled, argon-plasma (ICP) spectrophotometer (SPECTRO Analytical Instruments, Inc., Mahwah, N.J.). Water-extractable chloride (Cl^-) was determined by axially viewed ICP spectrometry at a wavelength of 134.7 nm, the most sensitive wavelength that is viable for high Cl^- concentrations, in a 1:2 soil (m)-to-water (v) suspension (Wheal and Palmer, 2010). Total soil N and C were analyzed by high-temperature combustion using an Elementar Vario MAX C/N instrument (Elementar Americas, Inc., Mt. Laurel, N.J.) (Bremner, 1996). Inorganic nitrate (NO_3-N) and ammonium (NH_4-N) were determined by steam distillation of a 2 *M* KCl soil extract with the additions of MgO and Devarda's alloy (Mulvaney, 1996).

Organic Soil Amendments and Analyses

Broiler litter and Milorganite® were the two organic soil amendments evaluated in this study. One-year-old broiler litter from a rice (*Oryza sativa* L.)-hull-bedding-cleanout material following five flock cycles from a commercial broiler operation in Lincoln, Ark. was used in this experiment. Milorganite® is a commercially available, activated wastewater sewage sludge that has undergone secondary aerobic microbial degradation and dried in a rotary kiln at 450 to 600 °C for 40 min. and is sold nationally as a lawn fertilizer (Cogger et al., 2011). Both organic soil amendments were characterized for their initial physical and chemical properties (Table 2). Initial water contents were determined gravimetrically. Similar to the soil analyses, EC and pH were determined potentiometrically in a 1:1 and 1:2 soil (m)-to-water (v) suspension, respectively. Total N and C were determined by high-temperature combustion. The NO_3-N and NH_4-N were determined by 2 *M* KCl extraction using a Skalar Continuous Flow Analyzer (Skalar Analytical Instruments, Breda, Netherlands). Total metals (i.e., P, K, Na, Ca, Mg, Cu, and Zn) were determined by ICP spectrometry following USEPA Method 3050B after a 6-h digestion at 95 °C in concentrated nitric acid (HNO_3), 30% hydrogen peroxide (H_2O_2), and concentrated hydrochloric acid (HCl) (USEPA, 1996).

Treatment Preparation

In addition to contaminated soil from two depth intervals, four soil amendments (i.e., inorganic fertilizer, broiler litter, Milorganite®, and an unamended control) were evaluated in this study. Five hundred grams (dry weight) of contaminated soil were placed into a bag and the appropriate amendments were added and thoroughly mixed. Based on the University of Arkansas System Division of Agriculture's Cooperative Extension Service's fertilization recommendation for establishment and maintenance of bermudagrass (Espinoza et al., 2006), a rate of 60 mg plant available N (PAN)/kg soil was selected to be added by the soil amendments to the contaminated soil . The inorganic fertilizer used was ammonium nitrate (34-0-0), which was added at a rate of 176 mg/kg soil (338 kg/ha). To balance the nutrient additions for plant growth in the inorganic fertilizer treatment, P was added at a rate of 131 mg/kg soil (251 kg/ha) as triple super phosphate (0-46-0). Because of the above-optimal, initial soil-test K concentration (Table 2), no K fertilizer was needed to support optimal plant growth, thus no K was added. The poultry litter treatment received 4.16 g poultry litter (dry weight)/kg soil based upon an estimated 30% mineralization rate. Total N mineralization rates for poultry litter have been calculated from previous research studies to range from 16% to 66% (Hadas et al., 1983; Chescheir et al., 1986; Sims, 1986; Gilmour et al., 1987; Bitzer and Sims, 1988; Golden et al., 2006). The Milorganite® treatment received 3.25 g Milorganite® (dry weight)/kg soil based upon an estimated 30% mineralization rate (Gilmour et al., 2000; Cogger et al., 2011).

Once the soil plus amendment mixture was prepared, the mixture was added to 6.4-cm diameter by 25-cm long Conetainers® (Stuewe and Sons Inc., Corvallis, Ore.) that had been sealed at the bottom with a plug to prevent soil and water loss (Kirkpatrick et al., 2006). The soil-amendment mixture was added to the Conetainers® to achieve a bulk density of 1.28 g/cm^3.

Greenhouse Experiment

Prior to plant establishment and to achieve approximate field capacity moisture conditions, 100 mL of distilled water was added to each Conetainer® to achieve a gravimetric soil water content of 20% and an approximate soil water potential of -33 kPa (Brady and Weil, 2002). Two, 7-cm long Bermudagrass sprigs, collected from the same natural gas drilling site where the contaminated soil was collected, were planted per Conetainer® to constitute a vegetation treatment. A no-vegetation treatment was also prepared. The Conetainers® were placed randomly in one of four racks (i.e., blocks), each containing one replication of all treatment combinations (n = 16), in a climate-controlled greenhouse. Each Conetainer® was weighed daily for nine weeks and soil moisture was gravimetrically adjusted to 20% by daily application of distilled water. During the 9-wk greenhouse experiment, the maximum, minimum, and average greenhouse air temperatures were 37, 21, and 28.5 °C, respectively. Ber-

Table 2. Physical and chemical characterization of the two organic amendments used in the 9-wk greenhouse study. Dry-weight means ± standard deviation are reported based on two replications.

	Organic Amendment	
Parameter	Broiler Litter	Milorganite®
Moisture Content (%)	31.80 ± 0.3182	7.44 ± 0.184
Electrical Conductivity (1:2) (dS/m)	13.98 ± 0.4596	7.01 ± 0.014
pH	8.8 ± 0.0	5.6 ± 0.07
Total N (%)	4.50 ± 0.066	7.10 ± 0.074
Total C (%)	37.30 ± 0.3040	38.63 ± 0.0424
NO_3-N (mg/kg)	304 ± 4.24	36 ± 0.98
NH_4-N (mg/kg)	11803 ± 18.384	1760 ± 5.472
Total Zn (mg/kg)	706 ± 31.8	411 ± 1.31
Total Cu (mg/kg)	289 ± 5.66	236 ± 3.54
Total P (%)	2.53 ± 0.212	2.28 ± 0.021
Total K (%)	4.18 ± 0.127	0.64 ± 0.00
Total Na (%)	0.99 ± 0.04	0.17 ± 0.00
Total Ca (%)	4.08 ± 0.827	2.04 ± 0.007
Total Mg (%)	0.85 ± 0.04	0.54 ± 0.01

mudagrass growth was facilitated on a12-h day length by metal halide, high-intensity discharge lights.

Vegetation Analyses

After nine weeks, bermudagrass shoots were cut at the soil surface, rinsed with distilled water, dried to a constant weight at 55 °C, and were ground to pass a 2-mm, stainless-steel mesh screen using a Wiley Mill Grinder (Thomas Scientific, Swedesboro, N.J.). Bermudagrass shoots were digested in concentrated HNO_3, 30% H_2O_2, and concentrated HCl on a heating block for elemental analysis (Kirkpatrick et al., 2006). Analyses for total P, K, Cu, and Zn were conducted by ICP spectrometry. Total N was determined by high-temperature combustion using an Elementar Rapid N III (Elementar Americas, Inc., Mt. Laurel, N.J.) (Donohue, 1992).

Soil was transferred from the Conetainers® to a tray and the roots were manually collected using forceps. Plant roots were placed on a 500-µm, stainless-steel sieve and rinsed with distilled water to remove any soil adhering to the roots. The rinsed roots were stained with a 10% ethanol solution containing 0.1 g methylene blue/L. Root length, volume, and surface area were determined with Win/Mac RHIZO version 5.0® image analysis system (Regent Instruments, Inc., Quebec City, Canada) (Thompson et al., 2008). Root biomass was determined by drying the roots to a constant weight at 55 °C following the root scanning.

Statistical Analyses

The experiment was designed and analyzed as a randomized complete block design with four blocks arranged in a 4 × 2 factorial treatment structure [i.e., soil amendment (four levels; inorganic fertilizer, broiler litter, Milorganite®, and an unamended control) and soil depth (two levels; 0-15 cm and 0-30 cm)]. Blocks were treated as a random effect and the two experimental factors were treated as fixed effects. Least squares means for significant effects were separated using a protected least significant difference (LSD) procedure at α = 0.05. All statistical analyses were conducted using SAS® Version 9.2 (SAS Institute, Inc., Cary, N.C.).

RESULTS AND DISCUSSION

Soil

Initial soil chemical analyses determined that soil from the 0-15-cm depth contained high salinity and Na and Cl^- concentrations compared to the 0-30-cm depth (Table 1). The soil previously contaminated with hydraulic fracturing drilling fluid lacked optimal N and P to support plant growth, but had excessive K. Chemical analyses also verified that the initial soil contained low concentrations of the toxic trace metals Cu and Zn. Soil particle-size analyses determined that both soil depths had a silty-clay-loam soil texture (Table 1).

Vegetation

Of the total of 64 bermudagrass sprigs planted at the beginning of the experiment, 11 died during the greenhouse study. For the unamended, inorganic-fertilizer-, broiler-litter-, and Milorganite®-amended soils, 1, 1, 7, and 2 plants, respectively, did not survive. Replacement bermudagrass sprigs were transplanted to the Conetainers® containing plants that died during the initial 2 wks of the study. Bermudagrass total (P = 0.0032) and shoot biomass (P = 0.0032) production did not differ among the inorganic fertilizer, broiler litter, and Milorganite® treatments, but were greater in all amended soils than in the unamended control soil during the 9-wk greenhouse study (Table 3). Root biomass was greater (P = 0.0256) in the inorganic fertilizer amendment compared to the unamended control and Milorganite® treatments. The root biomass of the broiler-litter-amended soil did not differ compared to the unamended control, inorganic fertilizer, Milorganite® treatments.

Table 3. Influence of four soil amendments on bermudagrass shoot, root, and total biomass following a 9-wk greenhouse study.

Soil Amendment	Root	Shoot	Total
	------------------------------mg/plant------------------------------		
None	46.9 b†	222.5 b	269. 4 b
Inorganic Fertilizer	146.0 a	868. 5 a	1014.5 a
Broiler Litter	107.4 ab	758.9 a	864.9 a
Milorganite®	74.7 b	606.1 a	680.8 a
LSD with broiler litter	63.8	372.7	421.5
LSD without broiler litter	60.7	358.6	405.1

†Means for a given parameter followed by the same letter do not differ (P > 0.05).
Notes: n = 32 for None, Inorganic Fertilizer, and Milorganite®; n = 31 for Broiler Litter.

Bermudagrass grown in soil from the 0-30-cm depth resulted in increased root length ($P = 0.0057$), surface area ($P = 0.0103$), volume ($P = 0.0287$), and root biomass ($P = 0.0117$) compared to bermudagrass grown in the 0-15-cm-depth soil (Table 4). The addition of the broiler litter or inorganic fertilizer resulted in greater ($P = 0.0320$) bermudagrass root volume compared to the unamended control treatment (Table 5). Roots in the broiler-litter-amended soil had greater ($P = 0.0483$) root surface area compared to the unamended control. The inorganic-fertilizer- and Milorganite®-amended treatments did not differ from the unamended control.

Bermudagrass shoot Na and Cl concentrations were unaffected by soil depth interval or the addition of soil amendments and averaged 3905 mg/kg and 12596 mg/kg, respectively, across all treatment combinations. Vegetation from the 0-15-cm-depth soil had a greater ($P = 0.0167$) shoot N concentration (1.46%) than vegetation grown in soil from the 0-30-cm-depth soil (1.21%). Shoot N concentrations were greater ($P = 0.0219$) in the Milorganite®-amended soil compared to inorganic fertilizer, broiler litter, and unamended control soils, which did not differ (Table 5).

The greatest ($P < 0.0001$) P concentration in the bermudagrass shoots resulted from the application of broiler litter to the soil, which was greater than that from inorganic fertilizer and Milorganite®, which were both greater than that from the unamended control (Table 5). Bermudagrass shoot P concentration in the broiler-litter-amended soils was two times greater than in the unamended control soil. Shoot K concentration was greater ($P = 0.0019$) in the Milorganite® and inorganic fertilizer treatments than in the unamended control (Table 5). Broiler-litter-amended treatments did not differ from the unamended control or inorganic fertilizer treatments, but contained lower shoot K concentration compared to the Milorganite® treatments.

Bermudagrass shoot Cu concentrations were greater ($P = 0.0084$) in the unamended control and Milorganite®-amended soils compared to those in the inorganic-fertilizer-amended soil while the broiler-litter-amended soil did not differ from all treatments (Table 5). Bermudagrass grown in the unamended soil resulted in the greatest ($P < 0.0001$) concentration of Zn in the bermudagrass shoots (Table 5). Vegetation grown in the 0-15-cm soil depth had greater ($P = 0.0431$) Cu concentration (9.3

Table 4. Influence of drilling-fluid-contaminated-soil depth on bermudagrass root length, surface area, volume, and biomass following a 9-wk greenhouse study.

Soil Depth	Length	Surface Area	Volume	Biomass
cm	cm/plant	cm^2/plant	cm^3/plant	mg/plant
0-15	471.9 b†	53.1 b	0.490 b	63.6 b
0-30	788.1 a	87.7 a	0.790 a	123.9 a
LSD	263.25	29.93	0.3085	41.71

† Means for a given parameter followed by the same letter do not differ ($P > 0.05$).
Notes: n = 32.

Table 5. Comparison of four soil amendments on bermudagrass root surface area and volume, bermudagrass shoot N, P, K, Cu, and Zn concentrations following a 9-wk greenhouse study.

	------------Roots------------		-----------------------------Shoot-----------------------------				
Soil Amendment	Surface Area	Volume	N	P	K	Cu	Zn
	cm^2/plant	cm^3/plant	------------------%------------------			-------mg/kg-------	
None	48.1 b†	0.377 b	1.22 b	0.059 c	1.26 c	9.7 a	105.1 a
Inorganic fertilizer	83.4 ab	0.804 a	1.26 b	0.102 b	1.49 ab	7.8 b	48.2 b
Broiler Litter	94.2 a	0.888 a	1.26 b	0.142 a	1.43 bc	7.9 ab	47.0 b
Milorganite®	56.0 ab	0.490 ab	1.61 a	0.097 b	1.69 a	9.7 a	65.3 b
LSD with broiler litter	40.09	0.4163		0.0215	0.230	1.85	23.76
LSD without broiler litter	38.55	0.4000		0.0204	0.222	1.80	22.83
LSD Inorg. and Milorg.®			0.2705				
LSD Litter and none			0.2945				
LSD Other			0.2828				

† Means for a given parameter followed by the same letter do not differ ($P > 0.05$).
Notes: Root n = 32 for None, Inorganic Fertilizer, and Milorganite®; n = 31 for Broiler Litter; Shoot N n = 30; Shoot P, K, Cu, and Zn n = 32 for None, Inorganic Fertilizer, and Milorganite®; n = 31 for Broiler Litter.

mg/kg) than plants grown in the 0-30-cm-depth soil (8.3 mg/kg).

Soil Amendments

Since the addition of plant nutrients from synthetic or organic soil amendments resulted in greater shoot biomass, soil amendments would likely increase the vegetative surface coverage to meet the 75% vegetation coverage required by the Arkansas Oil and Gas Commission (AOGC, 2014b). Total bermudagrass biomass was largely determined by shoot biomass and thus followed the same trend. Adams (2011) reported damaging symptoms and acute and chronic mixed hardwood trees, mixed shrub subcanopy, and ground vegetation mortality by the land application of hydraulic fracturing drilling fluid. In her study, the maximum Na and Cl concentrations were 805 and 746 mg/kg, respectively. Land application of drilling fluids to agriculturally productive lands has also shown similar harmful impacts. Nelson et al. (1984) reported ryegrass (*Lolium perenne* L.) and swiss chard (*Beta vularis* L.) yield reductions in drilling-fluid-amended soils resulting from increased concentrations of soluble salts. Miller and Pesaran (1980) and Miller et al. (1980) reported decreased growth in green beans (*Phaseolus vulgaris* L.) and sweet corn (*Zea mays* var. *Saccharata Sturt.*) when studying the effects of land-applying individual drilling fluid components.

Tucker (1985) concluded that the Na and Cl constituents of the hydraulic fracturing drilling fluid most adversely affected plant growth. Bermudagrass ion toxicity and mortality under saline soil conditions occurs due to the accumulation of Na^+ and Cl^- concentrations and subsequent decrease in K^+ concentrations in plant tissue (Chen et al., 2014; Adavi et al., 2006). However, the addition of soil amendments did not result in decreased bermudagrass shoot Na and Cl concentrations and lead to an increase in bermudagrass shoot K concentration in the inorganic-fertilizer and Milorganite®-amended soil. Bermudagrass continued to uptake K from the soil in a process known as "luxury consumption", where the plant accumulates nutrients above levels that are necessary for optimum growth (Burton and Jackson, 1962). Considering the effects of the soil amendment applications, the successful growth of bermudagrass was likely due to the plant's salt tolerance and other benefits of the amendments such as plant-available nutrients. The salt-tolerance range of bermudagrass has been classified as moderate (Marcum, 1999) to very tolerant (Devitt, 1989; U.S. Salinity Laboratory Staff, 1954) due to bermudagrass shoot's highly active salt gland excretion of Na^+ cations and shoot exclusion of excessive Na^+ and Cl^- (Marcum, 2006; Marcum and Pessarakli, 2006), which allows plant growth under saline soil conditions. Increased Na (356%) and Cl (498%) concentrations in bermudagrass shoots over an annual growing period due to increased salinity levels have been reported by Adavi et al. (2006). Other studies have also reported increased Na^+ and Cl^- ions in bermudagrass shoots under saline soil conditions (Ackerson and Youngner 1975; Chen et al., 2009; Chen et al., 2014; Thomas and Langdale, 1980).

The reduced plant survival in the broiler-litter-amended soil could be related to NH_3 toxicity due to the high level of NH_4-N and uric acid in the broiler litter, the initial soil pH of 8.0 (Table 1), and the average greenhouse temperature of 28.5 °C for the 9-wk study. Losada and Arnon (1963) and van der Eerden (1982) reported plant necrosis caused by ammonia toxicity due to the inhibition of photosynthetic phosphorylation that subsequently decreased carbohydrate production and plant growth. Vines and Wedding (1960) reported that ammonia toxicity occurred in alkaline soils because the pH level controlled the forms of ammonia present in the soil, where the undissociated ammonia was the form of ammonia that caused inhibition of plant tissue respiration (Eq. 1). Using composted broiler litter would avoid NH_3 toxicity issues (Kelleher et al., 2002).

$$NH_{3(g)} + H^+ \leftrightarrow NH^+_{4\,(aq)} \qquad \text{Eq. 1}$$

By applying the amount of broiler litter to provide 60 mg PAN/kg soil, excessive amounts of P were added. Broiler litter has one of the highest P concentrations of all animal manures (Sims and Wolf, 1994). The greatest plant uptake of P, calculated as the shoot biomass × shoot %P, was 1.4 mg/pot and occurred in the broiler-litter and inorganic fertilizer-amended soils (Tables 3 and 5). The greatest plant uptake of N, calculated as the shoot biomass × shoot %N, was 18.2 mg N/pot, which occurred in the inorganic fertilizer-amended soil due to the soluble inorganic N readily available for plant uptake (Tables 3 and 5).

Broiler-litter-amended soils typically contain elevated Cu and Zn concentrations because these trace elements are added to broiler feed as dietary supplements to improve weight gain, prevent diseases, and manage fungi in the broiler feed (Han et al., 2000). Because broiler litter and Milorganite® contain trace elements, caution must be taken to ensure that long-term application of these amendments does not increase trace element concentrations to toxic levels. Pederson et al. (2002) reported that short- and long-term application of poultry litter increased soil Cu and Zn concentrations, especially in the 5-10-cm soil depth interval. However, the addition of soil amendments resulted in similar or lower Cu and Zn concentrations in bermudagrass shoots compared to the unamended control, which can possibly be attributed to the trace elements not being readily plant available. Increased metal retention in the soil would be expected in highly alkaline soils because trace-element solubility generally decreases with increasing pH (Pepper et al., 2011). Han et al. (2000) reported low micronutrient removal by bermudagrass as a result of plant uptake. This observation agrees with Bates (1988) who reported low bermudagrass uptake of Zn in a reserve-pit-fluid-contaminated silt-loam soil.

Soil Dilution Effect

In addition to inadequate nutrient levels in the contaminated soil (Table 1), excessive EC, Na, and Cl concentrations inhibit vegetation growth. Soil EC and water-extractable Cl^- concentration were greater in the 0-15-cm compared to the 0-30-cm soil depth (Table 1). Since the hydraulic fracturing drilling fluid and flowback water were surface applied following natural gas extraction, mixing of the less contaminated 15-30-cm-depth soil (i.e., deep plow region) with the 0-15-cm-depth surface soil resulted in a dilution effect. Ahmad et al. (2012) and Hseu et al. (2010) recommended soil dilution for remediation of metal-contaminated surface soils.

All root properties increased (biomass, length, volume, and surface area) when bermudagrass was grown in the 0-30-cm-depth compared to the 0-15-cm-depth soil (Table 4). Increased root growth benefits vegetation by increasing drought stress tolerance, nutrient uptake, and vegetative growth (Brady and Weil, 2002). Ackerson and Youngner (1975), Adavi et al. (2006), and Dudeck et al. (1983) reported that increased root growth and decreased shoot growth allowed bermudagrass vegetation to tolerate the osmotic and ionic stresses associated with increasing soil salinity levels.

CONCLUSIONS

Based on the results of this study, the addition of the recommended plant nutrients enhanced bermudagrass growth. In addition, the mixing of the surface-applied hydraulic fracturing fluid with the 0-30-cm soil depth resulted in a dilution effect that decreased detrimental soil salinity concentrations. The results from this study can be used to develop an effective management strategy to establish vegetation in soil previously contaminated with hydraulic fracturing fluid and should include:

1. Plowing the soil to a depth of 30 cm to create a dilution effect caused by the mixing of the less contaminated, deep plow soil region with the 0-15-cm-depth surface soil since the hydraulic fracturing drilling fluid and flowback water were surface applied following natural gas extraction.
2. Applying inorganic fertilizer, broiler litter, or Milorganite® to the contaminated soil to provide adequate plant nutrients. In this study, the soil lacked optimal levels of N and P, but contained excessive levels of K. Organic amendments such as broiler litter and Milorganite® can utilize a waste product to provide similar plant nutrient concentrations as inorganic fertilizer.
3. Sprigging the contaminated soil with bermudagrass, a salt-tolerant plant.
4. Providing adequate moisture for plant growth.

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