Research article

Conservation management practices reduce non-point source pollution from grazed pastures[☆]

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ABSTRACT

Producers in Northwest Arkansas and globally need alternative management practices to ensure long-term sustainable and economical use of poultry litter, which is an abundant source of valuable carbon (C), nitrogen (N) and phosphorus (P). Project objectives were to measure the efficacy of conservation management practices (i.e., pasture aeration and subsurface litter incorporation) to reduce nutrient runoff compared to poultry litter surface applications from small watersheds under rainfed and grazed conditions. Watersheds (0.23 ha each) were assigned a treatment [pasture aeration, subsurface litter incorporation, or surface application of litter (positive control)] on a Leadvale (fine-silty, siliceous, thermic Typic Fragiudult) silt loam. Poultry litter was applied annually to each watershed from 2007-2012. Over the 4-yr study period, runoff loads of NO_3–N, total nitrogen (TN), soluble reactive phosphorus (SRP), and total phosphorus (TP) varied per conservation practice ($P \leq 0.05$). Specifically, average annual loads of NO_3–N, TN, SRP, and TP loads were reduced 49, 42, 28, and 35% following pasture aeration and by 78, 72, 55, and 59% from subsurface applying poultry litter, relative to surface applications, respectively. Greatest annual N loads and runoff corresponded with surface poultry litter applications, followed by pasture aeration, with subsurface incorporation of poultry litter resulting in lowest ($P \leq 0.05$) TN and NO_3–N loads. Overall, subsurface incorporation of poultry litter and pasture aeration are two promising conservation practices for reducing non-point source pollution in watersheds with nutrient imbalances. Further work needs to be done on factors influencing the efficacy of these conservation practices under rainfed conditions, as well as the economic feasibility of these conservation agricultural practices.

1. Introduction

Adverse water quality impacts due to runoff from perennial pastures have become an important concern, particularly in areas of the southeastern U.S. where producers have concentrated livestock operations with finite land for manure application (de Koff et al., 2011). Specifically, impairment of water systems from poultry litter applications on pastures in Northwest Arkansas has resulted in several ongoing lawsuits between Oklahoma and Arkansas (Sharpley, 2018). Producers in this area need alternative management practices to ensure long-term sustainable and economical use of this abundant source of valuable nitrogen (N) and phosphorus (P), especially in grasslands, which accounts for 46.8% of all agricultural lands in the US; the single largest land-use category of farmland (USDA-NASS, 2012). Since poultry litter (combination of bedding and manure) typically consists of approximately 3% N and 1.5% P, applications based on N crop needs can often lead to excessive application of P. Therefore, one of the greatest environmental challenges facing animal producers is excessive P runoff, leading to excessive algae growth (Schindler, 1977), that in turn leads to eutrophication of water bodies (DeLaune et al., 2004). Phosphorus runoff from animal manure has shown to be relatively high, even when manures are applied at recommended rates (Edwards and Daniel, 1993). In many areas of concentrated animal production, manure is most often surface applied, as it cannot be incorporated in perennial pastures via tillage as it would be in row crop systems. Therefore, subsurface application of poultry litter is a practical option in perennial pastures as minimal soil disturbance

occurs under this conservation practice, thus not adversely affecting root mass and soil loss (Pote et al., 2003, 2009). Poor incorporation poultry litter creates potential for surface runoff and ammonia volatilization. Consequently, and not surprisingly, many studies have shown runoff from fields receiving animal manure can have excessively high P concentrations (Edwards and Daniel, 1993; Shreve et al., 1995). Hence, research is needed on best management practices (BMPs), such as pasture aeration and applying litter in bands beneath the soil surface for their ability to reduce nutrient losses to the environment. Further, previous research on water quality impacts following subsurface banding of litter and pasture aeration has mainly been conducted under simulated rainfall (Pote et al., 2003; DeLaune and Sij, 2012; DeLaune et al., 2013; Sistani et al., 2010). Therefore, there is a need for evaluating nutrient runoff at the edge of field over multiple years following these conservation practices.

The hydrology of pasture systems plays an important role in the fate of nutrients. Pastures may become less permeable over time due to compaction from cattle and/or farm equipment, which can reduce infiltration rates, thus causing greater runoff volumes which leads to greater nutrient loads in runoff (Abdel-Magid et al., 1987). Accordingly, two potential BMPs that will be evaluated include pasture aeration and subsurface banding poultry litter.

The first, or pasture aerators (also known as renovators) are devices that either cut slits or punch holes in the soil surface using mechanical-disturbance with the goal of increasing forage production (Davies et al., 1989; Lemus, 2011; Vendramini and Silveria, 2009), reducing soil compaction (de Koff et al., 2011), and incorporating fertilizer, lime, or seed. Aerators can be of three types: coulters, which make narrow slits in the soil; rollers, with spikes or prongs that make indentations in the soil surface; and prongs (which are effectively mini-subsoilers) (Vendramini and Silveria, 2009). Pasture aeration has demonstrated to temporarily release organic matter and bound nutrients as a result of soil disturbance (Ingram et al., 2009). Pasture aeration can reportedly increase infiltration while also creating a rougher surface to reduce runoff (de Koff et al., 2011; Franklin et al., 2006, 2007). Additionally, aeration after litter application may promote greater soil contact and resultant adsorption to soil particles (Franklin et al., 2006).

An additional potential conservation practice that will be evaluated in this study is poultry litter incorporation using a piece of equipment referred to as the 'subsurfer'. The subsurfer applies litter in bands beneath the soil surface and is a tractor-drawn implement developed by the USDA-ARS (Pote et al., 2011). The implement injects ground poultry litter into the soil similar to conservation tillage and has been shown to reduce nutrient runoff compared to surface applications (Pote et al., 2003, 2009). The subsurface litter incorporator also reportedly decreases runoff and increases infiltration, while conserving nutrients for crops relative to surface-applied litter (Pote et al., 2009, 2011; Pote and Meisinger, 2014). Research also indicates that subsurface application decreases ammonia volatilization by 88–100% compared to conventional surface applications (Pote and Meisinger, 2014; Moore et al., 2011), which is important as ammonia loss can cause additional soil and water quality issues by decreasing the N:P ratio and accelerating P buildup (Marshall et al., 1998).

Research suggests pasture aeration and subsurface banding poultry litter are two promising BMPs for reducing nutrient runoff from pastures, while improving forage productivity (de Koff et al., 2011; Pote et al., 2003, 2009). Although, cattle grazing may negate beneficial effects by causing compaction, which leads to low soil permeability and reduced infiltration rates (Ludvikova et al., 2014). However, limited nutrient load data exists for these two BMPs under grazing conditions. Therefore, a long-term experiment to evaluate their efficacy compared to the 'business as usual practice' of surface applying poultry litter was conducted. The objective of this study was to compare long-term nutrient runoff volumes and loads following pasture aeration, subsurface litter incorporation, and poultry litter surface applications under rainfed and grazed conditions; as

well as, identify BMP impact on pasture hydrology and available forage yield.

2. Methods

2.1. Site description

The experiment was conducted at the USDA-ARS unit in Booneville, AR (35.08ºN -93.55ºW) from 2006-2012. This location is situated in the karst topography region Natural Resources Conservation Service (NRCS), Major Land Resource Area 118-A classified as the Arkansas Valley and Ridges, Eastern Part, in the Land Resource Region "N" (Soil Survey Staff, 2006). Three, 0.23 ha watersheds (each were the same size) were constructed and dominated by a Leadvale silt loam (fine-silty, siliceous, thermic Typic Fragiudult), with a slope <5%. Leadvale soils are classified as deep, moderately well-drained, slowly permeable soils with a 12–22% clay content in the upper 15-cm and a fragipan at 41–97 cm depth (Garner et al., 1980). The average annual rainfall is 121 cm, according to climatology data from 1971 to 2000 (NCDC, 2010), with the majority of precipitation occurring during spring (March–May) and fall (September–November) (Figure 1).

2.2. Experimental design and treatment applications

Watersheds treatments [pasture aeration, subsurface litter incorporation, and a surface application of litter (control)] were hydrologically isolated from surrounding land with earthern berms. The bottom of each watershed narrowed to a point containing a covered 30.5-cm H-series fiberglass flume equipped with a pressure transducer for measuring runoff volumes. The transducer was connected to a housed automatic water sampler (American Sigma Corporation; Ronkonkoma, NY), which was programmed to automatically collect 100 mL of sample for analysis from every 94.7 L of runoff. Flow rates were recorded and runoff was collected from samplers following each rainfall event. Loads per runoff event were calculated by multiplying nutrient concentrations x flow for each event. Annual nutrient runoff loads were calculated by summing the loads of individual events that occurred over each year. Background runoff data were collected in 2006 prior to treatment and manure application in order to evaluate hydrological differences.

Runoff samples were typically collected within 24 h (although on a few events within 48 h). Field sample carboys (Nalgene HDPE plastic) were washed between runoff events with tap water and a brush, followed by an acid rinse, then by several rinses with deionized water. Clean carboys then replaced ones containing samples in the field. Samples were not transferred to another container as they were transported at ambient temperature and processed immediately, which included: filtering soluble components, acidifying [0.45 um filters and concentrated HCl (one drop per every ten ml of sample)], and then frozen until analysis. When samples were analyzed, quality assurance included 10% (of all collected samples) duplicates for all analyses and 5% spiked samples.

Watersheds were dominated by tall fescue (*Festuca arundinacea* Schreb.) with lesser (approx. 30%) amounts of bermudagrass (*Cynodon dactylon* L.) and were continuously grazed by heifers throughout the year under rainfed conditions based on available forage (approximately 0.8 ha per animal). Each watershed was adjacent and cattle were independently allowed access to all watersheds throughout the year. During 2006, no treatments were applied in order to observe flow differences across watersheds post-berm construction. Soil samples were collected prior to the experimental initiation (April 12, 2006) and again annually between March 8 and April 15 from 2007-2012 (excluding 2008) at 0–10 and 0–15 cm depths. Soil samples (five cores which were composited by zone) were collected from three zones in each watershed at two depths (0–10 and 0–15 cm). Poultry litter was annually sampled prior to application. All data (poultry litter, soil, and runoff) during 2008 were excluded owing to equipment issues. Poultry litter was annually applied
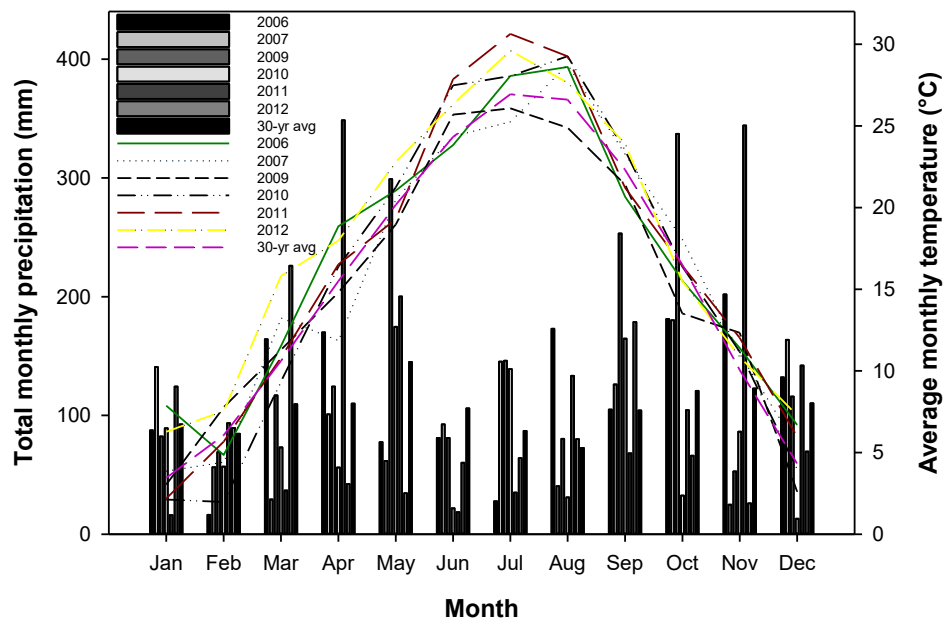
Figure 1. Total monthly precipitation (rain) and mean monthly air temperature (MT) from 2007-2012 at the USDA-ARS unit in Booneville, AR 30 yr avg. represent averages from 1981 to 2010. Weather data were taken at research centers and obtained from the U.S National Oceanic and Atmospheric Administration (NOAA).

during the spring to each watershed from 2007-2012, with minimal varying composition. Application rates ranged from 2.3-3.6 Mg ha^{-1} with all watersheds receiving the same volume of litter in a given year. The variability in application rate was due to the imprecise operation of the subsurfer. To compensate, the subsurface watershed was treated first. The amount of litter applied was determined and the same volume was then applied to the other two watersheds. The aerated and control treatments received surface poultry litter applications from 2007-2012. These two treatments (aeration and surface) received litter using a New Holland 7040 (NH7040) tractor equipped with a 00EPH BBI Endurance Hydraulic Spreader (Cornelia, GA). Following the surface application, the aeration watershed was aerated using an AerWay aerator (SAF Holland, Holland, MI). The aerator had tines (5° offset angle) that were 13 cm wide at the base and 20 cm long and cut slits perpendicular to the slope that were about 15 cm long and 10–15 cm deep. The aerator was operated using water ballast (~473 kg; de Koff et al., 2011). From 2007-2012, mechanized (internal auger system) subsurface poultry litter treatments were implemented by banding 5 cm wide and to an 8 cm depth in 76.2 cm rows, at the time of surface applications. The equipment used was a tractor drawn prototype and is further described by Pote et al. (2011). Briefly, four trench openers with a fluted coulter sliced the soil, followed by a double disk trench that covers injected litter with soil. This conservation tillage band technique minimizes soil disturbance and has the added benefit of pulverizing the poultry litter.

Available forage yields were determined (0.25 m^2) from three randomly collected locations in surface and aerated watersheds (top, middle, and bottom) and composited per treatment (control and aerated pasture treatments) to a 5-cm cutting height from cattle exclusion cages. Grab samples of biomass (1–2 kg) were collected from each watershed at harvest, weighed, dried at 55 °C in a batch oven (Wisconsin Oven Corporation, East Troy, WI) for 48–72 h, and re-weighed to determine moisture content. Harvests were collected at different periods during the initial year prior to the start of the study and during year one approximately monthly from May 2007 to April 2008.

2.3. Sample analysis

2.3.1. Soil sample analysis

Soil samples (0–10 and 0–15 cm) were analyzed for N, carbon (C), C:N, pH, and electrical conductivity (EC). Total N and total organic carbon (TOC) were determined by combustion using a Vario Max CN analyzer (Elementar Americas; Philadelphia, PA). Mehlich-3 (Mehlich, 1984) extractable As, Ca, Fe, K, Mg, Mn, Na, P and S were extracted using a 1:10 (soil:solution) ratio and measured by inductively coupled plasma optical emission spectroscopy (ICP-OES) on a Varian Vista-Pro ICP-OES (Agilent Technologies, Santa Clara, CA). Water soluble P (WSP) was measured on a subsample of the 1:10 (soil:water) sample extraction (Self-Davis and Moore, 2000) and analyzed colorimetrically by the Murphy and Riley (1962) method on a Skalar auto-analyzer (Skalar; Buford, GA). Electrical conductivity and pH were also measured on this extract. Soil samples were dried at 55 °C in a batch oven (Wisconsin Oven Corporation, East Troy, WI) for 48–72 h prior to analysis.

2.3.2. Litter sample analysis

A composite litter sample (six individual sub-samples total) was taken yearly during land application. Litter samples were analyzed (as is; fresh) for TN, TOC, nitrate (NO$_3$–N), ammonium (NH$_4$–N), soluble reactive P (SRP), TP, moisture, pH, and EC. Samples for NH$_4$–N, NO$_3$–N, SRP, pH and EC were extracted using a 1:10 sample/water ratio. Soluble reactive P was analyzed colorimetrically by the Murphy and Riley (1962) method on a Skalar auto-analyzer. Nitrate was analyzed by the Cd reduction method according to American Public Health Association Method 418-F (APHA, 1992), whereas NH$_4$–N was analyzed by the salicylate-nitroprusside USEPA Method 351.2 (USEPA, 1979). Litter pH and EC was measured on a subsample of the 1:10 (soil:water) sample extraction (Self-Davis and Moore, 2000). Total N and TOC in litter were determined by combustion using a Vario Max CN analyzer (Elementar Americas). Total P was analyzed by digesting 0.5 g oven-dried litter in concentrated nitric acid (HNO$_3$) and 30% hydrogen peroxide and

Table 1. Selected properties of poultry litter applied to watersheds from 2007 to 2012 (excluding 2008) at Booneville, AR.

Property	Year				
	2007	2009	2010	2011	2012
H_2O, %[†]	27.6	39.7	30.6	27.76	30.2
Total N, %	3.51	2.95	3.26	3.74	3.17
Total OC, %	23.5	26	26.4	27.7	27.4
NH_4–N, g kg^{-1}	2.62	3.88	5.78	3.84	4.08
NO_3–N, g kg^{-1}	0.29	-	0.02	1.61	1.62
pH	8.54	8.01	7.98	8.53	8.22
EC[‡], mS cm^{-1}	9.29	8.9	9.22	8.24	11.03
SRP, mg kg^{-1}[§]	1251	587	441	345	380
Total P, g kg^{-1}	10.82	8.14	10.59	12.26	11.90

[†] All properties are on an "as is" basis.

[‡] EC, electrical conductivity.

[§] SRP, soluble reactive phosphorus.

analyzed by ICP-OES using a Varian Vista-Pro ICP-OES (Method 3030E: APHA, 1992). Selected properties of poultry litter applied to watersheds from 2007 to 2012 are available in Table 1.

2.3.3. Water sample analysis

After rainfall events that resulted in runoff, every water sample was analyzed for TN, NO_3–N, NH_4–N, SRP, TP and TOC. For all runoff data, concentrations and loads are presented from 2007 to 2012. Runoff total N and TOC were determined with a Skalar TN-L (Shimadzu Corporation; Columbia, MD) on unfiltered samples (Pilon et al., 2018). Samples for NO_3–N, NH_4–N, and SRP were vacuum filtered through a 0.45-mm filter. Soluble reactive P was analyzed colorimetrically by the Murphy and Riley (1962) method on a Skalar auto-analyzer. Nitrate was analyzed by the Cd reduction method according to American Public Health Association Method 418-F (APHA, 1992), with NH_4–N being analyzed by the salicylate-nitroprusside USEPA Method 351.2 (USEPA, 1979). Total P in runoff was analyzed on unfiltered samples which were digested using concentrated HNO_3 and analyzed using a Varian Vista-Pro ICP-OES (Method 3030E: APHA, 1992).

2.4. Analysis of data and model development

Analysis of variance (ANOVA) tests of nutrient runoff loads (annual and per runoff event) were performed using the MIXED procedure of SAS (SAS V9.3; SAS Inst. Cary, NC) to determine load and concentration differences from best management practices compared to surface applied poultry litter. In this model, pasture management treatments (pasture aeration, subsurface litter incorporation, and a surface application of poultry litter) was considered a fixed effect, whereas year was considered a repeated measure. For the repeated measure, an autoregressive covariance was used and the denominator degrees of freedom for the

Type III F-test were adjusted with the Kenward-Roger method (Gomez et al., 2005). Considering, the -2 Loglikelihood changed under the repeated-measure analysis (dropped by at least 5 per covariance parameter) and the autoregressive correlation value (0.24) indicated a strong correlation among observations, thus the autoregressive covariance was used. For all models, ANOVA assumptions of normally-distributed residuals (Shapiro-Wilk test) and homogeneity of variances (Levene's F-test) were confirmed. When effects or interaction confluences were found, mean separations were performed using the SAS macro 'pdmix800' (Saxton, 1998) with Fisher's least significant difference (LSD) at a Type I error rate of 5% (SAS, 2007).

An additional model was run on the soil parameters (pH, C, N, C:N, EC, As, Ca, Fe, K, Mg, Mn, Na, P, S, and WSP) at 0–10 and 0–15 cm depths to evaluate conservation management practice influence on soil chemical levels. Pasture management treatments were the whole block, with the split-block being the sampling depth (fixed effects), with year and replication being random effects. Mean separation and significance levels were handled the same as the initial ANOVA model described above.

3. Results and discussion

3.1. Long-term soil nutrient status following best management practices of poultry litter handling

Across years, soil C, N, C:N, EC, As, Ca, Fe, K, Mg, Na, P, S, and WSP differed by sampling depth, with only soil pH, P, S, and WSP varying by pasture management ($P < 0.05$; Table 2). No pasture management treatment x sampling depth interaction existed for any soil parameter ($P \geq 0.05$). Overall, all parameters were affected by sampling depth, with greater ($P \leq 0.05$) nutrient and EC levels in the upper sampling depth (0–10 cm) relative to the deeper depth (0–15 cm). Pasture aeration

Table 2. Mehlich-III extractable elements and soil properties at the 0–10 and 0–15 cm depths and per conservation pasture management from 2007-2012 (excluding 2008 data) at the USDA-ARS unit at Booneville, AR, as both main effects were significant, although there was no pasture management x soil depth interaction ($P \geq 0.05$).

	pH	C	N	C:N	EC[‡]	As	Ca	Fe	K	Mg	Mn	Na	P	S	WSP
		%[‡]				mS cm^{-1}	mg kg^{-1}									
Pasture management															
Aeration	5.8 b[§]	2.27 b	0.25 a	9.18 a	57.96 a	0.09 a	942 a	127 a	138 a	90.3 a	176 b	215 a	89.9 a	13.5 a	9.9 a
Subsurface	6.05 a	2.29 a	0.25 a	9.2 a	50.2 a	0.1 a	998 a	135 a	145 a	89.5 a	195 a	221 a	84.9 a	11.7 b	9.4 a
Surface application	5.97 a	2.16 a	0.24 a	9.13 a	54.85 a	0.09 a	971 a	131 a	135 a	93.1 a	167 b	210 a	72.0 b	12.1 b	7.5 b
Soil depth															
0–10 cm	5.94 a	2.56 a	0.27 a	9.43 a	60.93 a	0.1 a	1084 a	140 a	151 a	102 a	179 a	233 a	91.9 a	13.7 a	10.4 a
0–15 cm	5.94 a	1.92 a	0.22 b	8.91 b	47.75 b	0.09 b	857 b	123 b	128 b	79.7 b	179 a	197 b	72.6 b	11.2 b	7.5 b

[‡] EC, electrical conductivity; WSP, water-soluble phosphorus.

[§] Different letters within treatment level (pasture management or soil depth) indicate a significant difference at a P-value of 0.05.

Table 3. Analysis of variance of runoff nutrient loads and concentrations (NO$_3$–N, NH$_4$–N, TN, TP, SRP, TSS, and TOC) by year from 2007-2012 (excluding 2008 data) at the USDA-ARS unit at Booneville, AR.

Effect		Den DF	F-Value	Pr > F
NO$_3$-C[†]				
Treatment	2	118	5.76	0.0041
Year	4	106	23.35	<0.0001
Treatment*Year	8	106	1.77	0.0905
NO$_3$-L				
Treatment	2	106	6.25	0.003
Year	4	106	9.55	<0.0001
Treatment*Year	8	106	2.02	0.0512
NH$_4$–N –C				
Treatment	2	120	0.15	0.8619
Year	4	108	4.41	0.0024
Treatment*Year	8	108	0.75	0.6459
NH$_4$–N -L				
Treatment	2	120	1.04	0.3569
Year	4	108	5.82	0.0003
Treatment*Year	8	108	0.81	0.5976
TN-C[¶]				
Treatment	2	107	5.57	0.005
Year	4	107	20.42	<0.0001
Treatment*Year	8	107	1.24	0.2814
TN-L				
Treatment	2	107	6.12	0.0034
Year	4	107	11.58	<0.0001
Treatment*Year	8	107	2.27	0.0279
TP-C				
Treatment	2	106	3.48	0.0345
Year	4	106	11.98	<.0001
Treatment*Year	8	106	0.45	0.8892
TP-L				
Treatment	2	105	6.63	0.0022
Year	4	105	9.08	<0.0001
Treatment*Year	8	105	0.92	0.5053
SRP-C				
Treatment	2	111	4.05	0.0201
Year	4	111	10.14	<0.0001
Treatment*Year	8	111	1.19	0.3136
SRP-L				
Treatment	2	111	7.23	0.0013
Year	4	111	6.79	<0.0001
Treatment*Year	8	111	0.66	0.7244
TSS				
Treatment	2	105	0.02	0.9758
Year	4	105	4.98	0.001
Treatment*Year	8	105	1.78	0.0885
TOC				
Treatment	2	107	2.38	0.0977
Year	4	107	2.77	0.0309
Treatment*Year	8	107	0.64	0.743

[†] C = concentration (mg L^{-1}); L = Load (kg ha^{-1}).

[¶] TN = total nitrogen; TP = total phosphorus; SRP = soluble reactive phosphorus; TSS = total suspended solids; TOC = total organic carbon.

reduced ($P \leq 0.05$) soil pH and increased soil S relative to surface and subsurface applications, whereas subsurface poultry litter applications increased Mn. In addition, surface applications resulted in the lowest soil Mehlich III P and WSP levels relative to conservation pasture management practices (Table 2). When litter is land applied without incorporation, P can be transported in runoff (Kulesza et al., 2014). Based on

Mehlich III P and WSP data, both conservation management practices (subsurface applications of poultry litter and aeration) resulted in increased soil Mehlich III P retention relative to 'business as usual' or surface poultry litter applications. Similarly, these practices likely minimized soil N losses, although if rainfall did not occur immediately following litter application, more of the NH$_4$–N fraction may have volatilized as NH$_3$ to the atmosphere.

3.2. Baseline flow of constructed watersheds

Total background runoff volumes for the year prior to aeration and manure application (2006) averaged 100,694, 111,496, and 97,882 L ha^{-1} for pasture aeration, subsurface applications, and surface application treatments, respectively. There were no differences in baseline flow for each watershed ($P = 0.13$); suggesting there was no variation in constructed watershed surface flow. However, there were annual flow differences, which corresponded to precipitation (Figure 1). In general, greatest flow occurred in 2011 (351,505 L ha^{-1}), with lowest runoff being observed in 2010 (90,890 L ha^{-1}).

3.3. Impacts of conservation pasture management practices on runoff water quality

Runoff concentrations of NO$_3$–N, TN, SRP, and TP varied based on management over the 4-year collection period ($P \leq 0.05$; Table 3). Due to the importance of nutrient loads across agricultural landscapes for identifying conservation practices, this paper will primarily focus on average runoff loads rather than runoff nutrient concentrations. Overall, the number of runoff water samples was 22, 56, 9, 27, and 39 for the three watersheds for 2007, 2009, 2010, 2011, and 2012, respectively, which corresponded to 8, 20, 3, 10, and 14 events. During year 1 (2006) baseline NO$_3$–N, TN, SRP, and TP loads for the surface poultry litter watershed were 1.13, 1.71, 0.4 and 0.45 kg ha^{-1}, respectively. Baseline NO$_3$–N, TN, SRP, and TP loads for the sub-surface litter watershed were 1.05, 1.47, 0.52, and 0.53 kg ha^{-1}, respectively. Lastly, the watershed receiving pasture aeration had 0.98, 1.78, 0.41, and 0.46 kg ha^{-1} NO$_3$–N, TN, SRP, and TP baseline loads, respectively. Therefore, baseline nutrient loads were similar among watersheds.

Averaged across 4-yrs of best management implementation under grazing conditions, loads per runoff event for NO$_3$–N, TN, SRP, TP, and flow varied per conservation management treatment ($P \leq 0.05$; Table 3). Overall, pasture aeration and subsurface applications of poultry litter into bands was effective ($P \leq 0.05$) at reducing NO$_3$–N, TN, TP, and runoff flow per event. Specifically, NO$_3$–N, TN, SRP, TP were reduced by 51, 46, 28, and 34% following pasture aeration and 81, 74, 58, 61% following subsurface incorporations of poultry litter, relative to surface poultry litter applications, respectively (Figure 2). Runoff volume per event was also reduced ($P \leq 0.05$) by the two conservation practices (by 42 and 43% for pasture aeration and the subsurface litter application, respectively). Authors hypothesized that enhanced infiltration under aeration (reduced runoff volumes) would be curtailed by compaction from cattle grazing; however, this was not observed during the study period. Similarly, previous research by Pote et al. (2003) evaluated impacts of incorporating dry poultry litter into pasturelands and reported minimized disturbance of the soil structure, forage crop, and thatch by using a knifing technique to incorporate poultry litter. This study also found that nutrient concentrations and losses were 80–95% less than when litter was surface applied. Further research is needed to identify how long the benefits of pasture aeration should be expected under both grazing and hay systems.

In addition, subsurface poultry litter applications reduced ($P \leq 0.05$) SRP loads per runoff event relative to surface applications of poultry litter, which was not different from the pasture aeration treatment averaged over 4-yrs ($P \geq 0.05$; Figure 2). Similarly, average runoff loads of NH$_4$–N, TSS, EC, TOC, and pH under surface application of poultry litter did not differ ($P \geq 0.05$) from either conservation management
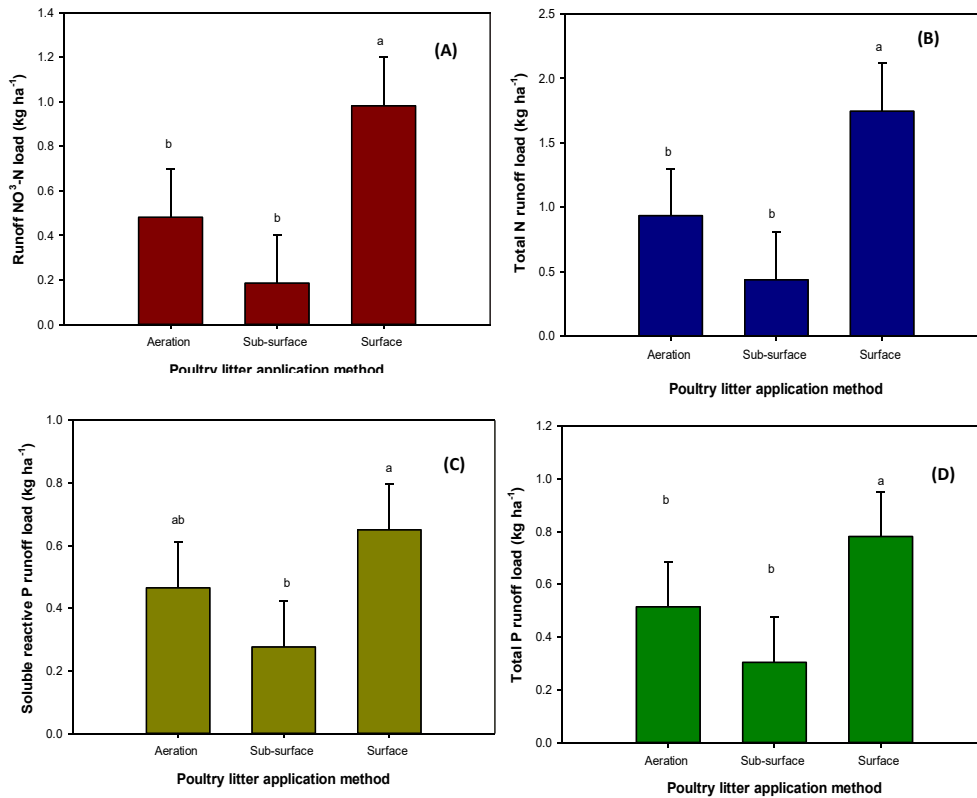
Figure 2. Average nutrient loads per runoff event for NO_3–N (A), total N (B), soluble reactive P (C), and total P (D) based on poultry litter management from 2007-2012 at the USDA-ARS unit in Booneville, AR. Different letters indicate a significant difference (per N or P fraction) at an a level of 0.05.

Table 4. Annual accumulative total runoff, total P (TP) load, soluble reactive P (SRP) load, total annual loads of N (TN), NH_4–N load, and NO_3–N load per conservation pasture management treatments at Booneville, AR from 2007 to 2012.

|	Runoff	TN	NH_4–N	NO_3–N		TP	SRP
	cm	kg ha^{-1}					
Treatment	2007						
Aeration	8.2	2.26	0.21	0.65		1.45	1.15
Subsurface	7.3	1.73	0.38	0.77		1.22	0.96
Surface application	6.7	2.51	0.29	1.08		1.57	1.43
	2009						
Aeration	21.3	5.67	0.95	2.04		5.59	5.87
Subsurface	24.8	4.61	1.12	1.35		3.29	2.98
Surface application	25.1	6.07	1.43	2.59		4.51	5.46
	2010						
Aeration	1.4	1.13	0.21	0.40		0.77	0.76
Subsurface	2.3	1.07	0.21	0.39		0.87	0.74
Surface application	2.5	2.73	0.35	0.88		1.49	1.47
	2011						
Aeration	25.0	27.58	6.01	15.07		13.17	11.76
Subsurface	20.6	10.71	1.89	5.08		7.67	7.14
Surface application	51.4	49.19	6.14	29.12		21.94	17.69
	2012						
Aeration	6.3	5.01	1.16	2.64		1.29	1.11
Subsurface	4.2	2.53	0.92	1.33		0.80	1.11
Surface application	15.8	12.05	1.95	6.74		3.06	2.72
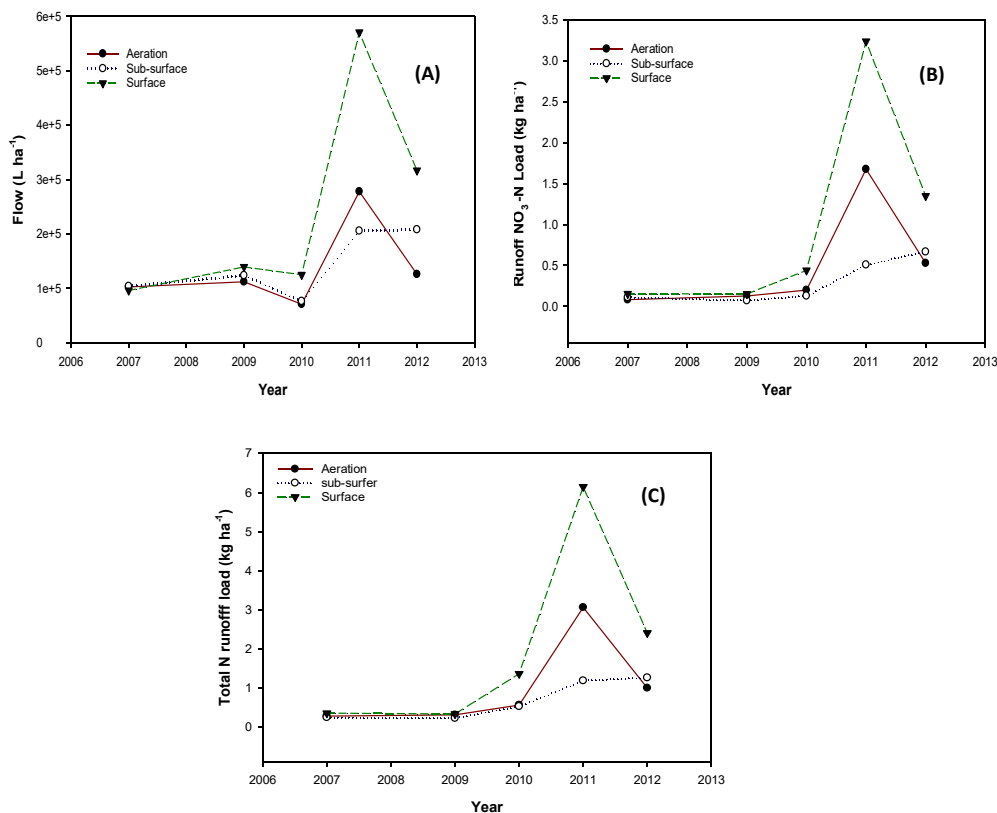
Figure 3. Annual (2007–2012) runoff flow (A), nutrient runoff loads for NO_3–N (B), and total N (C), based on poultry litter management from 2007-2012 at the USDA-ARS unit in Booneville, AR. Parameters are presented that had a significant ($P \leq 0.05$) year x treatment effect.

Table 5. Forage yield for individual and total harvest for Year 0 and Year 1 of pasture aerated and non-aerated (surface applied poultry litter, control) watersheds.

| | Surface applied | Aerated |
	kg DM ha^{-1}	
Year 0		
07/18/2006	7677	11790
08/30/2006	2221	2079
09/26/2006	1907	1746
11/04/2006	1050	1537
01/30/2007	768	902
03/02/2007	1345	1228
04/05/2007	3961	3907
Total	18,929	23,189
Year 1		
05/16/2007	8647	11308
06/06/2007	2579	4189
07/06/2007	3565	4071
08/01/2007	1356	2521
08/30/2007	1874	2146
10/02/2007	2434	3885
01/10/2008	922	877
02/13/2008	495	507
04/21/2008	4153	4296
Total	26,027	33,799

practice (Table 3). One explanation is that nutrient runoff benefits of aeration may be shorter lived than other conservation practices. Considering de Koff et al. (2011) found that regardless of the presence of cattle, poultry litter, or the amount of rainfall, effects of aeration were lost by 3 months following aeration. Nonetheless, several studies have found that subsurface litter incorporation and pasture aeration have a strong tendency to improve yield likely as a result of reductions in ammonia volatilization (Pote et al., 2003, 2011; Burgess et al., 2000). These results differ to that of Lamba et al. (2014), which found there was no differences in PO_4–P concentration in leachate between surface and subsurface banding of poultry litter.

When evaluating annual cumulative runoff loads per pasture management system, total runoff was greatest in 2009 and 2011, which corresponded with greater cumulative loads of TP, SRP, and TN and lowest runoff and corresponding loads in 2010 (Table 4). Overall, aeration reduced accumulated runoff, TP, SRP, TN, NH$_4$–N, and NO$_3$–N by 39, 35, 28, 42, 16, and 48%, respectively, across the 4-year study period. Overall greater reductions occurred during subsurface litter incorporation; therefore, average total cumulative runoff, TP, SRP, TN, NH$_4$–N, and NO$_3$–N decreased 42, 59, 55, 72, 55, and 78%, respectively, compared to surface applications of poultry litter (Table 4). Therefore, in general, subsurface applications of poultry litter tended to result in improved water quality compared to pasture aeration. Similarly, Sistani et al. (2010) found that subsurface banding broiler litter in grasslands substantially reduces nutrient and pathogen losses in runoff compared to surface applications in a rainfall simulation study, with TP averaging 6.5 times greater under the surface application treatment. Further work needs to be done to identify factors influencing the efficacy of this BMP under rainfed conditions.

Annual loads of NO$_3$–N, NH$_4$–N, TN, SRP, TP, and overall flow varied ($P \leq 0.05$) per year, with only NO$_3$–N, TN, and flow having a treatment x year effect ($P \leq 0.05$). Specifically, across all years and treatments, 2011 had greatest loads of N fractions (total and NO$_3$–N), as well as (and not surprisingly) overall runoff (Figure 3). Across years, 2011 had greater than average (30-year normal) precipitation during April (>234 mm), May (>64 mm), and August (>69.34 mm; Figure 1). Greatest N loads and runoff across the study period corresponded with surface poultry litter applications, followed by pasture aeration, and subsurface applications (Figure 3). Overall, subsurface applications of poultry litter resulted in lowest TN and NO$_3$–N loads (Figure 3). In addition, the efficacy of these conservation management practices can be obscured in low flow years and should be taken into consideration. Greater losses associated with N, rather than P are likely owing to the more water-soluble nature of this element. However, results provide evidence that long-term nutrient losses associated from surface poultry litter applications can be reduced through subsurface applications and to some extent pasture aeration for conserving water quality. Further research is needed on the economic feasibility of these practices.

3.4. Ancillary benefits of conservation pasture management

An auxiliary benefit of pasture aeration is reportedly increased forage production, owing to greater water and nutrient storage for plant uptake and removal (Self-Davis and Moore, 2000; Vallentine, 1991). Annual forage yield from the year following application was 46% greater than the initial year for the aerated watershed (33,799 kg ha^{-1} vs. 23,189 kg ha^{-1}) and 37% greater for the non-aerated watershed (26,027 kg ha^{-1} vs. 18,929 kg ha^{-1}; Table 5). Overall, pasture aeration produced 23% greater total annual yields than the non-aerated watershed. Though grazing cows or poultry litter deposition may have closed the slits made by the aerator, aeration still improved forage growth by breaking up layers of compaction. These results are similar to those observed by Davies et al. (1989) where aerated grazed plots produced dry matter yield increases of 33–120% compared to non-aerated grazed plots. Conversely, other work has observed little to no effect of pasture aeration on yields (Burgess et al., 2000; de Koff et al., 2011).

4. Conclusions

This work compares conservation management practices that improve nutrient retention and reduce non-point source pollution of poultry litter amended pastures. Over the 4-yr study period, despite the presence of cattle, pasture aeration, and overall subsurface poultry litter applications were effective practices for reducing NO$_3$–N, TN, TP, and runoff flow. Specifically, average annual loads of NO$_3$–N, TN, SRP, and TP loads were reduced 49, 42, 28, and 35% following pasture aeration and by 78, 72, 55, and 59% from subsurface applying poultry litter, relative to surface applications, respectively. Therefore, pasture aeration and subsurface applications of poultry litter may be beneficial in the management of pasture soils by enhancing water and P storage, thereby reducing runoff and nutrient losses, especially when high manure application rates are utilized. Further evaluations of factors (e.g., management; grazing vs. hay systems) affecting pasture aeration and subsurface poultry litter incorporation efficacy, as well as their attenuation (e.g., how long after pasture aeration is infiltration improved) are needed, which is essential before having these innovative approaches listed as NRCS Environmental Quality Improvement Program (EQIP) practices.

Declarations

Author contribution statement

Amanda J. Ashworth: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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