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Edge-of-Field Runoff Analysis following Grazing and Silvicultural Best Management Practices in Northeast Texas

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Abstract: Landowners and natural resource agencies are seeking to better understand the benefits of best management practices (BMPs) for addressing water quality issues. Using edge-of-field and edge-of-farm runoff analysis, we compared runoff volumes and water quality between small watersheds where BMPs (e.g., prescribed grazing, silvicultural practices) were implemented and control watersheds managed using conventional practices (i.e., continuous grazing, natural forest revegetation). Flow-weighted samples, collected over a 2-year period using automated samplers, were analyzed for nitrate/nitrite nitrogen (NNN), total Kjeldahl nitrogen (TKN), total phosphorus (P), ortho-phosphate phosphorous (OP), total suspended solids (TSS), and *Escherichia coli* (*E. coli*). Comparison of silvicultural planting to conventional reforestation practices showed a significant decrease in NNN loads ($p < 0.05$) but no significant differences in TKN, P, OP, TSS, or *E. coli*. Continuously grazed sites yielded >24% more runoff than sites that were under prescribed grazing regimes, despite receiving less total rainfall. Likewise, NNN, TSS, and TKN loadings were significantly lower under prescribed grazing management than on conventionally grazed sites ($p < 0.05$). Data suggests that grazing BMPs can be an effective tool for rapidly improving water quality. However, silvicultural BMPs require more time (i.e., >2 years) to establish and achieve detectable improvements.

Keywords: conservation; sediment; nutrients; *E. coli*; non-point source; water quality

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1. Introduction

Despite decades of remediation efforts since the adoption of the Clean Water Act in the United States (US), nonpoint source (NPS) pollution remains a substantial challenge and contributor to surface water quality impairments [1–3]. NPS runoff is a major source of nutrient loading, leading to eutrophication and oxygen depletion in downstream waterbodies [3–5]. NPS runoff can also transport fecal indicator bacteria and pathogens, leading to recreational impairments [6]. Collectively, pathogens, nutrients, organic enrichment/oxygen depletion, and sediment/turbidity account for 49% of Clean Water Act Section 303(d) impairments in the US and 69% in the state of Texas [1,7].

Surface water quality has been shown to often be related to land use and land cover within a watershed [8–11]. Topsoil and nutrient losses can have detrimental effects on soil productivity, agricultural performance [12,13], economic gains [14], and water quality [15–17]. Additionally, the nonpoint source transport of fecal material and potential associated pathogens is a concern for recreational safety [18,19]. In many states like Texas, private agricultural and silvicultural working lands make up the vast majority of the total land area, providing for significant economic, environmental, and recreational applications [20]. Thus, it stands to reason that farmers, ranchers, and other agricultural producers (e.g., forestry operations) are most often looked to for conservation improvement projects to reduce nutrient, sediment, and bacterial NPS pollutant loadings from working lands [21].

While the benefits of using sound management practices on working lands are generally well studied, grazing best management practice (BMP) research has primarily been concentrated in the US Midwest and western states [22]. Of the existing research, only a small percentage focuses on practices recommended by the Natural Resources Conservation Service (NRCS) [23,24]. The effects of grazing management practices in the south-central US on nearby surface water quality are similarly not well documented. Likewise, the effectiveness of silvicultural BMP has been extensively studied in the southeastern and western US but is lacking in the southcentral region of northeast Texas [25–27]. Furthermore, variability among study findings frequently results from site-specific climatic, cultural, and prior land use conditions that influence water quality [28,29].

To determine the water quality benefits of implemented BMPs, a robust water quality monitoring regime was implemented that assessed the field and farm-level changes in pollutant concentrations and loadings realized through the implementation of NRCS-recommended BMPs. We hypothesized that implementing the recommended BMPs would improve runoff water quality. Specifically, we sought to evaluate prescribed grazing and silvicultural BMPs and assess their benefits in comparison to conventional practices—i.e., continuous grazing and natural revegetation following timber harvest, respectively.

2. Materials and Methods

2.1. Site Description

Lake O' the Pines, located in the Piney Woods of northeast Texas (Figure 1), was created by the US Army Corps of Engineers in 1959 under authorization of the Flood Control Act of 1946 to primarily provide flood mitigation for the city of Jefferson [30,31] via the impoundment of Big Cypress Bayou. The lake also serves as a raw water supply for local power plants and industry and as a potable drinking water source managed by the North East Texas Municipal Water District [32]. The lake receives runoff from 2200 km^2 of largely rural and agriculturally dominated land.

In the early 2000s, water quality monitoring data began to reveal depressed dissolved oxygen concentrations [33]. Simulation modeling of the watershed suggested that nutrient loading from point and nonpoint sources was responsible for the dissolved oxygen decline [33]. The Texas Commission on Environmental Quality subsequently developed a Total Maximum Daily Load (TMDL) as well as a TMDL implementation plan (I-Plan) for the watershed [33,34]. As a result, the Lake 'O the Pines watershed was recommended and approved for participation in the NRCS National Water Quality Initiative (NWQI). Through the NWQI, the NRCS offered financial and technical assistance to farmers, ranchers, and forest landowners interested in improving water quality and aquatic habitats in priority watersheds. Qualifying producers received assistance for installing conservation practices aimed at reducing nutrient, sediment, and manure runoff from private working lands [35,36].

Historically, agriculture and silviculture have been mainstays in the watershed. The mixture of hardwood and pine forests common in the area provided timber resources for early settlers who began clearing land for crops and pastures. Commercial forestry remains prevalent today, with numerous pine plantations covering the countryside. Cotton production that was common in the late 1800s gave way to cattle production, dairies, and poultry production. Dairies have largely left the watershed, leaving poultry and cattle production as the primary agricultural enterprises. The watershed was once home to the poultry producer Pilgrim's Pride Corporation until 2011. Poultry production remains prominent in the watershed and is a considerable source of land-applied nutrient amendments, especially phosphorus. The over-application of poultry litter to meet nitrogen needs is considered the primary source of excess phosphorus now present in Lake O' the Pines. Application practices have been revised to now meet crop phosphorus needs and prevent overapplication, but excess phosphorus remains in the soil in many locations [33,34].

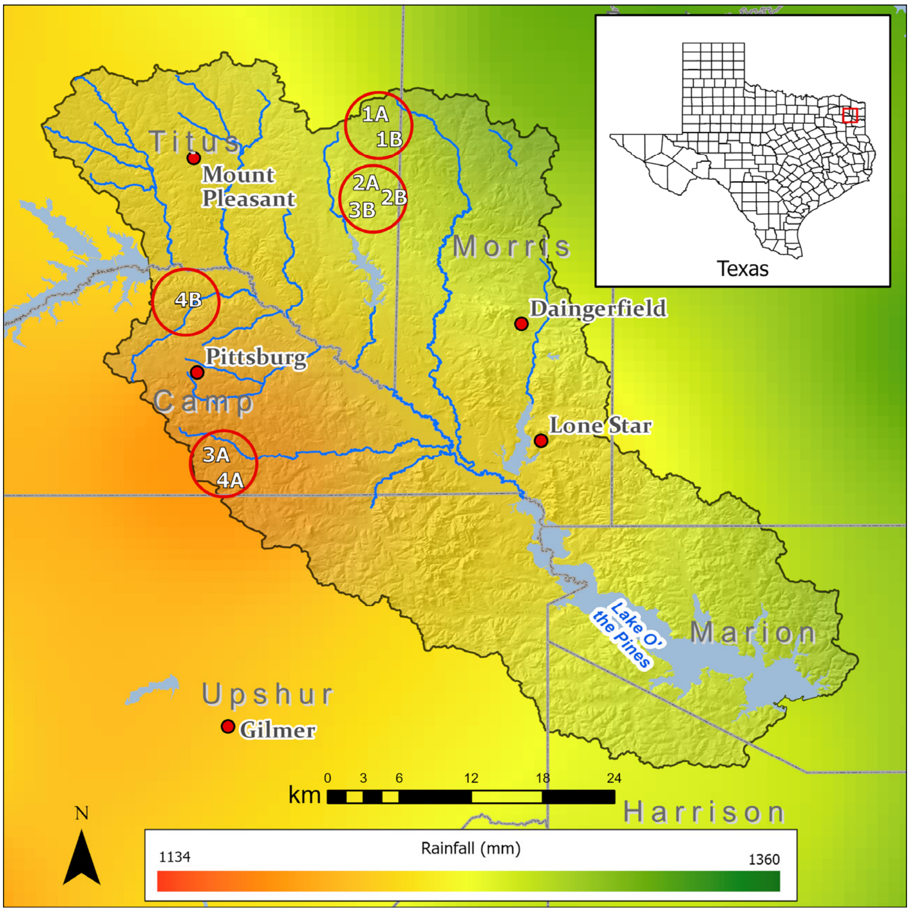

Figure 1. Lake O' the Pines watershed study area in northeast Texas, USA. Due to confidentiality agreements with landowners, the red circles with site numbers (Table 1) show approximate locations of edge-of-field and edge-of-farm sites with 30-year average rainfall (mm).

Table 1. Study sites, location, management practices, area (hectares), collection dates, and total number of runoff events. USDA Natural Resources Conservation Service conservation practice numbers are listed in parentheses.

Site	Type	Management Practices	ha	Slope (%)	Data Collection Period	No. of Events
1A	Field	Cover crop (#340), prescribed grazing (#528), nutrient management (#590), waste application	0.4	3.03	February 2016–January 2018	18
2A	Field	Forest planting (#381), prescribed grazing (#528), nutrient management (#590)	0.88	5.13	February 2016–January 2018	5
3A	Field	Control: natural forest revegetation only	0.33	4.92	February 2016–January 2018	12
4A	Field	Forest planting (#381), forest stand improvement (#666)	0.23	4.41	February 2016–January 2018	8
1B	Farm	Cover crop (#340), prescribed grazing (#528), nutrient management (#590), waste application	1.85	2.76	February 2016–January 2018	18
2B	Farm	Cover crop (#340), prescribed grazing management (#528)	3.78	2.53	February 2016–January 2018	12
3B	Farm	Cover crop (#340), prescribed grazing management (#528)	1.87	3.50	February 2016–January 2018	21
4B	Farm	Control: continuous grazing, periodic fertilizer application	1.18	6.71	February 2016–January 2018	24

The monitoring program for this study was established on multiple private properties practicing BMP implementation recommendations through the NRCS NWQI program in the Lake O' the Pines watershed (Figure 1). The mean annual precipitation for the area varies on a gradient from west (1134 mm) to east (1360 mm) (Figure 1) and is largely well dispersed throughout the year [37–39]. Summers are typically hot and humid, and winters are mild and cool [39]. Watershed elevation varies from 61 m to 187 m above the mean sea level [39,40]. Soils are derived from the Sabine Uplift and are predominantly sandy in nature, with more than 90% of the total area consisting of sandy or sandy loam soils [39–42].

2.2. Site Preparation

BMP implementation in this study followed NRCS Field Office Technical Guide [43] specifications and included the following: prescribed grazing (NRCS conservation practice #528); nutrient management (#590); cover crops (#340); silvopasture (#381); and forest stand improvement (#666). Treatments were based upon the management objectives of the landowner and recommendations from the NRCS. All treatments have the shared goals of reducing runoff and erosion and improving water quality [43]. Prescribed grazing is designed to improve or maintain vegetative cover and species compositions supportive of grazing, protect riparian areas, improve connectivity of wildlife habitats, and manage fine fuel loads for wildfire control [43]. Prescribed grazing therefore allows for the controlled harvest of vegetation while allowing the landowner to meet additional management objectives. Nutrient management involves the development of a management plan to control the application and runoff of nitrogen, potassium, and phosphorous on landscapes. Nutrient management plans include soil testing to prevent over-application of nutrients, timing of application to maximize absorption, and encouraging conservation practices that minimize runoff (e.g., vegetated filter strips) [43]. Cover cropping involves the planting of grasses, forbs, or leguminous species to provide seasonal vegetative cover for grazing, protection of the soil surface, and suppression of weedy species [43]. Finally, silvopasture involves the establishment of trees or shrubs and grazeable forage species on the same site, while forest stand improvement is the manipulation or maintenance of species composition through the selective control of unwanted species [43]. Control sites included continuous grazing (i.e., the status quo) and natural forest revegetation. In total, four edge-of-field and four edge-of-farm monitoring stations were established (Figures 1 and 2, Table 1).

Grazing BMPs required the landowners to implement grazing and nutrient management plans. Several grazed pastures also had winter cover crops planted to support winter grazing. Nutrient management included conducting soil testing to prevent the over-application of fertilizers and reducing runoff by practicing the Four R's of nutrient stewardship: "applying the right nutrient at the right rate, at the right time, in the right place" [43]. Nutrient application rates were developed for each property based on the individual producer's forage production goals.

Prior to the implementation of silvicultural treatments, each property (control and BMPs) was clear-cut and subject to the standard forest site preparation practices of root plowing and stacking debris in windrows. In the treatment plots, pine plantations were established via machine planting, and competing vegetation was chemically treated to minimize competition with planted trees during the first growing season.

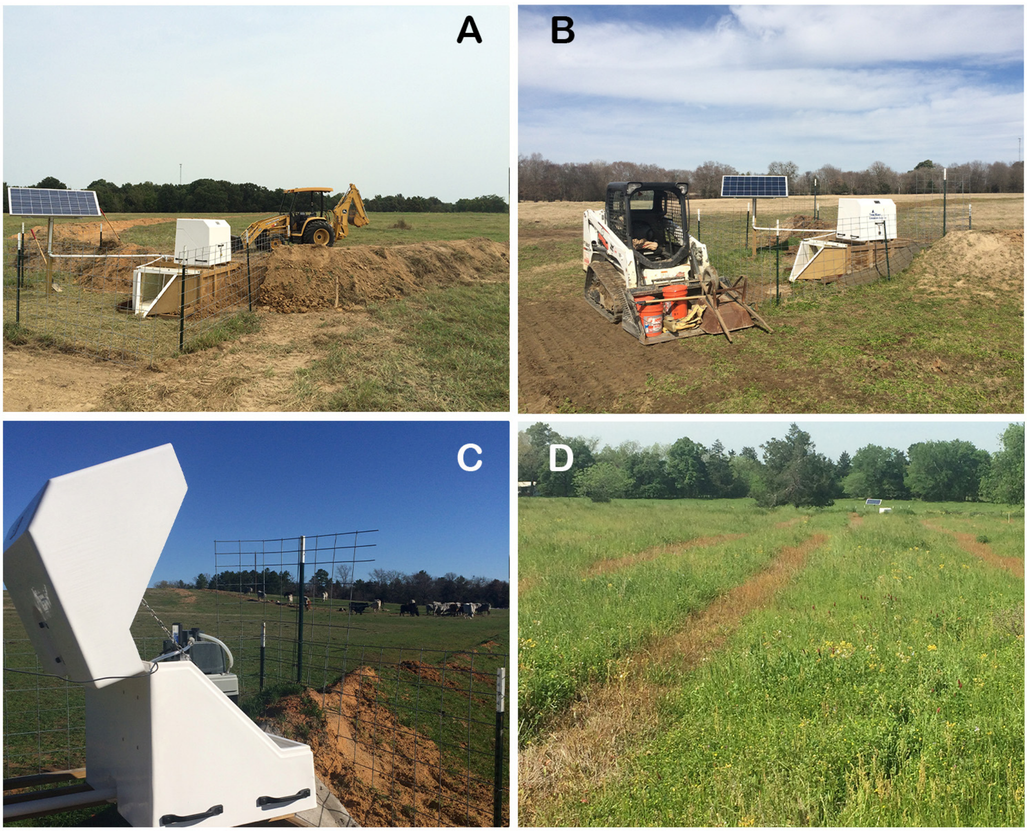

Figure 2. Autosampler deployment used in this study. Berm construction (**A**) and maintenance (**B**) on a farm-scale site; autosampler maintenance (**C**) on a continuous grazing site; and field-scale silvopasture planting (**D**) with seedlings planted in rows.

2.3. Sample Collection

Monitoring methods consisted of edge-of-field (single drainage) and edge-of-farm (multiple drainage) sampling implemented to quantify BMP influence on NPS pollutant loading. Earthen berms were constructed along the downslope edges of sites to route overland flow through 0.3 and 0.61 m H flumes on the field and farm plots, respectively (Figure 2). H flumes were equipped with Teledyne ISCO 730 bubbler flow modules to provide a stage-discharge relationship for flow rate measurement. Teledyne ISCO Avalanche refrigerated samplers were installed to automatically collect composite water quality samples and to measure and store flow rate at each site. An automated tipping bucket rain gauge was connected to an avalanche sampler on each property to measure precipitation.

Runoff volume and flow-weighted water quality samples were collected from natural storm events at each edge-of-field and farm site. Automated samplers were programmed according to the manufacturer's specifications to initiate sample collection once water levels were $\geq$1.194 mm above zero. Once enabled, the sampler rinsed the sampling tubing with ambient water prior to sample collection. Defined, pre-programmed flow intervals developed to collect each 1.32 mm of runoff over the plot area defined the sampling intervals. At each sampling interval, 200 mL of samples were composited into 20 L bottles, cooled to 3° $\pm$ 1° C, and held at that temperature until retrieval. Sampling continued at the defined volumetric interval until the water level in the H-flume dropped below the 1.194 mm threshold. Samples were retrieved and delivered to the laboratory within 24 h of sample initiation.

2.4. Sample Handling and Lab Analysis

After automated sample collection, samples were prepared in the field by capping 20 L sampling bottles, shaking them vigorously to resuspend water constituents, and then pouring out subsamples into appropriately preserved sterile plastic sample bottles provided by a National Environmental Laboratory Accreditation Program (NELAP)-certified laboratory (Table 2).

Table 2. Sample storage, preservation, and handling requirements for monitored parameters. Holding time begins when the automated sampler takes the first sample.

Parameter	Preservation	Sample Volume	Holding Time
Total Phosphorus	H_2SO_4 at 4 °C	150 mL	28 days
Nitrate/Nitrite Nitrogen	H_2SO_4 at 4 °C	150 mL	28 days
Total Kjeldahl Nitrogen	H_2SO_4 at 4 °C	200 mL	28 days
Escherichia coli	<6 °C	100 mL	24 h
Ortho-Phosphate	4 °C	150 mL	28 days
Total Suspended Solids	4 °C	250 mL	7 days

Bottles were labeled with event information, filled, sealed, and transported in ice to the laboratory for analysis. Constituents of concern included: total phosphorous (TP); orthophosphate (OP); nitrate/nitrite nitrogen (NNN); total Kjeldahl nitrogen (TKN); total suspended solids (TSS); and *Escherichia coli* (*E. coli*). If runoff volume for a particular runoff event was insufficient to fill all sample bottles, a pre-determined hierarchy of OP, NNN, TKN, TP, *E. coli*, and TSS was used. Samples were processed according to US Environmental Protection Agency (EPA) and Standard Methods (SM) protocols as follows: OP (EPA 365.3); NNN (EPA 300.0); TKN (EPA 351.2); TP (SM 4500-P); *E. coli* (SM 9223B); and TSS (SM 2540) [44,45].

2.5. Data Analysis

Due to NRCS program implementation timelines, pretreatment data were not attainable; therefore, a multiple watershed approach was used, where separate treatment and control catchments are measured simultaneously [46]. Data were first tested for normality using a Kolmogorov–Smirnov test [47,48]. All data were then log-transformed due to non-normal distributions. General simple linear regressions were used to evaluate relationships between runoff treatments and water quality parameters [49–51]. All statistical analyses were performed in the R Environment for Statistical Computing [52]. Comparisons included natural forest revegetation (control) versus forest planting (treatment) and continuous grazing (control) versus prescribed grazing (treatment). Log-transformed loads were modeled as a function of streamflow and treatment; separate models were fit for each parameter and comparisons (silviculture and grazing treatments). Differences in constituent loadings were considered significant at the 0.05 level.

3. Results

3.1. Sampling Variability

Constituent concentrations and load distributions varied greatly between sampled events and sites (Table S1). Loading variations occurred sporadically throughout the monitoring period and varied randomly by season across watersheds, largely due to antecedent moisture conditions. Recorded 24 h rain events that generated runoff ranged from 5.08 mm to 148.08 mm. Though most rain events produced no measurable runoff, there were several high-loading events that generated large runoff volumes and constituent concentrations. Compared to the 30-year average, drier-than-normal conditions persisted throughout the monitoring period. Long, dry periods between large rainfall events limited the number of runoff events generated. In 2016 and 2017, there was 1031.55 mm and 996.12 mm of rainfall, respectively, while the final two months of sampling in early 2018 received 320.5 mm, which is well below the 30-year average rainfall (1227 mm) for the region [53].

3.2. Effects of Grazing and Management

Prescribed grazing treatments resulted in statistically significant decreases ($p < 0.05$) in loads (kg ha^{-1}) over continuous grazing for TSS, NNN, and TKN (Figure 3) (Table S2). Although not statistically significant (p = 0.062), *E. coli* loading decreased as well with BMP implementation over all runoff events (Figure 3). Prescribed grazing treatments did not produce significant decreases in OP or P loading from continuous grazing (Figure S1) (Table S2).

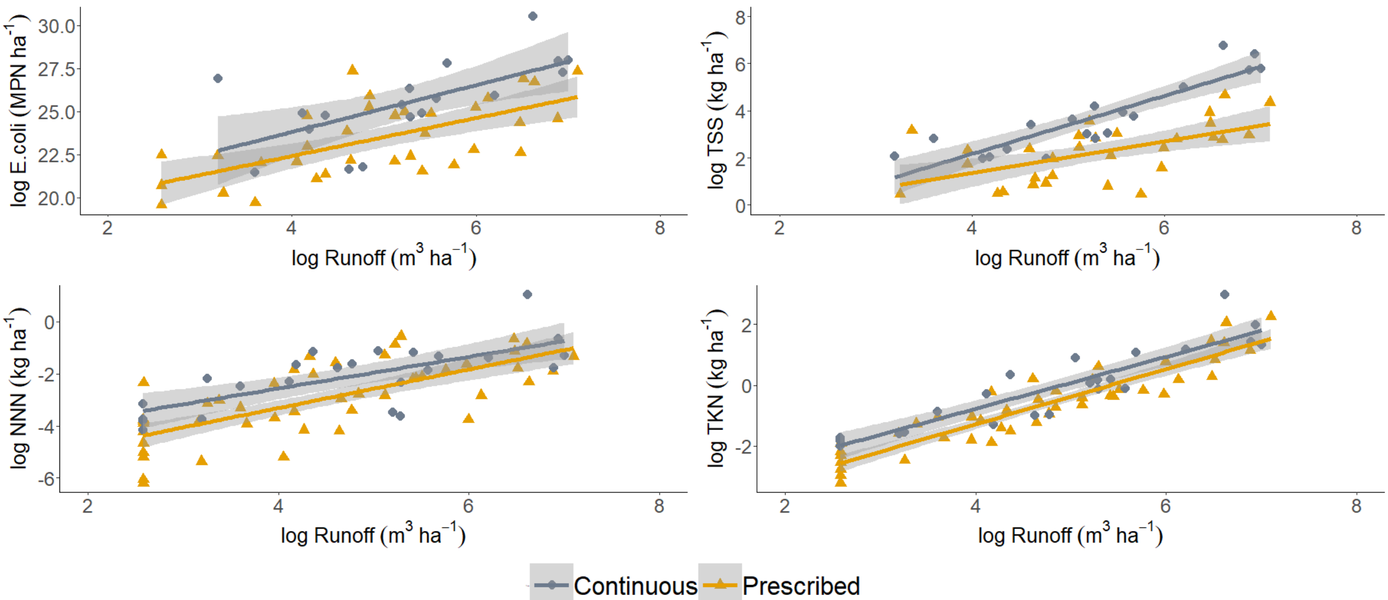

Figure 3. Prescribed versus continuous grazing loadings of *E. coli* (MPN ha^{-1}), TSS, NNN, and TKN (kg ha^{-1}). The data displayed is the averaged data for all two years of the study. The grey shading represents the 95% confidence interval.

Runoff volume was a significant predictor ($p \leq 0.03$) of loads of *E. coli*, NNN, TKN, OP, and P, but not for TSS (Table S2). Furthermore, TSS values in the continuous grazing treatment increased more rapidly with increased runoff than TSS values in prescribed grazing treatments (Figure 3). *E. coli* loading followed a pattern similar to TSS, while NNN, TKN, and OP loadings trended toward convergence with the control at high runoff volumes. This occurrence can likely be attributed to BMP treatment capacity exceedance during high runoff.

3.3. Effects of Silvicultural Management

Implementing silvicultural practices produced mixed results. Treatment was a significant factor in observed loads for NNN, TKN, and OP ($p < 0.05$), but not for TSS, *E. coli*, or P ($p \geq 0.09$) (Table S2). Of these, only NNN loads were lower for treatment plots. Interestingly, TKN and OP loads from the control were lower than from the treatment. Runoff volume was a significant predictor of TSS, TKN, OP, and P ($p < 0.01$), but not for NNN or *E. coli* ($p \geq 0.09$) (Figure 4, Figures S1 and S2).

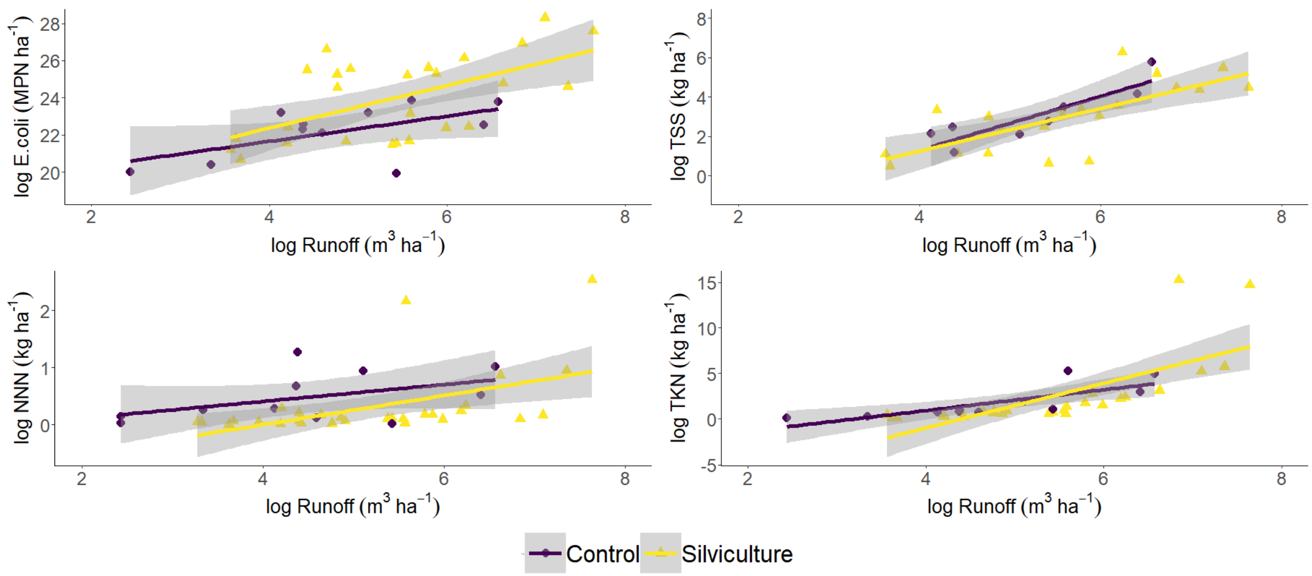

Figure 4. Natural forest revegetation (control) versus silvicultural BMP loadings of *E. coli* (MPN ha^{-1}), TSS, NNN, and TKN (kg ha^{-1}). The data displayed is the averaged data for all two years of the study. The grey shading represents the 95% confidence interval.

4. Discussion

4.1. Grazing Management

Nutrient, sediment, and *E. coli* loads are essential indicators of BMP effectiveness. Grazing management affects available grass cover and is known to influence offsite water quality by affecting runoff generation [54]. Continuous (high-intensity) grazing routinely results in limited ground cover and compacted soils [55,56]. This can increase runoff and, in many cases, pollutant transport. Our results corroborate this finding, as total rainfall required to generate runoff tended to be higher in prescribed than continuous grazing treatments, and prescribed grazing treatments tended to generate less runoff than continuous grazing during higher rainfall events (Figure 5). Continuously grazed land yielded on average 24% more runoff than land under prescribed grazing management, despite receiving less total rainfall over the course of this study. Differences in soils and slope (Table 1) may have contributed somewhat to this disparity, though the soils throughout the study region are predominantly sandy and have higher infiltration rates. Conversely, prescribed grazing management results in less soil compaction from enhanced grass growth and root development, and increasing ground cover leads to less runoff and more onsite sediment capture [54]. Combined, these effects generally produce lower constituent loadings from properly managed grazing lands. Results from this study support these statements, as prescribed grazing plots yielded less runoff and lower constituent loads.

Poultry litter fertilizer applications may partially explain the absence of an effect on phosphorous concentrations. However, poultry litter is also high in nitrogen [57,58], which was significantly reduced in the treatments. Our findings are similar to those of Brannan et al. [59], wherein they recorded reductions in N and P but not in OP. This may be attributed to the fact that nitrogen is more likely to be volatilized than phosphorous during the storage of manure [59]. Similarly, Harmel et al. [60] found that even though poultry litter contained more nitrogen than phosphorous, phosphorous concentrations in runoff were higher, except where supplemental inorganic nitrogen fertilizer was also applied. BMPs complementary to poultry litter application to promote greater infiltration (e.g., mechanical aeration of soils) can aid in trapping nutrients and reducing runoff [61].

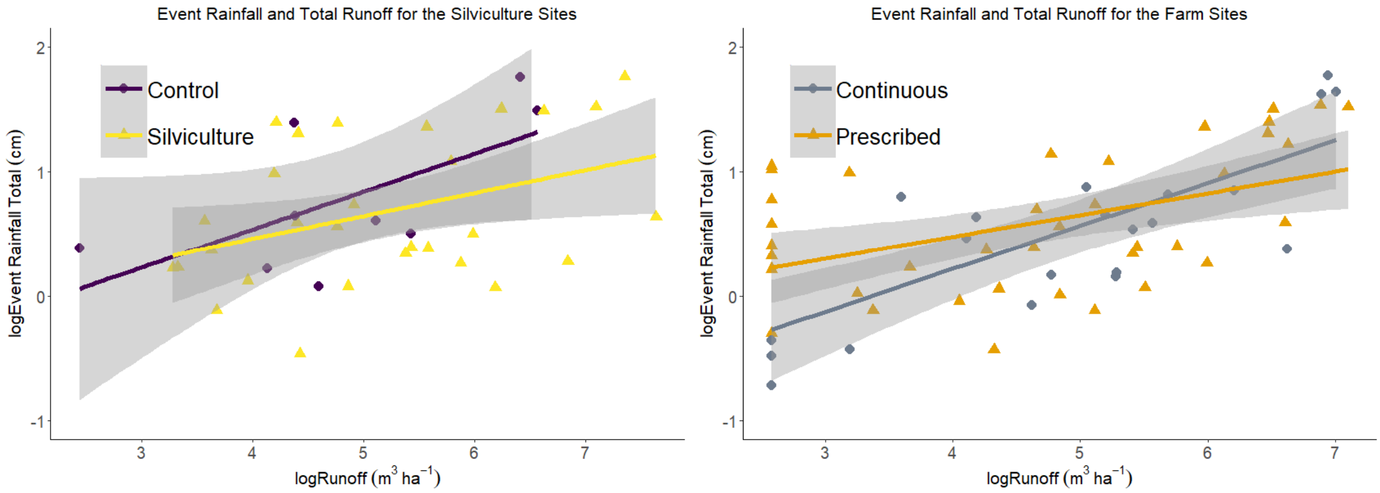

Figure 5. Natural forest revegetation (control) versus silvicultural BMP and prescribed versus continuous grazing runoff volume ($m^3\ ha^{-1}$) and event total rainfall (cm). The data displayed is the averaged data for all two years of the study. The grey shading represents the 95% confidence interval.

The lack of a statistically significant reduction in *E. coli* loads in pastures implementing prescribed grazing could be attributed to additional inputs from wildlife [62–64] and naturalized soil-borne *E. coli* strains [63,65,66] as well as the survivability of *E. coli* in feces. Sinton et al. [67], recognized that *E. coli* concentrations in cattle feces can increase by orders of magnitude for 1–3 weeks following deposition when moisture content remains above 80%. Therefore, even under rotational grazing, a viable *E. coli* source may remain onsite for some time. As a result, effective ways to reduce *E. coli* loading from cowpats may be to increase the distance of deposition from sources of water [68] or by adjusting grazing timing near waterways to avoid rainy seasons [69]. Lewis et al. [70] showed a marked decrease in *E. coli* concentrations over a period of 19 years following the implementation of grazing BMPs in California. In their study, *E. coli* concentrations were quite variable for the initial 8 years and then remained greatly diminished thereafter [70]. Another issue with *E. coli* concentration analysis is that loading values typically have high variance, which substantially reduces statistical detection power [71]. Initial results from grazing plots in our study strongly support the use of prescribed grazing as a BMP; however, project time constraints justify the need for longer-term BMP implementation assessment studies to confirm extended performance.

4.2. Silvicultural Management

Chemical treatment of understory vegetation in the silvicultural plantings minimized herbaceous ground cover and allowed planted trees to reach 1–1.5 m heights during the study period. The minimization of ground cover in the treatment via herbicide likely contributed to the lack of a significant positive response from the silvicultural BMPs. In the natural revegetation, or control site, vegetation (herbaceous and woody) was allowed to regrow uninhibited following root plowing and debris stacking. A mixture of densely packed hardwood tree species rapidly colonized this area and reached heights greater than 2 m during the study period. Due to more consistent ground and foliar cover in the control, runoff, though greater overall (Figure 5), was filtered somewhat, producing similar to better results than the silvicultural treatments.

In the control and treatment plots, stacked debris impeded runoff from moving offsite, causing increased water infiltration into the soil; however, the treated plot had noticeably more bare ground. Previous research has shown that clear-cut sites can exhibit increased constituent loads for multiple years post-treatment [72,73]. The results from the silvicultural BMP treatment and control plots suggest that the herbicide spraying component of the treatment should be reconsidered and perhaps eliminated, or at least limited to targeted applications. Finally, due to the timeframe for forest establishment, we suggest longer-term (5–10 years) studies for quantifying the water quality benefits of silvicultural BMPs [74–76].

5. Conclusions

This study evaluated the water quality benefits of grazing and silvicultural BMPs. Our 2-year study showed significant reductions in nitrogen and sediment loads following the implementation of prescribed grazing, suggesting this practice has the potential to rapidly improve surface water quality. Further, although not statistically significant, *E. coli* loads and runoff volume were reduced in prescribed grazing plots when compared to continuously grazed plots. Our findings suggest that prescribed grazing positively impacts water quality compared to continuous grazing. Conversely, the use of silvicultural BMPs did not produce rapid water quality improvements observable during our 2-year study. Only NNN loads were reduced, whereas other parameters were equal or elevated compared to the control plot. More time is needed to fully evaluate silvicultural BMPs due to the timeframe for forest reestablishment. However, our findings suggest some potential negative short-term impacts related to herbicide applications associated with NRCS forest establishment protocols. We suggest that herbicide applications as a component of NRCS forest management protocols be reassessed and applied only to targeted areas as necessary for successful timber establishment. This would support both establishment and improved water quality by retaining critical understory vegetation to filter runoff.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w15203537/s1. Table S1: Nutrient (kg/ha) and *E. coli* (MPN/100 mL) loads for each sampling location, Table S2: Linear regression results of treatment effect on variable. Figure S1: Results from a general linear model of prescribed versus continuous grazing for nutrients, Figure S2: Results from a general linear model of natural revegetation (control) versus silvicultural treatments for nutrients.

Author Contributions: Conceptualization, K.L.W. and L.G.; methodology, K.L.W. and L.G.; formal analysis, E.C.R., J.A.G. and L.G.; data curation, E.C.R., S.d., and J.A.G.; writing—original draft preparation, E.C.R., J.A.G. and L.G.; writing—review and editing, J.A.G., E.C.R., and S.d.; visualization, E.C.R. and J.A.G.; supervision, L.G. and K.L.W.; project administration, L.G.; funding acquisition, K.L.W. and L.G. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

BMP	Best Management Practice
E. coli	*Escherichia coli*
EPA	Environmental Protection Agency
I-Plan	Implementation Plan
LOP	Lake O' the Pines

NELAP	National Environmental Laboratory Accreditation Program
NNN	Nitrate/Nitrite Nitrogen
NPS	Non-point source pollution
NRCS	Natural Resources Conservation Service
NWQI	National Water Quality Initiative
OP	Ortho-phosphorus
P	Phosphorus
SM	Standard Methods
TKN	Total Kjeldahl Nitrogen
TSS	Total Suspended Solids
TMDL	Total Maximum Daily Load
TSSWCB	Texas State Soil and Water Conservation Board
US	United States

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