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Livestock grazing and vegetative filter strip buffer effects on runoff sediment, nitrate, and phosphorus losses

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Abstract: Livestock grazing in the Midwestern United States can result in significant levels of runoff sediment and nutrient losses to surface water resources. Some of these contaminants can increase stream eutrophication and are suspected of contributing to hypoxic conditions in the Gulf of Mexico. This research quantified effects of livestock grazing management practices and vegetative filter strip buffers on runoff depth and mass losses of total solids, nitrate-nitrogen (NO_3-N), and ortho-phosphorus (PO_4-P) under natural hydrologic conditions. Runoff data were collected from 12 rainfall events during 2001 to 2003 at an Iowa State University research farm in central Iowa, United States. Three vegetative buffers (paddock area:vegetative buffer area ratios of 1:0.2, 1:0.1, and 1:0 no buffer [control]) and three grazing management practices (continuous, rotational, and no grazing [control]) comprised nine treatment combinations (vegetative buffer ratio/grazing management practice) replicated in three 1.35 ha (3.34 ac) plot areas. The total 4.05 ha (10.02 ac) study area also included nine 0.4 ha (1.0 ac) paddocks and 27 vegetative buffer runoff collection units distributed in a randomized complete block design. The study site was established on uneven terrain with a maximum of 15% slopes and consisted of approximately 100% cool-season smooth bromegrass. Average paddock and vegetative buffer plant tiller densities estimated during the 2003 project season were approximately 62 million and 93 million tillers ha^{-1} (153 million and 230 million tillers ac^{-1}), respectively. Runoff sample collection pipe leakage discovered and corrected during 2001 possibly reduced runoff depth and affected runoff contaminant mass losses data values. Consequently, 2001 runoff analysis results were limited to treatment comparisons within the 2001 season and were not compared with 2002 and 2003 data. Analysis results from 2001 showed no significant differences in average losses of runoff, total solids, NO_3-N, and PO_4-P among the nine vegetative buffer/grazing practice treatment combinations. Results from 2002 indicated significantly higher losses of runoff and total solids from 1:0 no buffer/rotational grazing and 1:0 no buffer/continuous grazing treatment combination plots, respectively, compared among other 2002 season treatment combinations. The 2003 results showed significantly higher runoff and total solids losses from 1:0 no buffer/no grazing treatment combination plots compared among all 2003 treatment combinations and from 1:0.1 vegetative buffer/no grazing treatment combination plots compared among all 2003 treatment combinations and with respective 2002 treatment combinations. However, the 2003 results indicated effective vegetative buffer performance with significantly lower runoff, total solids, and NO_3-N losses from the larger 1:0.2 buffer area compared among the smaller 1:0.1 buffer area and 1:0 no buffer treatment combinations. The 2003 results also indicated a highly significant increase in losses of NO_3-N from 1:0.1 buffer/no grazing treatment combination plots compared among other 2003 season treatment combinations and with respective 2002 treatment combinations. Overall results from this study suggest a shift from significantly higher 2002 season plot losses of continuous and rotational grazing treatment combinations to significantly higher 2003 season losses of no grazing treatment combinations. We speculate this shift to significantly higher runoff and contaminant losses from no grazing treatment combination plots during 2003 reflects the variability inherent to a complex and dynamic soil-water environment of livestock grazing areas. However, we also hypothesize the environmental conditions that largely consisted of a dense perennial cool-season grass type, high-relief landscape, and relatively high total rainfall depth may not necessarily include livestock grazing activities.

Key words: cool-season perennial grasses—livestock grazing management—sediment and nutrient losses—surface runoff—vegetative filter strip buffers—warm-season perennial grasses—water quality

Livestock grazing can significantly affect the complex soil-water environment (Schepers and Francis 1982; Owens et al. 1989; Nelson et al. 1996; Krzic et al. 2006). Grazed pastures can be key contributors of phosphorus (P) to surface waters (Downing et al. 2000; James et al. 2007) and have higher P losses than ungrazed pastures (Gillingham and Thorrold 2000). Nitrogen (N) losses from agricultural/grazing fields to surface and subsurface waters also have been documented (Madramootoo et al. 1992; Sauer et al. 2000; Stout et al. 2000). Studies have indicated that N and P losses from continuously grazed pastures are generally higher than rotational grazing and ungrazed pastures (Ritter 1988; Mathews et al. 1994).

Although livestock grazing activities generally have been reported to adversely impact the hydrology of pasture areas, Sharpley and Syers (1976) determined that P transport due to grazing animals was significantly less than P losses from fertilizer addition. Nash et al. (2000) found that cattle grazing did not result in large stores of available P compared to P fertilization. Mathews et al. (1994) also found the grazing method of well-managed pastures may have little effect on short-term soil nutrient distribution, especially when

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grazing occurs during months when temperatures are high.

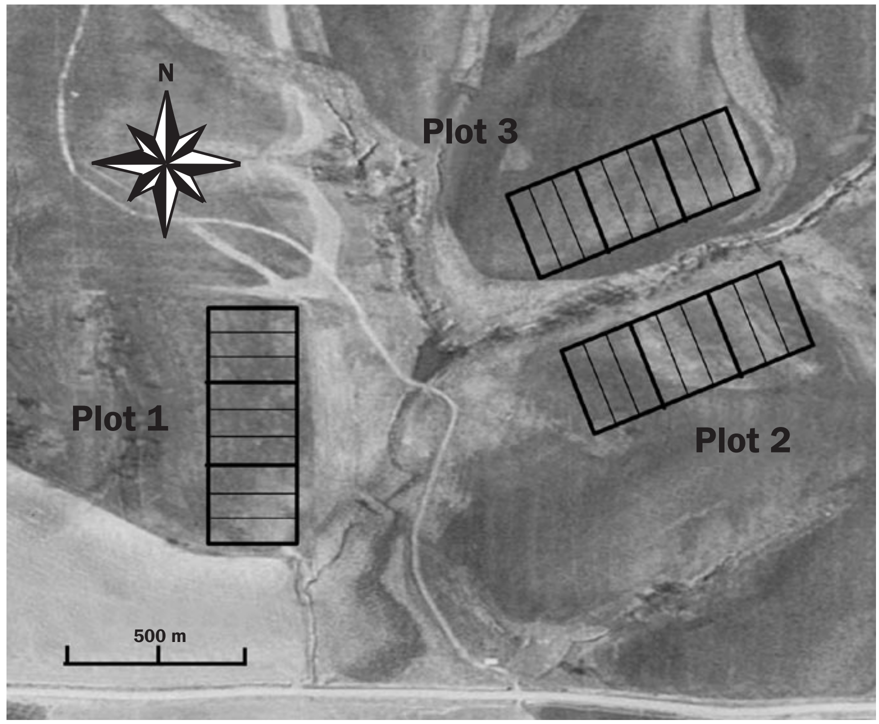
Vegetative filter strip buffers are bands of vegetation located downslope of cropland, livestock grazing areas, and other potential sources of surface runoff and contaminants (Dillaha et al. 1989). Vegetative buffers provide erosion control and filter nutrients, pesticides, sediment, and other pollutants from agricultural runoff by reducing sediment carrier energy. Contaminant reduction also occurs through interception adsorption, infiltration, and degradation of pollutants dissolved in water (Hubbard et al. 2003). Other researchers have reported on the effectiveness of vegetative buffers in treating agricultural runoff (Snyder et al. 1998; Smith et al. 2000; Bharati et al. 2002; Gharabaghi et al. 2001; Koelsch et al. 2006) and consider them a best management practice for surface runoff pollutant removal (Dillaha et al. 1989; Mickelson and Baker 1993; Gilley et al. 2000; Lee et al. 2000; Wang et al. 2005; Hay et al. 2006). Vegetative buffer studies also showed significant reductions of NO_3-N, PO_4-P, and total P in runoff (Patty et al. 1997; Wenger et al. 1999).

Smooth bromegrass (*Bromus inermis* Leyss.) is a common Midwest grass variety that has been extensively established in livestock grazing areas. It is a strongly rhizomatous, sod-forming perennial grass that was introduced from Eurasia in 1884 (USGS 2006) and was reported to be the most agronomically important bromegrass species in the United States (Hitchcock 1950). This aggressive cool-season grass type is fairly resistant to temperature extremes and drought due to its highly developed root system and grows best on deep, well-drained silt or clay loam soils (Roberts and Kallenbach 2006). Now considered to be naturalized over most of North America, smooth bromegrass has escaped throughout its range and is often considered a highly competitive weed of roadsides, forests, prairies, fields, lawns, and lightly disturbed sites (USGS 2006). Cool-season grasses, such as smooth bromegrass, tend to lay over in runoff flow and are not considered appropriate grass species for vegetative buffers (Schultz et al. 1997).

The literature cited in this manuscript focuses on the effects of livestock grazing management practices and vegetative buffers on runoff water quantity and quality. However, grazing practice and vegetative buffer effects that were investigated in this study may vary with different field conditions that include vegetation species, type of contaminant, slope of the runoff area, grazing paddock area:vegetative buffer area ratio, and activities on the runoff source area. Consequently, this research quantified grazing practice and vegetative buffer effects on runoff depth, sediment, and nutrient total mass losses with further discussion given to paddock and vegetative buffer area perennial grass species, vegetation density, runoff flow characteristics, and slope conditions.

Figure 1

Grazing management practice and vegetative filter strip buffer study landscape and plot area layout at Iowa State University Rhodes Research and Demonstration Farm, central Iowa, United States. Bolded plot boundary lines indicate paddock areas for three grazing practices (continuous, rotational, and no grazing control), and unbolded lines depict nine paddock area:vegetative buffer area ratio (1:0.2, 1:0.1, and 1:0 no buffer control) treatment combination runoff units per plot distributed in a randomized complete block design (aerial photo from NASA World Wind).



Materials and Methods

Site Description. This study was conducted during 2001 to 2003 at the Iowa State University Rhodes Research and Demonstration Farm in southwest Marshall County, central Iowa, United States (41° 53.615' N, 93° 12.073' W). The study site total area was 4.05 ha (10.02 ac) comprised of three plots, each approximately 1.35 ha (3.34 ac). Each plot included three 0.4 ha (1.0 ac) paddock areas and was selected on uneven terrain with a slope range of 4% to 15% in a smooth bromegrass pasture (figure 1). Vegetation types in both paddock and vegetative buffer areas were approximately 100% grasses with a trace of mixed broadleaf species. Average grass tiller populations for paddocks and vegetative buffers were estimated at 62 million and 93 million tillers ha^{-1}(153 million and 230 million tillers ac^{-1}), respectively. Populations were estimated from tiller counts conducted in randomly assigned 0.10 m^2 (1.08 ft^2) sampling areas using a method from Arora et al. (2003).

The major soil association at the research site is the Downs-Gara association with silty and loamy soils formed on upland loess and glacial till. The dominant soil is Downs silt loam, a fine-silty, mixed, mesic Mollic Hapludalfs (Oelmann 1981). After initial soil sampling in April 2001, diammonium phosphate ($[NH_4]_2HPO_4$) was applied to plot areas testing below the optimum range of 11 to 15 ppm P. Sandbags were placed around plot area perimeters and between each paddock to minimize cross contamination between adjacent paddocks from runoff by rainfall events.

Experimental Design and Data Analysis. The use of livestock grazing management practice treatments (continuous grazing to a residual sward height of 5.1 cm [2.0 in], rotational grazing to a residual sward height of 5.1 cm [2.0 in], and an ungrazed control) were included to evaluate effects of grazing management practices on water quality. Grazing was initiated on May 29, 2001, with three mature cows (average weights = 657, 613, and 625 kg [1,448, 1,351, and 1,378 lb]) in each grazed paddock (Haan et al. 2007). In the continuous grazing system, cattle were removed from paddocks after sward height was reduced to 5.1 cm, and paddocks were allowed a rest period of 7 to 10 days to limit regrowth and simulate continuous grazing. Cattle were removed from paddocks for 35 days after the 5.1 cm sward height reduction for the rotational grazing system. Total grazing days for continuous and rotational grazing systems for 2001, 2002, and 2003 were 491 and 378 cow days ha^{-1}, 400 and 316 cow days ha^{-1}, and 396 and 316 cow days ha^{-1}, (1,213 and 934 cow days ac^{-1}, 988 and 781 cow days ac^{-1}, 979 and 781 cow days ac^{-1}), respectively.

The role of vegetative buffers on losses of runoff, total solids, nitrate-nitrogen (NO_3-N), and ortho-phosphorus (PO_4-P) was evaluated using grazing paddock area:vegetative buffer area ratios of 1:0.2, 1:0.1, and 1:0 no buffer (control) for all vegetative buffer/grazing management practice treatment combinations (table 1). The term "area ratio" represents the ratio of paddock land area draining into a vegetative buffer area. The research site included nine vegetative buffer/grazing practice treatment combinations, replicated in three 1.35 ha (3.34 ac) plot areas for a total of 27 runoff collection units (figure 1), each 2.28 m (7.5 ft) wide × 22.80 m (75 ft) long. Vegetative buffers at the downslope end of runoff collection unit areas were 4.56 m (15 ft) × 2.28 m and 2.28 × 2.28 m for the 1:0.2 and 1:0.1 area ratios, respectively. All vegetative buffer/grazing practice treatment combinations were distributed over the paddock and runoff unit plot areas in a randomized complete block design (Cochran and Cox 1957). All runoff unit areas within paddocks were hydrologically isolated by an 8.0 cm (3.0 in) high barrier that included 15 cm (6.0 in) wide sheet metal borders, driven approximately 7.0 cm (2.8 in) into the ground.

Table 1

Paddock area:vegetative buffer area ratios (1:0.2, 1:0.1, and 1:0 [no buffer] control) and grazing management practice (continuous [con], rotational [rot], and no grazing [ng] control) treatment combination matrix for 2001 to 2003 vegetative buffer/grazing management practice study at Iowa State University Rhodes Research and Demonstration Farm, central Iowa, United States.

Plot area ratios	Grazing management practice		
(paddock area:vegetative buffer area)	Continuous (con)	Rotational (rot)	No grazing (ng)
1:0.2	1:0.2con	1:0.2rot	1:0.2ng
1:0.1	1:0.1con	1:0.1rot	1:0.1ng
1:0	1:0con	1:0rot	1:0ng

A tipping-bucket flow meter system (Hansen and Goyal 2001) was used to measure and collect runoff water from each runoff unit after a rainfall event. A perforated 10 cm (4.0 in) diameter polyvinyl chloride (PVC) "T" collector pipe was used at the downslope end of paddocks (no buffer control) and vegetative buffers (1:0.2 and 1:0.1 area ratios) to direct runoff water to the tipping-bucket system through 6.0 m (20 ft) to 9.0 m (30 ft) long PVC flow pipes. Runoff samples were collected in 19 L (5.0 gal) plastic tanks through a plastic tube connected to an orifice in the 90° elbow at the end of runoff unit flow collector pipes. Data loggers (Onset Computers Inc., Massachusetts, United States) connected to magnetic switches were used to record runoff volume-calibrated "tips" for tipping-bucket units.

All plots and tipping-bucket units were checked at least weekly, and runoff samples were collected after rainfall events of 25 mm (1.0 in) depth or higher. This lower depth boundary value was established to maximize sample size consistency and meet or exceed minimum runoff sample volumes (100 mL and 10 mL [6.10 in^3 and 0.61 in^3]) required for sediment and nutrient analyses, respectively. Runoff samples were prepared and stored according to standard protocols (American Water Works Association 1998) until analysis at the Department of Agricultural and Biosystems Engineering Water Quality Laboratory, National Swine Research and Information Center, Iowa State University, Ames, Iowa, United States.

Runoff volume (L) was determined from tipping-bucket units and was converted to equivalent depth (mm) across each vegetative buffer runoff collection unit area. Total solids concentrations (g kg^{-1}) in runoff were measured using a gravimetric oven-drying method (American Water Works Association 1998). The NO_3-N concentrations (mg L^{-1}) were analyzed by automated flow injection cadmium reduction method (American Water Works Association 1998) using a Lachat Quickchem 2000 Automated Ion Analyzer system (Hach Company, Colorado, United States). Concentrations of PO_4-P (mg L^{-1}) were analyzed using automated flow injection ascorbic acid method (American Water Works Association 1998) on a Lachat Quickchem 2000 Automated Ion Analyzer system. All total solids and nutrient (NO_3-N and PO_4-P) concentrations were converted to total mass losses units of g and mg, respectively. The General Linear Model Procedure and Least Squares Mean (LSMEANS) Test (SAS Institute 2004) were used to analyze differences among grazing paddock area:vegetative buffer area ratio and grazing management practice treatment means at 90% and 99% probability levels.

Results and Discussion

Runoff Analysis and Vegetative Buffer Performance. There were a total of 12 rainfall events used for analysis during the 2001, 2002, and 2003 project seasons. Rainfall event data for each project season are shown in table 2. This manuscript discusses analyses of average runoff total mass losses data from rainfall events for each of the three project seasons: 2001 (total event rainfall = 332 mm [13.1 in]), 2002 (total event rainfall = 129 mm [5.1 in]), and 2003 (total event rainfall = 397 mm [15.6 in]). Relatively lower 2001 runoff depths (table 3) compared to total event rainfall (332 mm [13.1 in]) may be attributed to runoff collection pipe leakage that was discovered and repaired during the 2001 project season. Consequently, 2001 analysis results were only compared among treatments within the 2001 season and were not compared with 2002 and 2003 data.

Least squares mean (LSMEANS) average losses of runoff, total solids, NO_3-N, and PO_4-P for 2001, 2002, and 2003 are shown in tables 3 and 4. Results from the 2001 season showed no significant differences ($p \leq 0.10$) in losses of runoff, total solids,

NO_3-N, and PO_4-P among the nine treatment combinations. Results from 2002 (table 3) indicated significantly higher ($p \leq 0.10$) losses of runoff and total solids from 1:0 no vegetative buffer (control)/rotational grazing and 1:0 no buffer/continuous grazing treatment combination plots, respectively, compared among other runoff and total solids treatment combinations from 2002.

Results from 2003 (table 3) showed significantly higher losses ($p \leq 0.10$) of runoff and total solids from 1:0 no buffer/no grazing (control) treatment combination plots compared among 2003 treatment combinations and 1:0.1 vegetative buffer/no grazing treatment combination plots compared among 2003 treatment combinations and with the respective 2002 treatment combination. The 2003 results also indicated significantly higher ($p \leq 0.10$) runoff and total solids losses from 1:0.1 vegetative buffer/no grazing treatment combination plots compared to the respective 2002 season treatment combination. However, the 2003 results in table 4 showed highly significant ($p \leq 0.01$) losses of NO_3-N from 1:0.1 vegetative buffer/no grazing treatment combination plots compared among other 2003 season and respective 2002 season treatment combinations.

Results from 2001 and 2002 project seasons (tables 3 and 4) indicated no significant differences ($p \leq 0.10$) between the larger 1:0.2 and smaller 1:0.1 vegetative buffer area treatments for losses of runoff, total solids, NO_3-N, and PO_4-P and are similar to results from Arora et al. (2003) and Webber et al. (2009). However, the 2002 results (table 3) showed the 1:0 no buffer treatment for runoff and total solids losses was significantly higher ($p \leq 0.10$) compared among 1:0.2 and 1:0.1 buffer treatments. The 2002 results also showed significantly higher ($p \leq 0.10$) losses of runoff and total solids from 1:0 no buffer/rotational and 1:0 no buffer/continuous grazing treatment combinations compared among other 2002 treatment combinations, which are consistent with findings from other studies (Ritter 1988; Mathews et al. 1994).

The 2003 results (table 3) showed the 1:0.2 buffer area treatment was more effective in reducing runoff and total solids losses from livestock grazing areas than the 1:0.1 buffer area and the 1:0 no grazing (control) treatments. However, results from the 2003 season tended to contradict 2002 results and other similar findings, indicating runoff and contaminant losses from continuously grazed pastures are generally higher than rotational grazing and ungrazed pastures (Ritter 1988; Mathews et al. 1994; Mwendera et al. 1997; Sauer et al. 2000).

For over 20 years prior to 2001, the Rhodes research site had been managed as a single unit for beef cattle grazing and hay harvest (Haan et al. 2007). Schultz et al. (2004) reported that 5 to 10 years may be required to modify soil conditions in a new grass management system, and Dosskey et al. (2007) found that most change in vegetative buffers occurred within three growing seasons after establishment, with infiltration characteristics accounting for most of that change. Moreover, cool-season grass species like dense smooth bromegrass established in paddocks and vegetative buffers at the Rhodes site are not as effective in reducing runoff and contaminants as some warm-season grass types (Schultz et al. 1997; Lee et al. 1998; Broadmeadow and Nisbet 2004).

Haan et al. (2007) also reported that livestock grazing stimulates new shoot and root growth, and ungrazed pastures can gradually lose their capacity to sequester sediment and nutrients. Steinke et al. (2007) found total P losses were similar for both prairie and turfgrass vegetative buffer species in a study assessing runoff quantity and quality. They suggested the natural nutrient biogeochemical cycling can result in nutrient loss to surface waters, regardless of vegetation type or plant size in vegetative buffers.

Vegetation and Runoff Flow Characteristics. The Rhodes research site is an excellent location for smooth brome-

Table 2

Rainfall data (event date, event number [E1 to E12], and rainfall depth) for 2001 to 2003 vegetative buffer/grazing management practice study at Iowa State University Rhodes Research and Demonstration Farm, central Iowa, United States.

Project year	2001	2002	2003
Event date, number, and rainfall depth	7-19-01 E1 76 mm	6-12-02 E5 42 mm	5-4-03 E8 52 mm
	8-3-01 E2 58 mm	7-10-02 E6 44 mm	6-26-03 E9 58 mm
	9-7-01 E3 127 mm	8-23-02 E7 43 mm	7-5-03 E10 48 mm
	10-22-01 E4 71 mm		9-12-03 E11 108 mm
			11-4-03 E12 131 mm
Total rainfall depth	**332 mm**	**129 mm**	**397 mm**

Table 3

Grazing management practice (con, rot, and ng for continuous, rotational, and no grazing [control], respectively) and paddock area:vegetative buffer area ratio (1:0.2, 1:0.1, and 1:0 [no buffer] control) treatment least squares mean (LSMEANS) values for average runoff depth (mm) and total solids losses (mg) for 2001 (not compared with 2002 and 2003 data), 2002, and 2003 project season rainfall events at Iowa State University Rhodes Research and Demonstration Farm, central Iowa, United States. Significant differences ($p < 0.10$) are indicated by different letters among treatments (b) and project years (c). Total events rainfall for 2001, 2002, and 2003 is 332 mm (13.1 in), 129 mm (5.10 in), and 397 mm (15.6 in), respectively.

	Grazing management practice			Paddock: vegetative buffer area ratio		
Quantity (units)	**con**	**rot**	**ng**	**1:0.2**	**1:0.1**	**1:0**
2001* runoff (mm)	4.40a	4.13a	2.05a	2.46a	4.11a	4.02a
2002 runoff (mm)	5.26a	5.65b	5.33a	5.31a	2.76a	8.17b
2003 runoff (mm)	5.50a	13.73a	17.23bc	4.86a	15.55bc	16.04b
2001* total solids (g)	114a	95.0a	48.2a	60.4a	83.9a	113a
2002 total solids (g)	182b	96.2a	28.0a	78.0a	24.4a	204b
2003 total solids (g)	45.8a	101a	200bc	51.8a	140bc	164b

* Data from 2001 were not compared with 2002 and 2003 data.

Table 4

Grazing management practice (con, rot, and ng for continuous, rotational, and no grazing [control], respectively) and paddock area:vegetative buffer area ratio (1:0.2, 1:0.1, and 1:0 [no buffer] control) treatment least squares mean (LSMEANS) values for average losses (mg) of nitrate-nitrogen (NO_3-N) and ortho-phosphorus (PO_4-P) for 2001 (not compared with 2002 and 2003 data), 2002, and 2003 project season rainfall events at Iowa State University Rhodes Research and Demonstration Farm, central Iowa, United States. Significant differences ($p < 0.10$) among treatments are indicated by a different letter (b).

	Grazing management practice			Paddock: vegetative buffer area ratio		
Quantity (units)	con	rot	ng	1:0.2	1:0.1	1:0
2001* NO_3-N (mg)	228a	202a	25.4a	55.6a	205a	195a
2002 NO_3-N (mg)	115a	188a	195a	148a	79.4a	271a
2003 NO_3-N (mg)	94.6a	200a	†371bc	117a	†304bc	244b
2001* PO_4-P (mg)	159a	127a	50.3a	108a	121a	107a
2002 PO_4-P (mg)	100a	208a	385a	217a	147a	329a
2003 PO_4-P (mg)	228a	493a	209a	262a	281a	387a

* Data from 2001 were not compared with 2002 and 2003 data.

† Significant differences ($p < 0.01$) among treatments (b) and project years (c). Total events rainfall for 2001, 2002, and 2003 = 332 mm (13.1 in), 129 mm (5.10 in), and 397 mm (15.6 in), respectively.

grass establishment with its silt loam soils and well-drained steep terrain. Brueland et al. (2003) estimated the average maximum smooth bromegrass tiller density of their Rhodes research plots to be approximately 50 million tillers ha^{-1} (124 million tillers ac^{-1}) in 1996. In contrast, Arora et al. (2003) and Webber et al. (2009) determined average tiller populations for grass species that included smooth bromegrass were approximately 9.0 million and 2.7 million tillers ha^{-1} (22 million and 6.7 million tillers ac^{-1}), respectively, for vegetative buffer plots at two other central Iowa research sites. The Rhodes research site paddock and vegetative buffer plot areas were estimated in 2003 at 62 million and 93 million tillers ha^{-1} (153 million and 230 million tillers ac^{-1}), respectively. Smooth bromegrass can become heavily established with adequate rainfall during spring and early summer, and depending on soil moisture availability, may regrow in September and October (USGS 2006). The 30-year average annual precipitation at the Rhodes site was 891 mm (35.0 in), with the majority of rainfall (54%) occurring from May to August (Haan et al. 2007). Precipitation was above average during 2001 (932 mm [37.0 in]) and 2003 (965 mm [38.0 in]) and below average during 2002 (716 mm [28.0 in]) (NOAA 2001, 2002, 2003).

The use of certain grass species as alternatives to smooth bromegrass for pastures and vegetative buffers has been extensively researched (Schultz et al. 1997; Lee et al. 1998; Mitchell et al. 1998; Moore et al. 2004; Roberts and Kallenbach 2006). Self-Davis et al. (2003) researched various forage plant species and cover effects from small vegetated plots and determined that tall fescue (*Festuca arundinacea* Schreber.) significantly reduced runoff and increased infiltration. Research comparing smooth bromegrass to warm-season species, like switchgrass (*Panicum virgatum* L.) and big bluestem (*Andropogan gerardii* L.), showed that warm-season grasses provided more effective vegetative buffers for reducing runoff and contaminant losses (Schultz et al. 1997). Lee et al. (1998) found that switchgrass under simulated rainfall conditions removed significantly more NO_3-N, PO_4-P, and total P than cool-season vegetative buffers that included smooth bromegrass. Lee et al. (1998) also reported that warm-season switchgrass vegetative buffers were more effective in removing total solids compared to nutrients, and the buffers were least effective in removing NO_3-N.

Schultz et al. (1997) determined that switchgrass is preferred for vegetative buffers due to its dense, stiff stems that slow runoff, and cool-season grasses such as smooth bromegrass are not appropriate because they do not tend to remain upright under the flow of water. Broadmeadow and Nisbet (2004) also indicated that vegetative buffer efficiency was likely to be significantly reduced on slopes greater than 4% due to smooth bromegrass vegetation becoming flattened by surface runoff during high rainfall. Although warm-season grasses have been extensively documented as effective vegetative buffer species, certain types also have been suggested for incorporation into livestock pasture areas for a rotational grazing management sequence (Mitchell et al. 1998; Moore et al. 2004; Roberts and Kallenbach 2006; Tracy and Faulkner 2006). However, while environmental and financial concerns are highly important to landowners regarding the use of native prairie vegetation in livestock grazing systems (Doll and Jackson 2009), warm-season grass species tend to be more difficult to establish than some cool-season varieties, and warm-season grasses are recommended for slopes of 0% to 5% (USDA SCS 1979).

Another potential problem of incorporating warm-season grasses into a smooth bromegrass system was reported by Vinton and Goergen (2006), who suggested that smooth bromegrass may have a competitive advantage over warm-season switchgrass on higher-N soils. Consequently, increased N deposition associated with livestock grazing and fertilizer application at the Rhodes site could result in an even greater smooth bromegrass competitive advantage. Potential results of establishing this new perennial grass system may require the use of special vegetation management strategies that could include prescribed burning (USGS 2006) to control encroaching smooth bromegrass in warm-season grass vegetative buffer areas.

The Rhodes research site has a maximum slope of approximately 15%, and smooth bromegrass is one of the few suitable grasses recommended for slopes greater than 10% (USDA SCS 1979). This is mainly due to the "sod" growth characteristic of smooth bromegrass versus the "bunch grass" growth pattern of some warm-season species like switchgrass and big bluestem (Schultz et al. 1997). To better understand the effects of smooth bromegrass on surface runoff under the steep terrain conditions at the Rhodes site, a quantitative approach may be helpful. To determine surface runoff flow velocity under different vegetation types and slope conditions, the Manning equation is widely used because of its simplicity and accuracy (Fangmeier et al. 2006). Assuming steady, uniform flow, the Manning equation can be expressed as

$$v = R^{0.67}\, S^{0.50}\, n^{-1}\,, \tag{1}$$

where v is the mean velocity (m s^{-1}), n is the Manning coefficient of channel roughness (dimensionless), R is the hydraulic radius (m), and S is the slope of the energy grade line (dimensionless). For most channel-lining materials such as soil and concrete, the Manning *"n"* value does not vary significantly as the depth of flow varies and is normally assumed to be constant. However, for vegetative channels and flow paths, the Manning *"n"* value varies greatly with depth of flow (USDOT 1986).

Ree (1949) studied the hydraulic characteristics of vegetation and determined the Manning *"n"* value varied from approximately 0.40 at 30% (initial) vegetation submergence to 0.03 at 100% (complete) submergence for a Bermuda grass channel on a 5% bed slope. To simplify application of Manning *n* values to initial and complete vegetation submergence conditions, the USDA Natural Resources Conservation Service (NRCS) determined a Manning *"n"* value range of 0.50 to 0.02, respectively, for all channel vegetation types (IDOT 2006).

Since smooth bromegrass paddock and vegetative buffer vegetation at the Rhodes site is in the same Retardance Class (B) as Bermuda grass (USDA SCS 1979), the NRCS Manning *"n"* value range of 0.50 to 0.02 should be a reasonable estimate. Substituting the Manning *"n"* values of 0.50 and 0.02 into equation 1 ($R^{0.67} = 0.34$, $S^{0.50} = 0.40$; for $R = 0.20$ m [0.66 ft] and $S = 0.15$ [15% slope], respectively), the runoff velocities (v) equal 0.27 m s^{-1} (0.89 ft sec^{-1}) and 6.80 m s^{-1} (22.31 ft sec^{-1}) for initial and complete vegetation submergence, respectively. The upper 6.80 m s^{-1} (22.31 ft sec^{-1}) value is a 25-fold increase in runoff velocity, possibly due to concentrated flow and smooth bromegrass vegetation submergence. This high flow velocity value also exceeds by almost 5-fold the NRCS Permissible Velocity value of 1.5 m s^{-1} (4.9 ft sec^{-1}) recommended for smooth bromegrass established on slopes greater than 10% (USDA SCS 1979). Because higher runoff velocities estimated by the Manning equation are inversely related to runoff residence time and, subsequently, nutrient removal in the vegetative buffer area, these data appear to be consistent with the significantly high 2003 project season runoff analysis results.

Researchers have reported that vegetative buffers are most effective when flow is shallow and slow (Barling and Moore 1994) and that concentrated flow through vegetative buffers can be substantial and may greatly limit filtering effectiveness (Dosskey et al. 2002). Moreover, the Rhodes research site is located in the Southern Iowa Drift Plain Landform, a generally high-relief landscape surface that is characterized by an extensive drainage network of deeply incised rills, ravines, and stream channels (Prior 1991) and may be prone to concentrated flow conditions.

Although indications of concentrated flow channeling and vegetation flattening were observed in some Rhodes research site vegetative buffer plots following significant rainfall events during the final 2003 project season, statistically based hydraulic radius (R) measurements and vegetation analyses of the vegetative buffers were not conducted. Consequently, an R value of 0.20 m (0.66 ft), indicating a minimal concentrated flow depth, was estimated for the vegetative buffers and was used in the Manning equation example calculation for this study. However, an increase in the R value (indicating increased concentrated surface flow suspected in the research plots), could result in a substantial increase in runoff flow velocity and a subsequent greater reduction in vegetative buffer effectiveness. Consequently, this suspected increase in concentrated surface flow could have contributed to significantly higher runoff and contaminant losses during the 2003 project season.

Summary and Conclusions

In this study, we evaluated effects of livestock grazing management practices and vegetative filter strip buffers on runoff depth and total solids, NO_3-N, and PO_4-P mass losses under natural rainfall events. Analysis results from 2001 and 2002 project season data indicated no significant differences between the larger 1:0.2 and smaller 1:0.1 vegetative buffer area treatments for losses of runoff, total solids, NO_3-N, and PO_4-P. These results are consistent with findings from some previous studies. The 2002 season results showed runoff and total solids losses from the 1:0 no buffer treatment plots were significantly higher ($p \leq 0.10$) compared among 1:0.2 and 1:0.1 buffer treatments.

The 2003 season results indicated the 1:0.2 buffer area treatment was more effective in reducing runoff and total solids losses from livestock grazing areas than the 1:0.1 buffer area and 1:0 no buffer (control) treatments, and there were no significant differences in total mass losses of NO_3-N between 1:0.2 buffer area and 1:0 no buffer treatments. These results also indicated significantly higher losses of runoff and total solids for the 2002 project season 1:0 no buffer/rotational grazing and 1:0 no buffer/continuous grazing treatment combination plots compared among 2002 treatment combinations. These levels shifted to significantly higher losses of runoff, total solids, and NO_3-N for the 2003 1:0 no buffer/no grazing and 1:0.1 vegetative buffer/no grazing treatment combinations compared among 2003 season treatment combinations and versus respective 2002 treatment combinations.

We speculate this shift to significantly higher total mass losses from 1:0 no buffer/no grazing and 1:0.1 buffer/no grazing treatment combination plots during the 2003 season reflects the inherent variability of a complex and dynamic soil-water environment. However, we also hypothesize the study site environmental conditions that largely comprised a dense perennial cool-season grass type, high-relief landscape, and relatively high total rainfall depth may not necessarily include livestock grazing activities.

Research findings from other related studies also indicated concentrated surface flow channeling associated with high-relief landscapes can significantly reduce vegetative buffer performance. Vegetation breakdown of ungrazed pasture grasses also may result in appreciable sediment and nutrient losses, and significant changes in runoff and infiltration characteristics of newly established perennial grass systems can occur in as little as three growing seasons. Consequently, the combined effects of these potential soil-water environmental conditions and effects documented in this study may have contributed to significantly higher 2003 project season runoff and contaminant losses from ungrazed treatment combination plots compared to respective 2002 season results.

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