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Grazing Management Effects on Sediment, Phosphorus, and Pathogen Loading of Streams in Cool-Season Grass Pastures

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Erosion and runoff from pastures may lead to degradation of surface water. A 2-yr grazing study was conducted to quantify the effects of grazing management on sediment, phosphorus (P), and pathogen loading of streams in cool-season grass pastures. Six adjoining 12.1-ha pastures bisected by a stream in central Iowa were divided into three treatments: continuous stocking with unrestricted stream access (CSU), continuous stocking with restricted stream access (CSR), and rotational stocking (RS). Rainfall simulations on stream banks resulted in greater ($P < 0.10$) proportions of applied precipitation and amounts of sediment and P transported in runoff from bare sites than from vegetated sites across grazing treatments. Similar differences were observed comparing vegetated sites in CSU and RS pastures with vegetated sites in CSR pastures. Bovine enterovirus was shed by an average of 24.3% of cows during the study period and was collected in the runoff of 8.3 and 16.7% of runoff simulations on bare sites in CSU pastures in June and October of 2008, respectively, and from 8.3% of runoff simulations on vegetated sites in CSU pastures in April 2009. Fecal pathogens (bovine coronavirus [BCV], bovine rotavirus group A, and *Escherichia coli* O157:H7) shed or detected in runoff were almost nonexistent; only BCV was detected in feces of one cow in August of 2008. Erosion of cut-banks was the greatest contributor of sediment and P loading to the stream; contributions from surface runoff and grazing animals were considerably less and were minimized by grazing management practices that reduced congregation of cattle by pasture streams.

Erosion and precipitation runoff from pastures and rangelands are major sources of sediment and phosphorus loading of streams (CAST 2002; Alexander et al., 2008), which can lead to the eutrophication and impairment of freshwater sources (Sharpley et al., 1994). If unmanaged, grazing cattle may congregate in riparian areas of pastures in search of high-quality forages, drinking water, and thermoregulation (Kauffman and Krueger, 1984), which often results in decreased vegetation height and cover (Miller et al., 2010b), increased soil compaction (Greenwood and McKenzie, 2001), and concentration of feces (Ballard and Krueger, 2005; Haan et al., 2010) near pasture streams. Therefore, allowing cattle unrestricted access to pasture streams may increase precipitation runoff and transport of sediment and nutrients in runoff (Russell et al., 2001; Butler et al., 2006; Haan et al., 2006). Additionally, feces deposited in or near a pasture stream increases the risks of fecal-borne coliforms, pathogens, and nutrients reaching the water source (Larsen, 1996; Entry et al., 2000; McDowell, 2006) because most nonpoint source pollutants from pastures arise from congregation areas near streams (Line et al., 1998; Pionke et al., 2000). Allowing grazing cattle unrestricted access to streams in 4-ha pastures, heavily stocked with 25 mature cows year-round, increased turbidity and the concentrations of total suspended sediments, total Kjeldahl N, ammonium N, total P, and *Escherichia coli* in the streams (Vidon et al., 2008).

Excluding grazing cattle from pasture streams by fencing increased vegetative cover (Ranganath et al., 2009; Miller et al., 2010b) and reduced concentrations of suspended sediment (Line, 2000; McKergow et al., 2003; Muenz et al., 2006), orthophosphate-P (Muenz et al., 2006), ammonium N (Muenz et al., 2006), and fecal coliform and enterococci (Line, 2003) in pasture streams. However, the effects of livestock exclusion from riparian zones on the geomorphology and water quality of streams have been inconsistent (Sarr, 2002; McKergow et al., 2003; Ranganath

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Abbreviations: BCV, bovine coronavirus; BEV, bovine enterovirus; BRV, bovine rotavirus; CSR, continuous stocking with restricted stream access; CSU, continuous stocking with unrestricted stream access; RS, rotational stocking; PCR, polymerase chain reaction.

et al., 2009; Miller et al., 2010a) as a result of differences in soil types (McKergow et al., 2003), the size and placement of the enclosures (Sarr, 2002; Ranganath et al., 2009), and the site conditions when the site enclosures were established (Sarr, 2002; Agouridis et al., 2005). Furthermore, impacts of exclusion on stream geomorphology, water quality, and aquatic habitat are likely related to the density of congregation of cattle near the stream as affected by the stocking rate (Bear et al., 2010) and factors affecting distribution of the cattle, including pasture size, shape, topography, shade, and vegetation, and the physiological state and experience of the cattle (Bryant, 1982; Bailey, 2005).

Grazing by rotational stocking increases vegetative cover and reduces sediment and P transport in precipitation runoff if adequate residual forage is maintained (Haan et al., 2006). Likewise, sediment losses from stream banks in pastures grazed by rotational stocking were similar to streams within riparian buffer strips (Lyons et al., 2000). Thus, turbidity and concentrations of fecal coliforms and fine substrates in streams in rotationally stocked pastures were less than continuously stocked pastures (Lyons et al., 2000; Sovell et al., 2000).

As an alternative to management practices requiring fencing, off-stream water has been used to reduce the proportion of time that cattle are in or near pasture streams (Miner et al., 1992; Godwin and Miner, 1996). As a result of altering the distribution of grazing cattle, providing off-stream water sources has reduced total sediment, N, P, and fecal coliforms in pasture streams (Sheffield et al., 1997; Byers et al., 2005). Franklin et al. (2009) reported that providing off-stream water to cattle only reduced the proportion of time that cattle were in riparian zones of tall fescue pastures in Georgia when temperature–humidity indices were <72. Porath et al. (2002) also found off-stream water to be effective only in reducing the proportion of time that cattle were in streams of 12-ha foothill pastures in Oregon early in the grazing season but attributed the lack of response late in the grazing season to a reduction in upland vegetation late in the grazing season in pastures with off-stream water. Bagshaw et al. (2008) found no effect of providing water 150 m from the stream on distribution of cattle grazing New Zealand hill country pastures, but this study was conducted on small pastures (1.1 ha) for short periods (6 d). The lack of response in cattle distribution to off-stream water may have resulted from the proximity of the off-stream water to the stream because cattle prefer to graze within 200 m of a water source (Gillen et al., 1984).

Although previous studies have linked stream bank erosion to grazing cattle (Kauffman et al., 1983; Trimble, 1994), these studies fail to account for differences in the sources of the sediment and P. Bank erosion may be caused by mass bank failure, primarily linked to stream hydrology (Simon et al., 2000) or gully, rill, or inter-rill erosion, which may be linked to grazing cattle through the formation of cattle paths and bare ground on the stream banks (Elliott et al., 2002; Strunk, 2003).

The cause and source of stream sediment and P are not fully understood in grazed pastures. The objective of this study was to quantify the effects of three grazing management practices on the amounts of sediment, P, and fecal pathogen loading of a pasture stream in central Iowa.

Materials and Methods

Site Description

A 2-yr study was conducted during the 2008 and 2009 grazing seasons at the Iowa State University Rhodes Research Farm (42°00′ N, 93°25′ W) in the Willow Creek watershed in central Iowa (Fig. 1). The site contains six adjoining 12.1-ha, cool-season grass pastures bisected by a 141-m reach of a perennial flowing stream. Soils at the study site were classified as Ackmore (fine-silty, mixed, nonacid, mesic Aeric Fluvaquent) and Nodaway (fine-silty, mixed, nonacid, mesic Mollic Udifluvent) silt loams. The pastures primarily contained a mixture of smooth bromegrass (*Bromus inermis* L.) and reed canarygrass (*Phalaris arundinacea* L.), with lesser amounts of tall fescue (*Festuca arundinacea* Schreb.), Kentucky bluegrass (*Poa pratensis* L.), and legumes. Pastures were not fertilized during the study or for at least three grazing seasons before the study.

In 2005, the pastures were grouped into two blocks and randomly assigned to one of three grazing treatments. Treatments included continuous stocking with unrestricted stream access (CSU), continuous stocking with stream access restricted to 4.9-m-wide stabilized crossings (CSR), or rotational stocking (RS). In the CSR treatment, cattle were not allowed access to the streamside buffer (~0.91 ha), which reached approximately 33 m on either side of the stream. Pastures in the RS treatment were divided into a five-paddock rotation, with four upland paddocks (2.78 ha) and a single riparian paddock (0.91 ha). Upland paddocks were grazed for a maximum of 14 d or until half of the forage was estimated to be removed as measured by a falling plate meter (Haan et al., 2007). The falling plate meter provides an estimate for standing live forage mass based on its height when

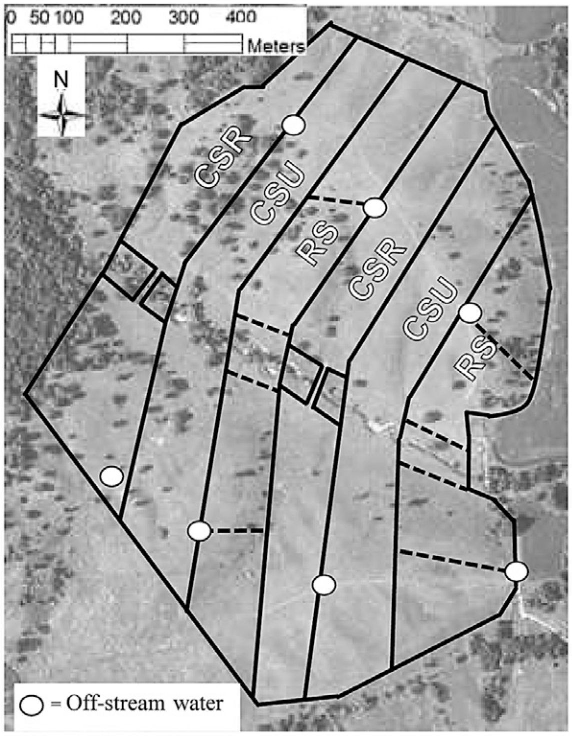

Fig. 1. Pasture design of the Rhodes Research Farm. CSR, continuous stocking with restricted stream access; CSU, continuous stocking with unrestricted stream access; RS, rotational grazing.

a 0.25-m^2 (4.8 kg m^{-2}) square plexiglass sheet is place on top of the grass. Riparian paddocks were grazed for a maximum of 4 d or to a minimum sward height of 10 cm (Clary and Leininger, 2000) as measured by the falling plate meter. This experiment and pasture treatments and data related to the temporal and spatial distribution of the grazing cattle have been described previously (Haan et al., 2010; Schwarte et al., 2010). Data related to characteristics of the riparian area and stream bank erosion in these pastures during the first 3 yr of the study were reported by Nellesen et al. (2011). The rainfall–runoff simulation experiment described here was conducted beginning in 2008, during the fourth and fifth years of experimental treatments at this site.

Ninety fall-calving Angus cows (*Bos taurus* L.) (initial body weight [mean ± SD], 618.6 ± 47.4 and 576.9 ± 48.7 kg in 2008 and 2009, respectively) were blocked by age and weight and assigned to one of the six pastures. Cows were stocked on the pastures from mid-May to mid-October for 153 d in 2008 and 2009. Cattle had access to a P-free mineral (calcium: max. 300 g kg^{-1} min. 250 g kg^{-1}; NaCl: max. 194 g kg^{-1}, min. 162 g kg^{-1}; magnesium: 10 g kg^{-1}; potassium: 5 g kg^{-1}; copper: 1 g kg^{-1}; manganese: 3.75 g kg^{-1}: selenium: 24 mg kg^{-1}: zinc: 3.75 g kg^{-1}; vitamin A: 550,000 IU kg^{-1}; vitamin D_3: 220,000 IU kg^{-1}; and vitamin E: 880 IU kg^{-1} [Kent Feeds, Inc., Muscatine, IA]) in mineral feeders. A data-logging HOBO weather station (Onset Co., Bourne, MA) recorded precipitation using tipping buckets throughout the grazing season.

Rainfall Simulations

Because the average height of the stream bank was approximately 4.6 m, the total area of bare ground, cut-banks, and depositional areas on the stream banks was measured within 4.6 m of the stream with a tape measure in June, August, and October of 2009 and in April of 2010. Each patch or area of a ground cover characteristic was individually and systematically measured with the tape measure. Vegetated ground cover was considered to be the difference between the total bank area and the area that was bare ground, cut-banks, or depositional areas.

Rainfall simulations were conducted in June, August, and October of 2008 and April of 2009 (year 1) and June, August, and October of 2009 and April of 2010 (year 2). These simulations were conducted at three vegetated and three bare locations with similar slopes (0.21 ± 0.075 SD radians) on the stream banks on each side of the stream in each CSU and RS pasture and three vegetated locations on the stream banks on each side of the stream within the riparian buffer in each CSR pasture (total of 60 simulations for each month of measurements). The same sites were used in successive simulations.

Drip-type rainfall simulators (1.0 × 0.5 m) (Bowyer-Bower and Burt, 1989) were placed parallel to the bank slope at a height of 1.0 m from the soil surface at the uphill end of the simulator and leveled, allowing simulated rainfall to reach 56% of terminal velocity (Gunn and Kinzer, 1949). Application water, derived from municipal water, was filtered through a 0.45-μm sediment filter, and precipitation was applied for 1.5 h at a rate of 8.4 cm h^{-1} to simulate a storm with a 100-yr recurrence (Huff and Angel, 1992). At 10-min intervals, the amounts of precipitation and runoff were recorded, and runoff was subsampled and added to a composite sample for each simulation. At the end of each simulation, subsamples of the composited sample were taken for analysis of sediment, P, bovine enteric viruses, and *E. coli* O157:H7. Application water was sampled daily for baseline levels of P, bovine enteric viruses, and *E. coli* O157:H7. Water samples were stored in coolers until transport to the laboratory. Samples for analysis for sediment and P were frozen until analysis. Samples for analysis of bovine enteric viruses and *E. coli* O157:H7 were refrigerated overnight at 4°C and analyzed the following day.

To quantify factors affecting the amounts of precipitation runoff and sediment, P, bovine enteric virus, and *E. coli* O157:H7 transported, the characteristics of each site were measured before each simulation. Ground slope was measured with a digital level (Stabilia, South Elgin, IL). Forage sward height was measured with a falling plate meter (4.8 kg m^{-2}) (Haan et al., 2007). Forage mass was determined by hand-clipping an adjacent 0.25-m^2 area with the same sward height as the rainfall site to a stubble height of 2.5 cm (Haan et al., 2006). Surface roughness was measured as the standard deviation of the length of adjacent pins on a 41-pin meter with a length of 2 m (Betteridge et al., 1999). Proportions of bare and fecal-covered ground were determined by counting the number of pins from the pin meter that contacted bare or fecal-covered ground (Betteridge et al., 1999). Soil samples were taken at three sites adjacent to each simulation location at depths of 0 to 5 cm and 5 to 10 cm for determination of antecedent soil moisture.

Fecal Dry Matter and Pathogen Excretion

To determine total fecal dry matter excreted, two cows in each pasture were pulse-dosed with 30 g of Cr-mordanted fiber (Russell et al., 1993) in June and August of both years. After dosing, fecal samples were collected at 0, 18, 22, 26, 30, 42, 54, 66, 78, 90, 102, and 114 h. Fecal samples were dried and ground through a 1-mm screen of a Wiley mill (Arthur H. Thomas Co., Philadelphia, PA). Fecal samples and Cr-mordanted fiber were ashed and then extracted with phosphoric acid–manganese sulfate–potassium bromate solution (Williams et al., 1962). Chromium in the extracts was determined by atomic absorption spectrophotometry with an air-acetylene flame. The initial concentration (C_0 in g kg^{-1}) and rate of passage (k_p in h^{-1}) of Cr were estimated from passage kinetics of the Cr-mordanted fiber using nonlinear regression analysis (SAS Inst. Inc., Cary, NC) with a two-compartment, age-dependent model (Pond et al., 1988). Gut fill was calculated as:

$$\text{kg} = \text{Amount of Cr dosed}/C_0 \qquad [1]$$

Fecal output was calculated as:

$$\text{kg d}^{-1} = \text{Gut fill} \times k_p \times 24 \qquad [2]$$

To measure the incidence of shedding of the fecal pathogens, fresh fecal samples were aseptically collected immediately post-excretion from all 90 cows in June, August, and September of both years, stored overnight at 4°C, and analyzed.

Stream Bank Erosion

Stream bank erosion was measured on 10 equidistant transects along the stream in each pasture. In 2004, total stream bank area was measured, and fiberglass erosion pins, 1.6 cm diameter by 84 cm length, were driven 78 cm perpendicularly into the bank at 1-m intervals from the side of the stream to the top of the bank (Nellesen et al., 2011). In 2008 and 2009, erosion pins were measured monthly from May through October, with a measurement of 63 cm (75% of total length) recorded if an erosion pin was lost to bank erosion (Lawler, 1993). Net erosion and erosion/deposition activity were calculated as the means of the measurement and absolute value of the measurement of each pin in each transect, respectively (Nellesen et al., 2011).

Net erosion and erosion/deposition activity as well as sediment and P loss throughout each grazing season were calculated as the sum of the monthly values. To separate effects of freeze–thaw cycles from effects occurring during the grazing season, data from the grazing season (May–November) were calculated separately from winter data (November–May).

Laboratory Analysis

Sediment in application water and runoff samples was determined by filtering 20 mL of each sample through pre-weighed, 0.45-μm filter paper. The filter paper was dried for 24 h at 100°C and weighed (APHA, 1995). Total P concentration in application water and runoff samples was determined by digestion of 5-mL samples, followed by colorimetric analysis with the ascorbic acid method (Hach Co., Loveland, CO) (AOAC, 2003).

To measure fecal P, fecal samples from each cow were composited on an equal dry weight basis within month and year and analyzed by combustion in a muffle furnace at 550°C for 4 h followed by an acid extraction of the ash with 6 mol L^{-1} hydrochloric acid, a molybdovanadate reaction, and colorimetric determination against a standard curve (Spectronic Instruments, Rochester, NY) at 400 nm (AOAC, 1990). Total fecal P excretion was calculated by multiplying the fecal P concentration by the fecal output calculated according to Eq. [2].

The incidence of BEV, BCV, and BRV in application water, runoff, and fecal samples was determined by a multiplex real-time, reverse transcription polymerase chain reaction (PCR) following the methods presented in Cho et al. (2010) with modifications to detect BEV in the samples. Primers and the probe for BEV were adopted from a previous work by Jimenez-Clavero et al. (2005) modified to cover newly reported BEV strains and then included in the real-time, reverse transcription PCR. Extraction procedure and PCR conditions remained the same as reported by Cho et al. (2010).

To determine the presence of *E. coli* O157:H7, fecal samples (10 g) were added to 90 mL of GN broth containing 8 μg mL^{-1} vancomycin, 50 ng mL^{-1} of cefixime, and 10 μg mL^{-1} of cefsulodin (Smith et al., 2004). Water samples (10 mL) were inoculated into 90 mL of GN broth. After overnight incubation at 37°C, a 1-mL aliquot was concentrated using O157-specific immunomagnetic beads (Dynal; Invitrogen, Carlsbad, CA) and plated onto selective agar (sorbitol MacConkey agar with cefixime and tellurite). Pale colonies (nonsorbitol fermenters) were counted and confirmed to be *E. coli* O157:H7 using latex agglutination (Oxoid, Basingstoke, UK).

Statistical Analysis

Pasture is considered the experimental unit for all analyses. Precipitation runoff, sediment and P transport, and site characteristic data from the rainfall simulations were analyzed using the MIXED procedure of SAS. Because there were few bare areas other than cut-banks or depositional areas on the banks in the CSR pastures, pasture treatment and site vegetation were combined to form five site classes: CSU bare (CSUbare), CSU vegetated (CSUveg), CSR vegetated (CSRveg), RS bare (RSbare), and RS vegetated (RSveg). The model included the fixed effects of block, year, site class, month, and the interaction of site class and month. Random effects included year × site class × month and block × site class × simulation site to account for repeating the simulation trials at the same simulation sites. Because of non-normal distribution of data, sediment and P concentrations and sward heights were log transformed before analysis.

Stepwise multiple regression in SAS was used to determine the effects of site characteristics (slope, roughness index, sward height, surface cover, and soil moisture) on the percentage of precipitation and the amounts of sediment and P transported in runoff. Variable site characteristics with a significance of $P >$ 0.15 were omitted.

Amounts of bare ground, cut-bank, and depositional area on the stream banks were analyzed by month using the MIXED procedure of SAS with fixed effects of block and treatment and a random effect of block × treatment.

Fecal dry matter and P excretion data were analyzed using the MIXED procedure of SAS with a model statement of year, treatment, month, and their interactions. Random effects included block × treatment and block × treatment × cow because fecal analysis was done on the same cows within treatments in both months of a given year. Net erosion and erosion/deposition activity were analyzed using the MIXED procedure of SAS with a model statement of block, year, treatment, season (grazing vs. winter), and the interactions of season × treatment, season × year, and year × treatment. Random effects included block × treatment and year × season × treatment. Differences between means with significant treatment effects in all analyses were determined by comparing the LSMeans using the PDIFF statement along with a Tukey adjustment for multiple comparisons. Significance was determined at a level of $P < 0.10$. Treatment differences for the incidences of the viruses and *E. coli* O157:H7 shed by the cattle or collected in the precipitation runoff were not statistically analyzed because of very low occurrence.

Model Calculations

To quantify the sources of sediment, P, and pathogen loading of pasture streams, a model was developed, and the amounts from direct fecal deposition, transport in surface runoff from the stream banks, and stream bank erosion were determined (Fig. 2).

Because distribution of cattle feces is proportional to the amount of time spent within a pasture zone relative to a stream (Ballard and Krueger, 2005; Haan et al., 2010), the amounts of fecal dry matter and P excreted daily per cow were multiplied by the number of days in a month and the percentage of time cattle spent within the stream zone (0–3 m from stream center) as measured by GPS collars from Schwarte et al. (2010) to calculate the total amounts of fecal dry matter and P deposited into the stream each month. Annual dry matter and P deposition in the stream per pasture were calculated as the sum of the monthly values multiplied by the stocking rate of 15 cows per pasture.

To predict precipitation runoff from each rainfall event that occurred over the grazing seasons in both years, the REG procedure of SAS used rainfall simulation data comparing the amount of simulated precipitation applied to the amount of runoff at 10-min intervals from each site class within each month and year to produce runoff regression equations (Table 1). Because the application rates during the simulations were 8.4 cm h^{-1}, these run-off values should represent a near–worst-case scenario. Linear regressions were used because quadratic equations did not improve the correlation coefficients. Amounts of daily precipitation throughout the entire grazing season of both years were entered into the regression equation at the nearest date to calculate predicted runoff from each site class from a 0.5-m^2 area of land. These runoff quantity data were multiplied by the means of the sediment and P concentrations in the runoff of each rainfall simulation site class, weighted for the volume from each simulation, to yield the predicted amounts of sediment and P transported from each site class during a runoff event based on a 0.5-m^2 area of land. Mean sediment and P transported within 0.5-m^2 sites of each site class of a pasture were multiplied by the amount of land in that site class within 4.6 m of the stream to calculate the total amounts of sediment and P transported in runoff from the stream bank within each pasture in each month of each grazing season. Although rainfall simulations could not be conducted on the stabilized stream crossings, P and sediment loads in runoff from these areas were calculated using concentrations and rates from the CSUbare site class and multiplied by the area of bank covered with the stabilized crossing to account for sediment and P loading of the runoff from these stream crossings. Previously, runoff from stabilized sites on 3% slopes with rainfall intensities of 50 mm h^{-1} have been reported to be approximately half of that from bare ground (Singh et al., 2008). Therefore, sediment and P loads in runoff from the CSUbare site class were halved to calculate the sediment and P loss per m^2. Annual sediment and P transported in runoff during the grazing season of each year were calculated as the sum of the amounts of sediment and P transported monthly.

Sediment and P losses from cut-banks and depositional areas were included in the total sediment and P losses. The volume of stream bank sediment lost was calculated by multiplying the area of the bank within each pasture by the net erosion, as measured from the erosion pins each month during the grazing season. To calculate the volume of sediment and P lost via cut-bank erosion in 2009, the area of cut-bank within each pasture was multiplied by net erosion measured from transects located on cut-banks.

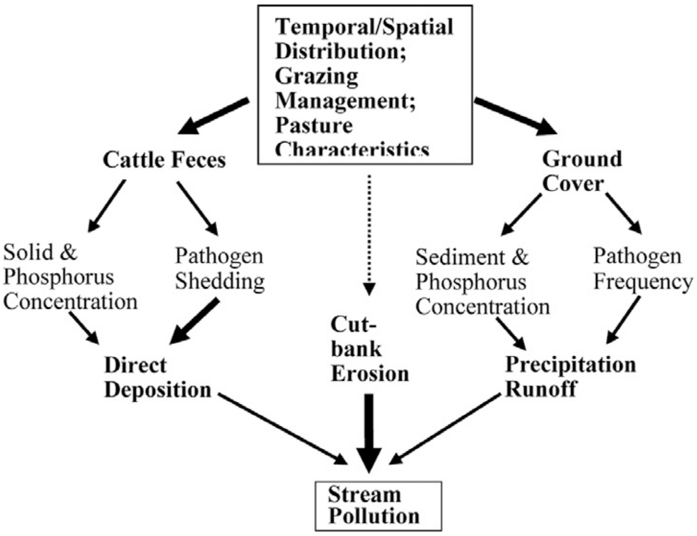

Fig. 2. Model of nonpoint-source pollution loading of pasture streams.

The amounts of sediment and P lost from the total bank or cut-bank areas were calculated by multiplying the volume of sediment lost from the total bank or cut-bank area by the bulk density and total P concentration data of bank soil samples taken from the A and C soil horizons (Nellesen et al., 2011). Total sediment and P loss from the total bank or cut-bank area in each pasture were calculated as the sum of the sediment and P loss from A and C soil horizons on both sides of the stream.

Results

Stream Bank Cover

The amounts of bare and vegetated ground and cut-bank did not differ ($P > 0.10$) among the treatments (Table 2). However, the stream banks in the CSU treatment had a greater ($P < 0.10$) proportion of depositional area than did the stream banks in the CSR treatment.

Rainfall Simulations

As designed, simulation sites designated as bare treatments had a greater ($P < 0.01$) proportion of bare ground than vegetated

Table 1. Estimations of the effects of rainfall simulation site class on the quantity of runoff from precipitation on pasture stream banks.

Month	Treatment†														
	CSUveg			CSUbare			CSRveg			RSveg			RSbare		
	Intercept	Coeff.	R^2	Intercept	Coeff.	R^2	Intercept	Coeff.	R^2	Intercept	Coeff.	R^2	Intercept	Coeff.	R^2
							Year 1‡								
June	−1170.9§	191.2	0.3624	−1578.1	412.8	0.9230	−498.1	121.6	0.1921	−1572.1	223.7	0.3689	−463.3	312.9	0.5028
Aug.	−1889.9	153.5	0.4885	−5646.1	420.6	0.9495	−914.3	52.3	0.1581	−4790.3	223.7	0.6365	−5306.8	410.0	0.8969
Oct.	−1456.1	202.4	0.5793	−5088.5	414.6	0.9322	−1863.6	115.6	0.3076	−2924.7	233.8	0.6254	−5119.7	398.2	0.9103
Apr.	−2516.4	200.0	0.4359	−4093.0	400.4	0.9397	−1706.2	120.3	0.3042	−3309.2	232.9	0.5888	−4348.8	368.7	0.8795
							Year 2								
June	−2135.5	183.8	0.3814	−3213.8	422.7	0.9030	−976.2	75.3	0.2046	−1517.6	128.8	0.2854	−2762.6	397.7	0.8100
Aug.	−1160.9	137.4	0.2590	−4157.0	428.9	0.9584	−373.0	21.4	0.1286	−1612.3	83.0	0.2235	−3569.4	345.0	0.7384
Oct.	−2145.3	250.1	0.4571	−3736.0	441.5	0.9805	−1647.2	107.3	0.2558	−2648.8	221.5	0.4837	−3920.7	426.5	0.9144
Apr.	−2718.3	229.5	0.6138	−3303.5	439.6	0.9856	−1171.8	70.4	0.1883	−2391.1	192.4	0.5071	−4363.4	394.2	0.8568

† CSU, continuous stocking with unrestricted stream access; CSR, continuous stocking with restricted stream access; RS, rotational stocking. Simulation on vegetated (veg) or bare (bare) ground.

‡ Year 1 = June, Aug., and Oct. 2008 and Apr. 2009. Year 2 = June, Aug., and Oct. 2009 and Apr. 2010.

§ Measurement is based on a 0.5-m^2 area from rainfall simulation. Independent variable is precipitation (x), and dependent variable is runoff (yr).

sites, and the slopes of the sites did not differ ($P > 0.10$) among treatments (Table 3) and did not vary by month or year. Forage sward heights at CSRveg sites were greater ($P < 0.10$) than at CSUveg sites, and all vegetated sites had greater ($P < 0.05$) sward heights than bare sites did. Sward height was greater at the rainfall simulation sites in year 2 (Year; $P = 0.0002$) than in year 1 (data not shown). Likewise, sward height differed between each month (Month; $P < 0.10$), with height being greatest in June, followed by August, October, and April. Multiple month × treatment effects also occurred (Month × Treatment; $P < 0.10$). Forage mass of CSRveg sites did not differ ($P > 0.10$) from CSUveg or RSveg sites but was greater ($P < 0.05$) than CSUbare or RSbare sites. Forage mass was greater in June than in the other months of the study (Month; $P < 0.05$).

Moisture contents of the top 5 cm of soil were lower ($P < 0.10$) in the CSUveg and CSUbare sites than in the CSRveg sites (Table 3). Also, moisture contents of the lower 5 to 10 cm of soil were lower ($P < 0.10$) in the CSUveg and CSUbare sites than in the RSveg sites. Soil moisture contents at both depths were greater in year 2 than in year 1 (Year; $P < 0.10$) and were greater in June than in August and October (Month; $P < 0.05$). Similarly, soil moisture contents at both depths were greater in April than in August (Month; $P < 0.05$), and soil moisture content in the lower 5 cm was greater in October than in August (Month; $P < 0.05$). Soil roughness of the sites did not differ ($P > 0.10$) among treatments but did differ by month (Month; $P < 0.05$) because sites in April were rougher than the sites in June and August (Table 3).

Table 2. Effects of grazing management on the percentage of stream bank ground cover in different months from June 2009 to April 2010.

Item	Treatment†	June	Aug.	Oct.	Apr.
Bare ground, %	CSU	20.04	12.00	12.14	17.38
	CSR	4.59	4.01	0.85	4.82
	RS	12.92	5.69	4.24	6.18
	SEM‡	4.23	1.96	2.77	3.49
Vegetated ground, %	CSU	29.06	35.64	44.29	35.10
	CSR	76.60	79.62	82.10	70.02
	RS	53.61	67.78	73.22	63.86
	SEM	14.32	10.95	10.17	12.48
Cut-bank, %	CSU	34.14	28.81	25.68	28.40
	CSR	13.22	12.69	12.69	19.48
	RS	16.52	15.91	14.77	20.62
	SEM	6.53	9.17	8.02	1.09
Depositional area, %	CSU	16.77	23.54a§	17.89a	19.12
	CSR	1.85	0.00b	0.62b	0.75
	RS	16.95	10.62ab	7.76ab	9.34
	SEM	8.08	5.00	3.37	4.74

† CSR, continuous stocking with restricted stream access; CSU, continuous stocking with unrestricted stream access; REs, rotational grazing.

‡ Standard error of the mean ($n = 6$).

§ Means within a column with different letters differ ($P < 0.10$).

Table 3. Effects of grazing treatment and ground cover on rainfall simulation characteristics conducted in June, August, and October 2008 and April 2009 and in June, August, and October of 2009 and April 2010.

Item	Treatment†					Statistics	
	CSUveg	CSUbare	CSRveg	RSveg	RSbare	SEM‡	*P* value
Bare ground, %	16.8a§¶	79.3b	5.0a	13.6a	61.8b	5.8	<0.0001
Slope, rad.	0.23	0.21	0.23	0.24	0.22	0.02	0.9339
Sward height, cm#	1.53c (3.6)	0.15a (0.2)	2.20d (8.0)	1.95cd (6.0)	0.74b (1.1)	0.12	<0.0001
Forage mass, kg ha^{-1}	1327.8abc	141.0a	2365.3c	1997.8bc	655.9ab	399.7	0.0049
Antecedent soil moisture, 0–5 cm g kg^{-1}	149.51a	148.30a	201.52b	189.11ab	184.47ab	12.56	0.0223
Antecedent soil moisture, 5–10 cm g kg^{-1}	143.08a	143.84a	166.19ab	171.00b	168.47ab	6.94	0.0163
Roughness index	1.01	0.95	1.19	0.99	1.01	0.07	0.1312
Runoff, L h^{-1}	14.98a	32.09b	6.35c	14.01a	28.89b	0.64	<0.0001
Runoff, %	36.55a	78.71b	15.32c	33.98a	70.76b	3.89	<0.0001
Sediment, kg ha^{-1}¶	4.73a (112.3)	8.29b (3983.2)	2.72c (14.2)	4.73a (111.9)	7.16b (1290.2)	0.33	<0.0001
Phosphorus, g ha^{-1}¶	6.29a (536.2)	9.31b (11,085.7)	4.18c (64.5)	6.21a (495.7)	8.18b (3565.4)	0.33	<0.0001

† CSR, continuous stocking with restricted stream access; CSU, continuous stocking with unrestricted stream access; RS, rotational stocking. Simulation on vegetated (veg) or bare (bare) ground.

‡ Standard error of the mean ($n = 16$).

§ Means within a row with different letters differ ($P < 0.10$).

¶ Means averaged across years and months.

Log transformed for data analysis (Ln[x + 1]). Natural, untransformed number in parentheses.

Table 4. Regressions predicting runoff and sediment and phosphorus loading during rainfall simulations on bare and vegetation sites from site characteristics conducted in June, August, and October 2008 and April 2009 and in June, August, and October 2009 and April 2010.

Item	Independent variable	Coefficient	Partial R^2
Runoff, % of applied precipitation	intercept	31.03	–
	bare ground, %	0.47	0.5050
	sward height, cm	−1.06	0.0610
	antecedent moisture content, g kg^{-1} (0–5 cm)	0.05	0.0055
	roughness index, cm	−5.42	0.0046
	slope, radians	16.18	0.0022
	total	–	0.5782
Sediment, kg ha^{-1}	intercept	−1,564.16	–
	bare ground, %	61.40	0.3811
	slope, radians	5,964.1	0.0181
	total	–	0.3992
Phosphorus, g ha^{-1}	intercept	−1,996.75	–
	bare ground, %	142.78	0.4302
	sward height, cm	−80.90	0.0045
	slope, radians	11,654.0	0.0136
	total	–	0.4483

Precipitation runoff, expressed as volume (L h^{-1}) or as a proportion of applied precipitation, was greater ($P < 0.05$) from bare sites than from vegetated sites across grazing management treatments (Table 3). RSveg and CSUveg sites had greater ($P < 0.05$) amounts and proportions of runoff than the CSRveg site. Of the characteristics measured, the proportion of runoff of applied precipitation was best predicted by the proportion of bare ground, with sward height, antecedent soil moisture (0–5 cm), roughness index, and bank slope having some effect ($R^2 = 0.5782$) (Table 4).

Similar to runoff, transport of sediment ($P < 0.05$) and P ($P < 0.10$) in runoff were greater from bare sites than from vegetated sites across grazing management treatments, and the RSveg and CSUveg sites had greater ($P < 0.05$) amounts of sediment and P transported in runoff than the CSRveg sites (Table 3). Sediment transport in precipitation runoff was best predicted by the proportion of bare ground and slope ($R^2 = 0.3992$). Phosphorus transport was most accurately predicted by the proportion of bare ground, sward height, and slope ($R^2 = 0.4483$). Of the characteristics measured, the proportion of bare ground was the most significant factor for determining the proportion of runoff of applied precipitation and the amounts of sediment and P transport in runoff, resulting in the following regressions (Fig. 3):

$$\text{Runoff: \% of applied precipitation} = 27.83 + 0.5565x \ (R^2 = 0.5050) \qquad [3]$$

$$\text{Sediment loss: kg ha}^{-1} = -218.6 + 61.65x \ (R^2 = 0.3811) \qquad [4]$$

$$\text{P loss: g ha}^{-1} = -68.18 + 150.3x \ (R^2 = 0.4302) \qquad [5]$$

where x is the proportion of bare ground (%).

Simulated precipitation runoff was greater in April and October than in August (Month; $P < 0.01$) (data not shown). Similarly, sediment transport in runoff was greater in April and June than in August (Month; $P < 0.01$), and P transport in runoff was greater in October than in August (Month; $P < 0.05$). These effects were likely caused by wet conditions observed in early spring and lower sward heights and forage mass observed early and near the end of the grazing season. Sediment and P transport in runoff were greater in year 1 than in year 2 (Year; $P < 0.10$), which was likely the result of the above-average rainfall that occurred in May and June of year 1 (2008) (Schwarte et al., 2010).

Escherichia coli O157:H7, BCV, and BRV were not detected in runoff samples during the study. Total *E. coli* counts were not analyzed, and incidences may have occurred. Bovine enterovirus, an indicator of fecal contamination (Ley et al., 2002), was found in 8.3 and 16.7% of the runoff samples from CSUbare sites in June and October 2008, respectively, and in 8.3% of the CSUveg sites in April 2009 (data not shown). No observations of BEV were detected in runoff samples from the RSveg, RSbare, and CSRveg sites.

Fecal Dry Matter and Phosphorus Output and Pathogen Shedding

Fecal dry matter output by the cows did not differ ($P > 0.10$) among treatments (Table 5). Fecal dry matter output was greater in 2009 than in 2008 (Year; $P < 0.05$) and was greater in June than in August (Month; $P < 0.05$). Mean P concentrations of the feces were greater ($P < 0.05$) in the CSR and CSU treatments than in the RS treatment. Mean P concentrations of the feces were also greater in August than in June (Month; $P < 0.01$) and increased more in RS treatment feces from June to August than in the other treatments (Treatment × Month; $P < 0.01$). As a result of the differences in fecal P concentration, total P excretion in the feces tended to be greater ($P = 0.1110$)

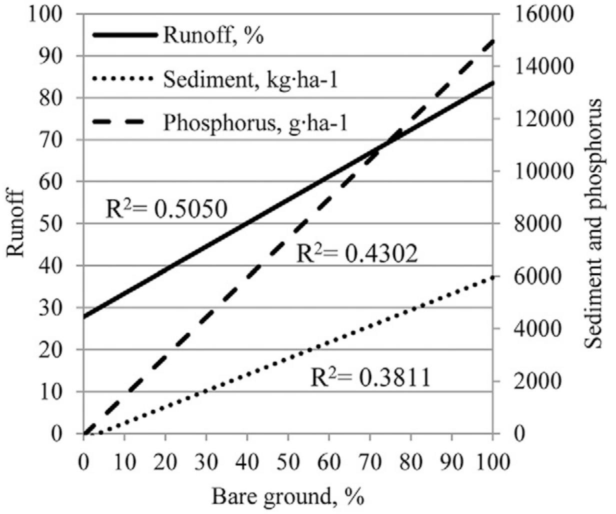

Fig. 3. Correlation between the percentage of applied precipitation, sediment, and phosphorus loading in runoff versus the percentage of bare ground during rainfall simulations conducted in June, August, and October 2008 and April 2009 and in June, August, and October 2009 and April 2010.

for the CSR and CSU treatments than for the RS treatments and also differed by year, with greater amounts excreted in 2009 (Year; $P = 0.0073$).

Bovine enterovirus was found in feces from 4.4, 28.8, and 41.1% of cows in June, August, and September 2008, respectively, and from 38.9, 18.9, 13.3% of cows in June, August, and September 2009, respectively (Table 6). Bovine coronavirus was shed in the feces of one cow in August 2008. *Escherichia coli* O157:H7 and BRV were not detected in the fecal samples during the experiment.

Stream Bank Erosion

There were no significant differences in net erosion or in erosion/deposition activity among treatments or seasons or between years (Fig. 4). Averaged over treatments, years, and seasons, the stream banks had a net erosion of 5.2 cm and erosion/deposition activity of 11.1 cm per season per year.

Model Results

Comparisons of the estimations of the annual sediment and P loading of the pasture stream by precipitation runoff, cattle feces, and stream bank erosion show that cut-bank erosion is the greatest contributor to sediment and P loading of pasture streams because losses from cut-banks were approximately 1.5 times the measured losses from the total stream bank erosion (Table 7). Averaged over 2008 and 2009, stream bank erosion accounted for 99.5 and 94.4% of the sediment and P, respectively, transported to the pasture streams. Although the amounts of sediment and P loading from direct fecal deposition or precipitation runoff were small when compared with bank erosion, the sedimentation of the stream via direct deposition of feces was 46.4% less than that in precipitation runoff across grazing treatments at a stocking density of 0.106 cows m^{-1} stream. However, the amount of P entering the stream via fecal deposition was 32.5% greater than that in precipitation runoff. This difference was likely the result of the soil P at the study site being between 0.18 to 0.35 g kg^{-1} (Nellesen et al., 2011), whereas fecal P was approximately 20 times greater at 4.8 to 6.8 g kg^{-1}.

Discussion

Previous studies measuring stream water quality have shown that pastures and rangelands are the largest contributors to phosphorus levels in surface waters (Downing et al., 2000; Alexander et al., 2008). Results of this study showed that considerable amounts of sediment and P are lost from pasture stream banks on an annual basis; however, the major source of the sediment and P in pasture streams is eroding stream banks, specifically cut-banks, and not surface runoff or fecal deposition. Surface runoff and fecal deposition are undoubtedly linked to grazing animals; however, the effects of grazing animals on stream bank erosion are not fully understood. In this study, stream bank erosion was not linked to grazing treatment. As discussed by Magner et al. (2008) and Zaimes et al. (2008), many Midwestern pastures are located on long, narrow sections of land alongside streams that is not suitable for row-crop production. Therefore, erosion from pasture stream banks is likely enhanced by the land on which most pastures are located.

Sediment and P lost from eroding cut-banks accounted for most or all of the losses along the entire stream reach within each pasture (Table 7), suggesting that other areas of the stream banks are trapping eroded sediment and P lost from the cut-banks (Lauer and Parker, 2008). Although the amounts of cut-bank in the CSU pastures appeared to be numerically greater than the CSR or RS pastures, these differences were related to stream channel conditions. Streams in both CSU pastures and in one RS pasture had ox bows opposite from cut-banks, whereas CSR pastures had no ox bows (Fig. 1). Furthermore, the mean bank stability score of CSU pastures was 12 and 30% greater than CSR and RS pastures when the treatments were initiated in May 2005 (Nellesen et al., 2011), implying that the banks in the CSU pastures were more unstable than banks in the CSR and RS pastures at the initiation of treatments within these pastures. From May 2005 to September 2009, bank stability scores increased by 1.68, 1.66, and 4.03% yr^{-1} in CSU, CSR, and RS pastures, respectively, implying that stream bank stability in RS pastures was declining more rapidly than CSU or CSR pastures (Nellesen et al., 2011; Schwarte et al., 2010). However, trend analysis of the monthly erosion/deposition data from 2005 through 2007 showed that RS pastures had an increasing trend (i.e., a decrease in bank

Table 5. Effects of grazing management on fecal excretion of dry matter and phosphorus per cow over 2 years.

Item	Month	Treatment†			SEM‡
		CSU	CSR	RS	
Fecal dry matter, kg d^{-1}	June	7.02§	7.94	7.54	0.55
	Aug.	6.72	6.84	6.11	
Fecal P, g kg^{-1}	June	6.41a¶	6.05a	4.84b	0.17
	Aug.	6.77a	6.38a	5.74b	
Fecal P, g d^{-1}	June	44.7	47.8	36.5	2.4
	Aug.	44.7	43.3	35.3	

† CSR, continuous stocking with restricted stream access; CSU, continuous stocking with unrestricted stream access: RS, rotational stocking.

‡ Standard error of the mean ($n = 8$).

§ Means are averaged across years 2008 and 2009.

¶ Means within a row with different letters differ ($P < 0.10$).

Table 6. Incidence of viral and bacterial shedding in the feces of cattle.

Item†	2008			2009		
	June	Aug.	Sept.	June	Aug.	Sept.
Escherichia coli O157:H7	0‡	0	0	0	0	0
BCV	0	1 (1.1)	0	0	0	0
BRV	0	0	0	0	0	0
BEV	4 (4.4)	26 (28.8)	37 (41.1)	35 (38.9)	17 (18.9)	12 (13.3)

† BCV, bovine coronavirus; BEV, bovine enterovirus; BRV, bovine rotavirus.

‡ Percentage shown in parentheses ($n = 90$ cows sampled).

erosion), whereas no trend was observed in CSU and CSR pastures (Nellesen et al., 2011).

Although studies have shown significant reductions in stream bank erosion resulting from cattle exclusion (Kauffman et al., 1983; Trimble, 1994; Zaimes et al., 2008), other studies have not (Allen-Diaz et al., 1998; George et al., 2002; Nellesen et al., 2011). These results suggest that the effect of cattle on stream bank erosion is site- or method specific. In the current study, stream bank erosion was variable within treatments and seasons.

Managed grazing can reduce the impact of grazing cattle on surface runoff and stream water quality (Sheffield et al., 1997; Haan et al., 2006). However, sediment and P loading via fecal deposition and surface runoff together accounted for 0.5 and 5.6% of average sediment and P losses, respectively. A greater percentage of P loading than sediment loading was attributed to runoff and direct deposition because of the high concentration of P in the cattle feces. Additionally, if P is fed in concentrations higher than necessary, the total P concentration and the proportion of water-soluble P in fecal excretion increases (Dou et al., 2002). Because the forage P concentrations at the farm were adequate to meet the cattle's nutritional requirements (~2.0 g kg^{-1} dry matter) (Haan et al., 2007) and the mineral supplement used in this study was void of P, it is likely that the P excretion values observed in this study were lower than the values would have been if a P supplement had been offered. Therefore, direct deposition of cattle feces into a pasture stream may add a significant amount of P to the water if cattle are spending a large amount of time within the stream. However, in the current study, cattle in the CSU treatment spent 1.8% of their time in the stream, whereas cattle in the CSR and RS treatments spent 0.35 and 0.09% of their time in the stream, respectively (Schwarte et al., 2010). Although other researchers have reported that providing off-stream water reduced sediment, P, and fecal bacteria loading of pasture streams by altering the temporal and spatial distribution of grazing cattle (Sheffield et al., 1997; Byers et al., 2005), providing off-stream water to cows in the CSU and CSR pastures for 1 wk mo^{-1} did not affect cattle distribution in the pastures in this experiment (data not shown) (Schwarte et al., 2010).

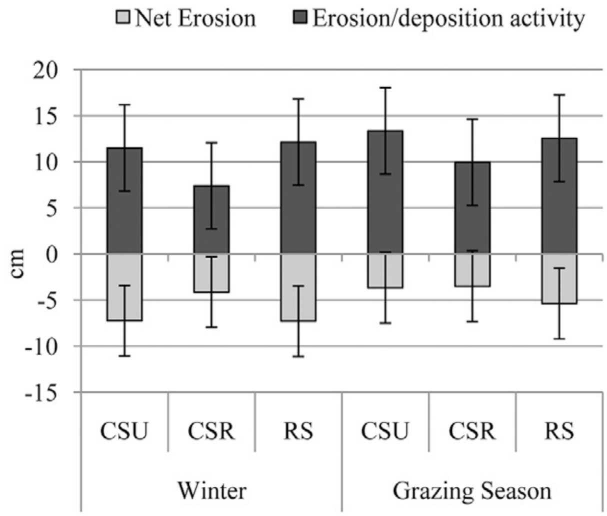

Fig. 4. Mean net erosion and erosion/deposition activity on stream banks of pastures grazed with treatments of continuous stocking with unrestricted stream access (CSU), continuous stocking with restricted stream access (CSR), and rotational grazing (RS) from mid-May to mid-October of 2008 and 2009. Bars signify SE (*n* = 12).

Rainfall simulations in the riparian buffer had less runoff and lower amounts of sediment and P transported in runoff than all sites where cattle had access. However, vegetated sites in the CSU and RS treatments also had less runoff and sediment and P transport in runoff than bare sites in either treatment.

Table 7. Estimates of sediment and phosphorus loading of pasture streams from stream bank runoff, cattle feces, and stream bank erosion in 2008 and 2009.

Item	Treatment†	Sediment			Phosphorus		
		2008	2009	Cut-banks‡	2008	2009	Cut-banks‡
		kg			g		
Runoff§	CSU	554.72	257.04	–	1122.26	812.45	–
	CSR	55.47	8.67	–	179.62	59.59	–
	RS	371.91	82.02	–	933.59	343.08	–
Cattle feces¶	CSU	267.98#	298.61	–	1795.48	1884.47	–
	CSR	41.35	77.64	–	256.07	476.90	–
	RS††	0	25.59	–	0	147.09	–
Net erosion				$\times 10^3$			
Grazing season	CSU	85.84	37.95	54.87	20.33	9.16	13.29
	CSR	84.92	–4.11	13.78	21.03	–0.29	2.85
	RS	188.25	30.40	49.96	42.22	7.95	9.59
Winter	CSU	49.12	170.08	412.26	11.47	42.90	99.80
	CSR	11.10	89.75	97.09	2.63	23.49	19.87
	RS	136.28	98.07	131.36	25.66	21.95	28.66

† CSR, continuous stocking with restricted stream access; CSU, continuous stocking with unrestricted stream access; RSU, rotational stocking.

‡ Amounts estimated to be lost from transects located on cut-banks in 2009.

§ Runoff data include precipitation occurring from 1 May to 31 Oct. 2008 and from 1 Apr. to 31 Oct. 2009. Precipitation data for April 2009 were retrieved from NOAA weather station in Marshalltown, Iowa (~15 mi from study site). Based on 141-m stream reach of site pastures with a 4.6-m bank height.

¶ Based on 15 cows stocked on a 12.1-ha pasture.

Total feces deposited into stream.

†† Cattle were not stocked in the riparian area at the same time as location determination except for September 2009.

Therefore, management practices to minimize bare ground on the stream banks are the most effective tool to reduce the amount of sediment and P entering pasture streams in precipitation runoff. These results are similar to results reported by Butler et al. (2006) and Haan et al. (2006), who observed minimizing bare ground as the most important factor in reducing sediment and P transport in precipitation runoff.

Cattle may shed fecal pathogens such as BCV, BRV, and *E. coli* O157:H7 (Crouch and Acres, 1984; Wells et al., 1991; Lucchelli et al., 1992). Shedding of pathogens in the present study was rare, occurring only once during the study, when BCV was shed by one cow. However, in 2007, the year before the study, *E. coli* O157:H7 was recovered from 12 of the 90 cows during the September collection, with 10 of these cows being present in one of the RS pastures (unpublished data). The presence of bovine enterovirus was analyzed because it has been proposed as a good indicator of fecal contamination (Ley et al., 2002). Results of this study showed that shedding of BEV was highly variable but was high enough to be infrequently detected in runoff samples. Additionally, because cattle were not stocked on the pastures before the rainfall simulation conducted in April 2009, BEV was able to survive the winter or was shed by another host source (Ley et al., 2002). This study shows that viruses shed by cattle may be transmitted through surface runoff, with a greater number transmitted on bare compared with vegetated ground. Therefore, the major factors in controlling the risk of pathogen loading of pasture streams, in order of importance, are the occurrence of pathogen shedding, the temporal/spatial distribution of grazing cattle, and surface runoff.

Conclusions

Estimations of annual sediment and P loading into the pasture stream show that stream bank erosion via cut-bank erosion is the greatest contributor of sediment and P to the pasture stream. Improvements in sediment and P loading from precipitation runoff may result by the use of cattle-excluded riparian buffers; however, the greatest differences in sediment and P loading of runoff occur between bare and vegetated ground on stream banks in grazed pastures. Minimizing the amount of bare ground on the stream banks is critical to minimizing the amounts of sediment and P in precipitation runoff and may be attained by the use of rotational stocking as well as riparian buffers. Additionally, pathogen loading of pasture streams by grazing cattle was infrequent and dependent on the pathogen shedding, temporal and spatial distribution of grazing cattle, and surface runoff from stream banks.

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