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Stream bank erosion as a source of sediment and phosphorus in grazed pastures of the Rathbun Lake Watershed in southern Iowa, United States

M. Tufekcioglu, T.M. Isenhart, R.C. Schultz, D.A. Bear, J.L. Kovar, and J.R. Russell

Abstract: Livestock grazing of riparian areas can have a major impact on stream banks and stream integrity if improperly managed. The goals of this study were to determine the sediment and phosphorus (P) losses from stream bank soils under varying cattle stocking rates and to identify additional factors that impact stream bank erosion in the southern Iowa Drift Plain. The research was conducted on 13 cooperating beef cow-calf farms within the Rathbun Lake Watershed in south central Iowa. Over three years, stream bank erosion rates were estimated by using an erosion pin method. Eroded stream bank lengths and area, soil bulk density, and total P (TP) content in stream bank soil were measured to calculate soil and TP losses via stream bank erosion. The length of severely eroded stream banks and soil compaction of the riparian areas of the pastures were positively related to stocking rates. There was no direct relationship between bank erosion and stocking rate. These results suggest that use of riparian areas as pasture can negatively impact the integrity of the major source areas and that the impact could be reduced through management of livestock stocking densities within these riparian areas.

Key words: livestock grazing—riparian pasture—stream bank erosion—water pollution

Sediment is a naturally occurring component of aquatic ecosystems; the transport and deposition of sediment are natural processes within fluvial systems. However, sediment imbalance, specifically excess sediment, is a significant concern for water quality and aquatic life. Sediment and sedimentation have been recognized as a leading cause of water body impairment nationally (USEPA 2003) and have been identified by the US Environmental Protection Agency as a priority area for improving the quality of the nation's waters. Phosphorus (P) has been identified as a major limiting nutrient for eutrophication of many lakes and streams (Correll 1998), and in most cases, P moves to surface waters attached to sediment as particulate P (Sharpley et al. 1987). Increased P concentration in streams often promotes toxic algal blooms and excess growth of other aquatic nuisance plants. Aerobic decomposition of the enhanced organic matter production may lead to hypoxic conditions and reduced stream integrity (Carpenter et al. 1998).

In combination with overland flow and bed sediment resuspension, bank erosion is one of the important pathways of nonpoint source pollutant transport into surface waters. Bank erosion accounts for 23% to 76% of a catchment's suspended sediment export (Laubel et al. 1999; Schilling and Wolter 2000; Laubel et al. 2003; Thoma et al. 2005; Nagle et al. 2007; Simon 2008). In addition to sediment, total phosphorus (TP) contribution to channels from stream bank erosion may vary from 7% to 56% of the total TP load to the channel (Roseboom 1987; Sekely et al. 2002; Laubel et al. 2003). Because of the greater number of variables involved in the erosion process and the unique relationships among them, the wide range of estimated sediment and P loads to streams from bank erosion has been reported in the literature. Variables, such as over-hanging banks; bank angle; bank vegetation cover; estimated stream power (Laubal 2003); and channel width, depth, and slope (Odgaard 1987), can influence the rate of bank erosion.

While stream bank erosion is a natural, continuous, fluvial process for all streams, it is often accelerated by human activities (Henderson 1986). Livestock grazing and row crop production are the two main agricultural practices in the Midwest responsible for this acceleration. Moreover, research in Iowa by Downing and Kopaska (2001) concluded that a watershed with a higher proportion of land as pasture may contribute more P to streams than a watershed with a higher proportion of land in row crop use, although pathways of this input were not identified. A recent study by Alexander et al. (2008) reported that 37% of the P contributed to streams and lakes came from nonrecoverable animal manure and seasonally applied fertilizers on adjacent pasture and rangelands. There are, however, considerable differences among various grazing practices. Research, conducted in Minnesota by Magner et al. (2008), in Iowa regions by Zaimes et al. (2008a), and by Nellesen et al. (2011), indicated that using rotational or intensive/short rotational grazing practices instead of continuous grazing could reduce the amount of sediment and P load to streams. Another study conducted in Iowa by Haan et al. (2006) suggested that reduction in sediment and P loss via surface runoff from grazed pastures can be achieved with grazing management practices that maintain forage cover, where sward height is more than 5 cm (2 in), to protect the soil surface from direct raindrop impacts.

The present study was conducted within the Rathbun Lake Watershed in south central Iowa. Rathbun Lake is the primary water source for 70,000 residents in southern Iowa and northern Missouri. In addition to providing drinking water, this 4,500 ha

Mustafa Tufekcioglu is an assistant professor in the Department of Forestry at Artvin Coruh University, Artvin, Turkey. **Thomas M. Isenhart** is an associate professor, and **Richard C. Schultz** is a professor in the Department of Natural Resource Ecology and Management at Iowa State University, Ames, Iowa. **Douglas A. Bear** is a research scientist, and **James R. Russell** is a professor in the Department of Animal Science at Iowa State University, Ames, Iowa. **John L. Kovar** is a soil scientist in the National Laboratory for Agriculture and Environment, Soil Tilth, USDA Agricultural Research Service, Ames, Iowa.

(11,119 ac) lake provides recreation opportunities for one million visitors annually and flood control for downstream land. Thirteen water bodies (Rathbun Lake and streams) in the Rathbun Lake Watershed were listed as impaired on the 2008 Iowa Department of Natural Resources 303d listing of impaired waters (IDNR 2008). Soil erosion from stream banks has been identified as an important source of sediment and associated P delivery to Rathbun Lake. Stream bank erosion accounts for 26% of the total estimated sediment delivery from the watershed (Braster et al. 2001). One potential contributing factor to this erosion is livestock grazing with unrestricted stream access along riparian areas that comprise 38% of the total watershed. In 2001, there were 468 livestock grazing and feeding operations in the Rathbun Lake Watershed, of which 90% were beef cattle operations. Of these operations, 350 rely on grazing with little or no confinement. Thus, identification and implementation of cost-effective grazing management and conservation practices that limit deterioration of riparian areas could improve the water quality of Rathbun Lake.

The objectives of this study were (1) to identify relationships among stream bank erosion variables, including erosion rate, livestock grazing stocking rate, precipitation rate, percentage of severely eroded bank length and area, and soil bulk density from severely eroded banks and (2) to compare erosion rate, soil loss rate, and soil TP loss rate along the reaches with different stream orders (1st, 2nd, and 3rd). The null hypotheses are (1) that there is no relationship among stream bank erosion variables and (2) that there is no difference in erosion rate, soil loss rate, and soil TP loss rate among the stream orders.

Materials and Methods

Study Sites and Treatments. The Southern Iowa Drift Plain is dominated by many steep erosion surfaces leading to the presence of rills, gullies, creeks, and rivers in integrated drainage networks created by the long geologic weathering processes (Prior 1991). In this region, stream bank erosion takes place in glacial materials deposited about a half million years ago. The major riparian soil association in the Rathbun watershed is the Olmitz-Vesser-Colo Association (USDA SCS 1971). These soils are classified as Cumulic Hapludolls, Argiaquic Argialbolls, and Cumulic Endoaquolls, respectively. The soils in this complex are moderately well to poorly drained. The 143,323 ha (354,159 ac) Rathbun Watershed consists of 38% pasture and hayland, 30% crop land, 12% Conservation Reserve Program (CRP), 13% woodland, and 7% urban/road/water (Braster et al. 2001).

Thirteen cooperating beef cow-calf farms, pasture size ranging from 3 to 107 ha (7 to 265 ac) (table 1), along stream reaches within the Rathbun Lake Watershed located in the Southern Iowa Drift Plain were chosen to conduct the study (figure 1). Site selection was based on three major requirements: (1) landowner permission to access a site during the three-year study period, (2) landowner willingness to keep a detailed grazing record to allow stocking rate calculations, and (3) all pasture stream reaches had perennial flow.

The riparian grazing treatments for this study had stocking rates (SR [Lu d m^{-1}]) ranging from 0 to 28 Lu d m^{-1} (0 to 8.5 Lu day ft^{-1}; livestock unit day per stream length), and stream order categories included 1st, 2nd, and 3rd stream orders (Strahler 1957) (table 1). Values for SR as Lu d m^{-1} were calculated as the product of the number of cows (NC [Lu]) and the number of days (ND [d]) they were grazed on the pasture over a calendar year divided by the grazed pasture stream length (SL [m]) on one side of the stream channel:

$$SR = NC \times ND\ (SL^{-1}). \tag{1}$$

However, because of differences in animals' metabolic size (Allen 1991), the equation used for the "NC × ND" calculation was modified as:

$$NC \times ND = (NC \times ND \times 1.00) + (NH \times ND \times 0.86) + (NB \times ND \times 1.20), \tag{2}$$

where NH is number of heifers and NB is number of bulls.

During the three years of the study, detailed information regarding number of cows, heifers, and bulls and their grazing days for each pasture was compiled in record books kept by the cooperating producers.

Two of the 13 farms were selected because their stream reaches were enrolled in the cool-season grass filter practice (CP 21) of the USDA CRP by fencing the livestock out of the portion of the riparian area immediately adjacent to the stream (USDA NRCS 1997). These 2 sites were used to represent the controls with the lowest stocking rates in the study. The stream reaches of CRP sites were located along 1st order streams (table 1). There were 6 other grazed pastures located along 1st, 3 along 2nd, and 2 along 3rd order streams. Also, all stream channels selected were in the widening stage (stage III) of the channel evolution model (Schumm et al. 1984). The dominant plant species on these continuously grazed pastures were tall fescue (*Festuca arundinacea* L. Schreb.), reed canarygrass (*Phalaris arundinacea* L.), bluegrass (*Poa pratensis* L.), orchardgrass (*Dactylis glomerata* L.), smooth bromegrass (*Bromus inermis* L. Leyss.), birdsfoot trefoil (*Lotus corniculatus* L.), clover (*Trifolium* L.), sedges (*Cyperaceae*), broadleaf weeds, and shrubs. On these continuously grazed pastures, cattle had full access to the stream and the entire pasture throughout the year-round grazing period.

Identifying Stream Bank Eroding Areas. Field observations from previous studies (Zaimes et al. 2006: 2008a) showed that severely and very severely eroded lengths of the stream reach were the most imminent and reactive parts of the entire stream reach that showed quick response to any changes in stream morphologic and hydrologic characteristics that are under the effects of different land use. Measuring erosion from these banks would allow us to precisely pinpoint how much and where the most erosion takes place in the entire stream reach. Severely eroding banks were defined as bare with slumps, vegetative overhang, and/or exposed tree roots. Very severely eroding banks were defined as bare, with massive slumps or washouts, severe vegetative overhang, and many exposed tree roots (USDA NRCS 1998). In October of 2006, lengths and heights of severely and very severely eroded stream banks along all 13 pasture stream reaches were visually identified and located using global positioning system (GPS) handheld units. The lengths of eroded stream bank segments were determined by walking along the top of the eroded banks and collecting "point feature" data at the start and end point of the eroded bank segment with GPS handheld units. Eroded bank heights were measured manually with survey rods at two or three different bank locations depending on the length and height variations of the eroded segment. The height data were manually entered into the GPS unit. Later in the laboratory, collected GPS data were transferred to geographic information system (GIS) software, Arc GIS 9.2 (Esri Inc.,

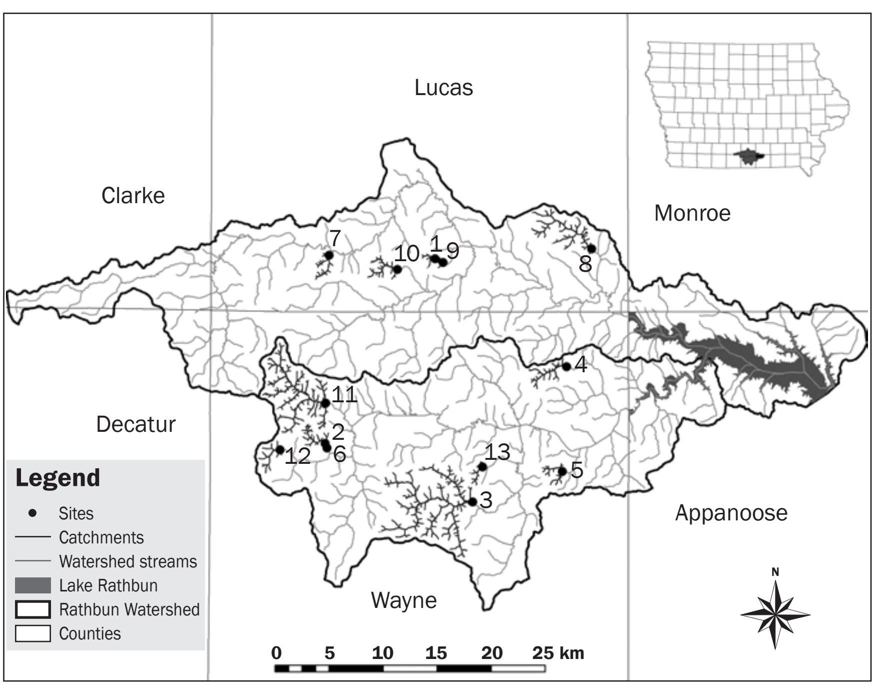
Table 1
Some characteristics of the studied pastures and their stream reaches: total bank length, bankfull height, pasture size, stocking rate, stream orders by Strahler method, and catchment size above the pasture site in the Rathbun Lake Watershed of southern Iowa.

Site ID	Total bank length (m)	Bank height (m)	Pasture size (ha)	Stocking rate (Lu d m^{-1})	Stream order	Catchment size (ha)
1 (CRP)	2,358	1.1	14	0	1st	253
2 (CRP)	2,324	1.5	10	0	1st	480
3 (Grazing)	1,844	2.9	29	3	3rd	5,660
4 (Grazing)	3,220	1.6	29	5	2nd	444
5 (Grazing)	3,556	1.6	51	5	1st	1,090
6 (Grazing)	612	1.6	3	8	1st	579
7 (Grazing)	2,080	1.1	107	9	1st	472
8 (Grazing)	2,276	1.5	55	12	2nd	2,007
9 (Grazing)	2,240	1.2	29	14	1st	393
10 (Grazing)	2,520	1.2	33	15	2nd	756
11 (Grazing)	2,078	3.0	48	18	3rd	3,630
12 (Grazing)	1,780	1.0	25	19	1st	709
13 (Grazing)	1,196	1.6	20	28	1st	318

Notes: CRP = Conservation Reserve Program. Lu d m^{-1} = livestock unit day per stream length. Total bank length includes both right and left bank lengths. For instance, in site 1 both right and left bank lengths are equal to 1,179 m.

Redlands, California), for synthesis and random selection of eroded bank lengths subject to pin installment. In Arc GIS, by using 2002 Color Infrared Digital Orthophotos, start and end points of eroded bank segments were connected to determine eroded bank length. Bank length was multiplied by the average eroded bank height to calculate eroded bank area for each eroded segment. To get the total eroded bank area from a given pasture stream reach, all eroded areas of each pasture reach on both sides of the channel were summed. To allow comparison of eroded bank area between different length of stream reaches for given pasture sites, total eroded bank areas per given stream reach (m^2) were divided by the length of stream reach (km) and recorded as an eroded bank area per kilometer length of stream (m^2 km^{-1}). The total eroded stream bank length (m) for each pasture reach was divided by the total stream bank length (m) including both right and left bank lengths of the reach to calculate the percentage of eroded bank length per pasture stream reach (%). Additionally, the pasture size and catchment size (table 1) for each study site were also measured using 2002 Color Infrared Digital Orthophotos and Digital Elevation Model, respectively, in Arc GIS.

Figure 1
Location of the thirteen study sites and their upstream channel systems within Rathbun Lake Watershed in Southern Iowa. Numbers represent site identification based on the magnitude of the stocking rates (Lu d m^{-1}) from smallest to largest. Site 1 is the Conservation Reserve Program site where stocking rate is 0 Lu d m^{-1}, and site 13 has the biggest stocking rate, 28 Lu d m^{-1} (see table 1).



Installation of Stream Bank Erosion Pins. The pin method was used to quantify the rate of stream bank erosion (Wolman 1959). This method was selected because it is practical for short time–scale studies needing high accuracy for measuring small changes in bank surfaces that may be subject to deposition or erosion (Lawler 1993). A random subset of eroded bank lengths equaling 15% of the total eroded bank length in each pasture stream reach was randomly selected for erosion pin installment. A total of 1,340 bank pins were installed in the study. The number of pin plots per pasture stream reach ranged from four to nine depending on the lengths of the randomly selected eroding segments. Within each plot, erosion pins were installed in two rows directly above one another for a total of 3 to 17 columns depending on the eroded segment length for each individual plot. The two rows were located at one-third and two-thirds of the stream bank height. When the bank height was less than 1 m (3.3 ft), only one pin row was installed at one-half the bank height. Bank pins were 6.4 mm (0.25 in) in diameter and 762 mm (30 in) length because erosion rates of up to 500 mm (19.7 in) per erosion event had been observed by previous researchers in similar watersheds in the region (Zaimes et al. 2006). Pins were installed in November of 2006. Exposed pin lengths were measured once each winter/spring (first week of May), summer (first week of August), and fall (last week of November) season in 2007, 2008, and 2009. For each measurement period, the previous length of exposed pins was subtracted from the most recent measurement. When the difference was positive, the exposed pin measurement represented erosion; if it was negative, the pin measurement represented deposition. An erosion rate of 600 mm (23.6 in) was assumed in the case of pins that were completely lost during an erosion event (Zaimes et al. 2006).

Soil Bulk Density Sampling from Stream Banks and Riparian Areas. The soil core method (3 cm [1.18 in] in diameter and 10 cm [3.94 in] in length) was utilized to determine stream bank and riparian area soil bulk densities (Naeth et al. 1990). Soil bulk density samples were collected based on horizonation of stream bank soils in each pin plot during the month of July in 2007. Two soil cores from the midpoint of each horizon were collected for the laboratory analysis. Since each horizon from the eroded bank surface had different widths, width-weighted averages were used to calculate mean soil bulk density for the mean bank height for the plot. Additionally, two surface soil cores (3 by 10 cm [1.2 by 3.9 in]) from the riparian areas, 8 m (26 ft) away and perpendicular to the middle column of each pin plot, were collected to determine the impact of cattle stocking rates on soil compaction of the riparian areas, regardless of whether the sampling location was vegetated or trafficked by the cattle. In the laboratory, soil bulk density samples were weighed after drying for one day at 105°C (221°F) (Blake and Hartge 1986).

Soil Phosphorus Sampling and Estimation of Soil and Total Phosphorus Losses from Stream Banks. Soil samples collected for bank soil bulk density were analyzed for soil TP content. A similar approach as in the bulk density calculation was also used to calculate mean TP content from a plot. These values were also used to calculate bank soil loss rates and soil TP loss rates (table 2). Samples used for soil TP analysis were first air dried and then sieved through a 2 mm (0.08 in) screen. Soil P determination was based on soil digestion in aqua regia (Crosland et al. 1995), followed by a colorimetric evaluation of the digested sample for P (Murphy and Riley 1962).

Stream bank soil loss rate (SLR [t km^{-1} y^{-1}]) per unit length of stream per year for each stream reach was estimated by multiplying eroded bank area (EBA [m^2 km^{-1}]) per unit length of stream with the product of bank erosion rate (BER [m y^{-1}]) per year and soil bulk density (SBD [t m^{-3}]) from a given stream bank reach (table 2):

$$SLR = EBA \times BER \times SBD. \qquad (3)$$

To estimate bank soil TP loss (TPL [kg km^{-1} y^{-1}]) rate per unit stream length per year from stream banks, the soil loss rate (SLR [t km^{-1} y^{-1}]) per unit stream length per year from the reach was multiplied by the mean soil P content (SPC [kg t^{-1}]) of the bank soils in given stream reach (table 2):

$$TPL = SLR \times SPC. \qquad (4)$$

Rainfall Data. Daily precipitation data were collected from six weather stations that were evenly distributed throughout the research sites within the Rathbun Lake Watershed. However, during the course of the study (November of 2006 to November of 2007), several of the weather stations malfunctioned because of lightning strikes. For those times when no data were collected by our stations (November of 2006 to November of 2007), weather data were obtained from the "Chariton Station" of the National Oceanic and Atmospheric Administration. Rainfall data were grouped according to the bank erosion measurement periods (e.g., winter/spring, summer, and fall).

Data Analysis. The impacts of livestock stocking rate and amount of precipitation on stream bank erosion were examined using the analysis of variance within the Statistical Analysis Systems (SAS Institute 2003). The sample size was the number of pin plots in each grazed pasture. Using REG procedure of SAS, multiple regression models, including livestock stocking rate, precipitation rate, and stream bank soil bulk density as the independent variables, were used to explain the variability in the dependent variable, stream bank erosion. Data were analyzed by using the average of three years value from each site; the model statement included the aforementioned variables, and the site was the experimental unit. Since the percentages of eroded bank length and soil bulk density from the top soil horizon were under the direct effects of stocking rate, they were not included in the model and were subject simple linear regression analysis (figure 2 and figure 3).

To compare the difference in both precipitation rate (table 3) and erosion rate (table 4) by yearly average, by seasons of each year, and by seasonal average, data were examined using the "lsmeans pdiff" function of MIXED procedure in SAS. The p-values were adjusted for multiplicity of tests with Tukey's method. The model statement included precipitation/erosion, season, year, and season year interaction. The site was also included in the model, as a random effect, to account for correlation between repeated measurements on the sites. The same model was used with seasonal precipitation amount (figure 4). Finally, MIXED procedure was also used to compare erosion rate, soil loss, and soil TP loss rate among different stream orders (figure 5). Significance level was considered as $p < 0.1$ since bank erosion is influenced many spatial, temporal, climatic, and anthropogenic impacts (Zaimes et al. 2008a, 2008b)

Results and Discussion

Lengths and Areas of Severely and Very Severely Eroding Stream Banks. Total bank lengths of the 13 study reaches ranged from 612 to 3,556 m (2,008 to 11,667 ft) (table 1). Percentage of severely and very severely eroded bank lengths per stream reach ranged from 13% to 36% of the total stream bank lengths, representing eroded stream bank areas that ranged from 428 to 1,121 m^2 km^{-1} (7,414 to 19,419 ft^2 mi^{-1}) (table 2). Livestock stocking rates were significantly correlated to the percentage of eroded stream bank lengths (p = 0.09) (figure 2). Similar results were found in a study by Lyons et al. (2000), who reported a significantly higher percentage of

Table 2

Stream bank erosion variables including erosion rate, soil bulk density, soil loss rate, soil phosphorus (P) content, and total phosphorus (TP) loss rate from severely and very severely eroded stream banks (presented as a percentage of the total bank length) and eroded bank area per unit stream length under different stocking rates and stream orders (table 1) in the Rathbun Lake Watershed of southern Iowa. Stream bank erosion rate is the average rate of all the pin plots in the given riparian grazed pasture.

Site ID	Erosion rate ($m\ y^{-1}$)	Soil bulk density ($t\ m^{-3}$)	Eroded bank length (%)	Eroded bank area ($m^2\ km^{-1}$)	Soil loss rate ($t\ km^{-1}\ y^{-1}$)	Soil P content ($kg\ t^{-1}$)	Soil TP loss rate ($kg\ km^{-1}\ y^{-1}$)
1 (CRP)	0.09	1.38	21	477	58	0.349	20
2 (CRP)	0.15	1.18	16	465	85	0.246	21
3 (Grazing)	0.38	1.58	19	1,095	664	0.276	183
4 (Grazing)	0.25	1.48	19	775	285	0.329	94
5 (Grazing)	0.26	1.44	24	645	245	0.281	69
6 (Grazing)	0.34	1.35	13	428	196	0.279	55
7 (Grazing)	0.17	1.48	27	605	150	0.305	46
8 (Grazing)	0.09	1.55	36	1,121	164	0.322	53
9 (Grazing)	0.10	1.47	29	756	116	0.300	35
10 (Grazing)	0.13	1.32	27	654	111	0.293	33
11 (Grazing)	0.38	1.53	18	1,061	612	0.269	165
12 (Grazing)	0.23	1.37	23	480	151	0.337	51
13 (Grazing)	0.25	1.59	31	1029	416	0.327	136
Average spring	0.16	—	—	—	185	—	55
Average summer	0.04	—	—	—	47	—	14
Average fall	0.02	—	—	—	19	—	5
Total average	0.22	1.44	23	738	251	0.301	74

Note: CRP = Conservation Reserve Program.

eroded banks (using the transect method) in continuously grazed pastures with stocking rates ranging from 0.5 to 5.9 ha^{-1} (0.2 to 2.4 ac^{-1}) animal units than in intensive rotationally grazed pastures with stocking rates ranging from 0.8 to 1.8 ha^{-1} (0.3 to 0.7 ac^{-1}) animal units during a six-month grazing period. On the other hand, there was no relationship between stocking rates and eroded stream bank areas, most likely because the study reaches occurred along streams of three different stream orders with incised channels that contributed to a high variability in average bank height, ranging from 1 to 3 m (3 to 10 ft) (table 1).

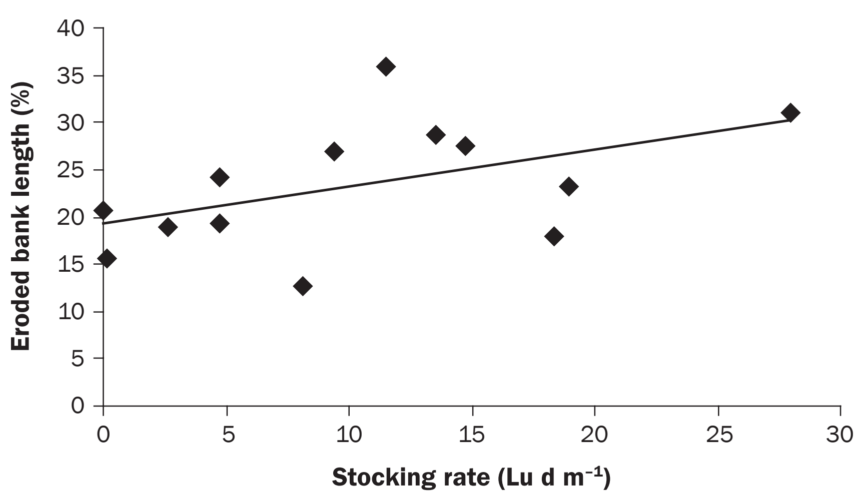


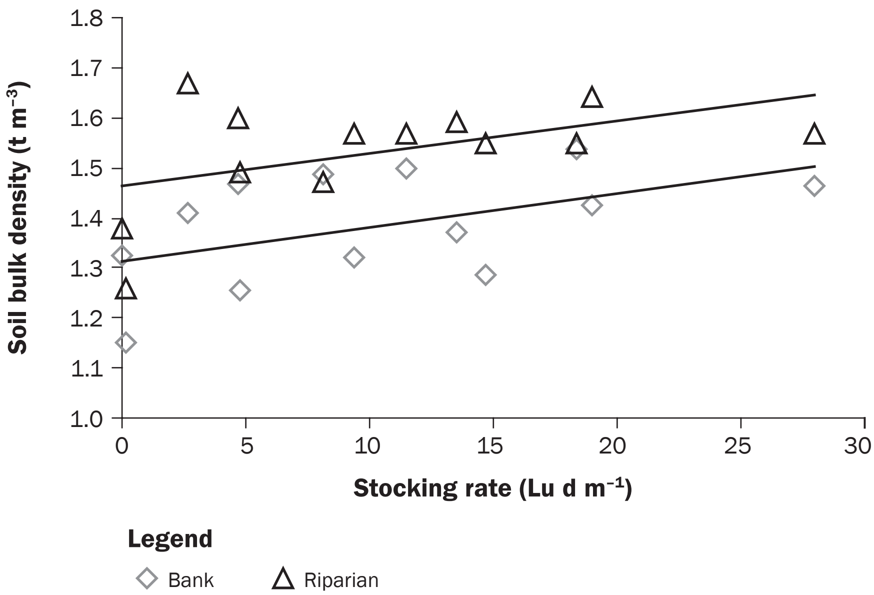
Figure 2

Relationship between stocking rates and percentage eroded bank length ($y = 19.3 + 0.4x$; $r^2 = 0.24$; $p = 0.09$) along both banks of a treatment reach. The Statistical Analysis Systems REG procedure was used to analyze the data.

Grazing of livestock on riparian areas can weaken soil structure by increasing soil compaction, thus increasing surface runoff and reducing vegetative cover that provides surface roughness against water erosion (Tufekcioglu 2006). In this study, the physical and/or mechanical impact of livestock on stream bank erosion was mainly related to the bank slope. Cattle grazing, drinking, and stream-crossing activities were concentrated on the gently inclined banks, under trees, and/or at localized channel access points, which increased the susceptibility of these banks to further erosion. These results are similar to those by Trimble (1994), Agouridis et al. (2005), and Evans et al. (2006); all these studies indicated in some degree that the use of stream bank by cattle along stream reaches is localized on the gently declined channel access points and/or loafing areas where shade is provided. Field observation also suggested that livestock have difficulty accessing more vertical banks, resulting in a little or no direct physical (grazing and trampling) impact on the erosion of these banks. On these banks, the eroded bank area and erosion rates are directly influenced by stream morphologic and hydrologic characteris-

Figure 3

Relationship between livestock stocking rates and soil bulk density of both top horizons of bank soil ($y = 1.3 + 0.007x$; $r^2 = 0.25$; $p = 0.08$) and in riparian areas, 8 m away from eroded stream banks ($y = 1.5 + 0.006x$; $r^2 = 0.23$; $p = 0.09$). The Statistical Analysis Systems REG procedure was used to analyze the data.



tics, which in turn are indirectly affected by riparian land use in broad prospective.

Stream Bank and Riparian Area Soil Bulk Densities. No significant correlations were observed between livestock stocking rates and stream bank average soil bulk densities, which ranged from 1.18 to 1.59 t m^{-3} (73.7 to 99.3 lb ft^{-3}) (table 2). Livestock trampling impacts on the top of the banks probably had little effect on total bulk density over the average depths of the banks. However, there was a significant relationship ($p = 0.08$) between stocking rates and the bulk density of the top bank soil horizon, which ranged from 10 to 27 cm (3.9 to 10.6 in) in depth (figure 3). Similar positive significant correlations were also found between the soil bulk density of the top horizon of the riparian soil, which ranged from 1.26 to 1.67 t m^{-3} (78.7 to 104 lb ft^{-3}), and stocking rates, which ranged from 0 to 28 Lu d m^{-1} (0 to 8.5 Lu day ft^{-1}; $p = 0.09$) (figure 3). Similarly, study by Dormaar et al. (1998) found parallel relationships between stocking rates ranging from 0.0 to 4.8 animal unit month (AUM) ha^{-1} (0 to 1.9 AUM ac^{-1}) and soil bulk densities ranging from 0.44 to 0.88 t m^{-3} (27.5 to 54.9 lb ft^3) from grazed pastures.

The increase in surface soil bulk density by livestock may lead to soil compaction and a change in soil structure, particularly a reduction in macropore size (>1,000 μm diameter), which in turn reduces water infiltration and percolation into lower soil horizons. This effect has the potential to increase surface runoff and decrease water-holding capacity. Greater runoff can result in greater transport of sediments and nutrients, especially P, to stream ecosystems. Such impacts were observed in a study by Kumar et al. (2010), who reported greater macroporosity in soils under a perennial buffer (0.02 m^3 m^{-3} [0.02 ft^3 ft^{-3}]) than under a rotationally grazed (0.005 m^3 m^{-3} [0.005 ft^3 ft^{-3}]) or continuously grazed pasture (0.004 m^3 m^{-3} [0.004 ft^3 ft^{-3}]). Similarly, Dormaar et al. (1998) concluded that heavy grazing (2.4 AUM ha^{-1} [0.9 AUM ac^{-1}]) and very heavy grazing (4.8 AUM ha^{-1} [1.9 AUM ac^{-1}]) treatments resulted in a reduction in water-holding capacity of the pasture soil compared to light grazing (1.2 AUM ha^{-1} [0.5 AUM ac^{-1}]). Mwendera and Saleem (1997) also reported significantly higher amounts of surface runoff and soil loss from heavily (3.0 AUM ha^{-1} [1.2 AUM ac^{-1}]) and very heavily grazed pastures (4.2 AUM ha^{-1} [1.7 AUM ac^{-1}]) than from lightly grazed (0.6 AUM ha^{-1} [0.2 AUM ac^{-1}]) and moderately grazed pastures (1.8 AUM ha^{-1} [0.7 AUM ac^{-1}]). Another study by Nguyen et al. (1998) found that high stocking rates significantly increased surface runoff with greater suspended solids and TP from plots during rainfall simulations compared to the plots with low stocking rates.

Relationship between Bank Erosion Rates and Independent Variables. Multilinear regression analysis of the data revealed a significant relationship ($p = 0.03$; $r^2 = 0.49$) between average stream bank erosion rate

Table 3

Differences in precipitation rate by seasons of the year in 2007, 2008, and 2009 and the average[1] for each season by year and average[2] for each year by seasons.

	2007			2008			2009			Average[1]		
Season	Rate (mm d^{-1})	N	SD	Rate (mm d^{-1})	N	SD	Rate (mm d^{-1})	N	SD	Rate (mm d^{-1})	N	SD
Winter/spring	2.75 (0.15)	13	a	2.22 (0.15)	13	a	1.91 (0.15)	13	a	2.29 (0.09)	39	d
Summer	4.03 (0.15)	13	b	6.29 (0.16)	12	b	2.92 (0.15)	13	b	4.41 (0.09)	38	e
Fall	2.42 (0.15)	13	ac	3.55 (0.15)	13	c	3.93 (0.15)	13	c	3.30 (0.09)	39	f
Average[2]	3.07 (0.09)	39	m	4.02 (0.09)	38	n	2.92 (0.09)	39	mk			

Notes: N = number of observations. Numbers in parentheses are the standard error. SD = significant differences. Different letters indicate significant difference ($p < 0.10$) among the seasons (winter/spring, summer, and fall [a, b, c, ac]) of each year, among average[1] of same seasons by years (2007, 2008 and 2009 [d, e, f]), and among average[2] of different season by each year (2007, 2008 and 2009 [m, n, mk]). Number of days for winter/spring season in 2007, 2008, and 2009 are 184, 142, and 169, respectively; for summer season are 116, 84, and 84, respectively; and for fall season are 95, 109, and 109, respectively.

Table 4
Differences in stream bank erosion rate by seasons of the year in 2007, 2008 and 2009, and average[1] for each season by year and average[2] for each year by seasons.

	2007			2008			2009			Average[1]		
Season	Rate (mm d^{-1})	N	SD	Rate (mm d^{-1})	N	SD	Rate (mm d^{-1})	N	SD	Rate (mm d^{-1})	N	SD
Winter/spring	0.60 (0.08)	13	a	1.19 (0.15)	13	a	1.24 (0.12)	13	a	1.01 (0.09)	39	d
Summer	0.29 (0.08)	13	ab	0.77 (0.16)	12	b	0.25 (0.12)	13	b	0.42 (0.09)	38	e
Fall	–0.01 (0.08)	13	b	0.14 (0.15)	13	c	0.34 (0.12)	13	b	0.16 (0.09)	39	f
Average[2]	0.29 (0.10)	39	m	0.69 (0.11)	38	n	0.61 (0.10)	39	n			

Notes: N = number of observations. Numbers in parenthesis are the standard error. SD = significant differences. Different letters indicate significant difference ($p < 0.10$) among the seasons (winter/spring, summer, and fall [a, b, c, and ac]) of each year, among average[1] of same seasons by years (2007, 2008, and 2009 [d, e, and f]), and among average[2] of different season by each year (2007, 2008, and 2009 [m, n, and mk]). Number of days for winter/spring season in 2007, 2008, and 2009 are 184, 142, and 169, respectively; for summer season are 116, 84, and 84, respectively; and for fall season are 95, 109, and 109, respectively.

(BER) per year and the independent variables including average precipitation rate (Pre) ($p = 0.02$) per year and stream bank soil bulk density (SBD) ($p = 0.03$):

$$BER = 1.4\ Pre + 59\ SBD - 214. \quad (5)$$

The increase in precipitation and bank soil bulk density increased bank soil erosion. Livestock stocking did not have effect on the bank erosion in the model. However, it was shown in the previous sections that stocking rate did affect the percentage of severely eroded bank and the soil bulk density from the top horizon of the bank and riparian soils. Stream bank erosion is an evolving, complex process that involves many interactions of factors across multiple scales. Such interacting factors include type and intensity of riparian land use; bank soil properties; discharge characteristics; and morphologic features of the stream channels, such as stream bed slopes and sinuosity. Although one of the study's objectives was to find interacting relationships among some of these factors, one argument suggests that the bank erosion rate variable was biased by selection of only those banks that exhibited similar erosion rates (severely and very severely eroded banks). This conflict/incompatibility in the study design weakens the conception that pastures under high livestock stocking can affect the integrity of the riparian areas and associated stream bank erosion. However, the study was also designed to find differences in percentage of eroded bank lengths and soil bulk density related to the different stocking rates that were discussed above sections.

There was a significant positive relationship in the first year between the amounts of erosion of the seasons and precipitations of the seasons ($p < 0.0001$) (figure 6). In contrast, during the second and third years of the study there was no relationship between erosion and precipitation amounts of the seasons. This result can be related to the significantly ($p < 0.05$) high precipitation amount during the summer of 2008 (52.3 cm [20.6 in]) and fall of 2009 (49.8 cm [19.6]) compared to other seasons of these two years (figure 4). In other words, the seasonal trend in the average erosion amounts (winter/spring > summer > fall) (table 2) was only followed by a seasonal trend in the precipitation amounts of the year 2007 (winter/spring > summer > fall) (figure 4). The other study years (2008 and 2009) did not follow the similar trend in precipitation.

Although low precipitation rates recorded in the winter/spring seasons of 2008 (2.22 mm d^{-1} [0.087 in day^{-1}]) and 2009 (1.91 mm day^{-1} [0.075 in day^{-1}]) compared to the winter/spring season of 2007 (2.75 mm d^{-1} [0.108 in day^{-1}]) (table 3), higher erosion rates were recorded for the winter/spring seasons of 2008 (1.19 mm d^{-1} [0.047 in day^{-1}]) and 2009 (1.24 mm d^{-1} [0.049 in day^{-1}]) compared to 2007 (0.60 mm d^{-1} [0.024 in day^{-1}]) (table 4). Rather than the effects of precipitation amount itself on the bank erosion, these differences in winter/spring erosion by years are probably due to rainfall characteristics (frequency, intensity, and duration) with the responding stream discharge and freeze-thaw cycles of each winter/spring season of the years for each site, which were not measured.

Differences in erosion rates were, however, observed among years, seasons of each year, and seasons (table 4). Second (0.69 mm d^{-1} [0.027 in day^{-1}]; $p = 0.004$) and third year (0.61 mm d^{-1} [0.024 in day^{-1}]; $p = 0.026$) bank erosion rates were significantly higher than those in the first year (0.29 mm d^{-1} [0.011in day^{-1}]) (table 4). Except summer and fall seasons of 2009, winter/spring and summer of 2007, and summer and fall seasons of 2007, bank erosion rates among seasons of each year were significantly different ($p < 0.10$) (table 4). Average winter/spring erosion rates (1.01 mm d^{-1} [0.040 in day^{-1}]) were significantly higher than rates in the summer (0.42 mm d^{-1} [0.017 in day^{-1}]; $p < 0.0001$) and fall (0.16 mm d^{-1} [0.006 in day^{-1}]; $p < 0.0001$) (table 4), similar to findings of other studies (Prosser et al. 2000; Zaimes et al. 2006; Evans et al. 2006; Simon et al. 2006; Nellesen et al. 2011). Average summer erosion rates were also significantly higher than fall rates ($p = 0.0174$). This suggests that, regardless of the quantity, the impact of precipitation amount on bank erosion during the winter/spring was higher compared to the precipitation impacts in the summer and fall seasons. This observation may be due to higher moisture content of stream bank soils, which results from low evapotranspiration rates during the winter months and coincides with increases in spring stream discharge and stage. A study by Simon et al. (2000) found that major bank failures took place during prolonged wet periods, rather than during peak storm events due to an increase in soil unit weight and a decrease in matric suction in which the binding capacity of the soil particles was reduced.

During the study period, average erosion rates (0.24 m y^{-1} [9.4 in yr^{-1}]) (table 2) on the 11 grazed pastures were higher than the average erosion rates (0.10 m y^{-1} [3.9 in yr^{-1}]) of a similar 3-year erosion study on 7 grazed pastures (stocking rates ranging from 7.6 to 29.3 AUM, average bank height ranging from 1.8 to 2.1 m [5.9 to 6.9 ft], and precipitation ranging from 54 to 100 cm y^{-1} [21 to 39 in yr^{-1}]) that was conducted on the same landform (Southern Iowa Drift Plain) approximately 80 km (49.7 mi) east of the Rathbun watershed from 2002 to 2004 (Zaimes et al. 2008a). When comparing the 15-year precipitation data prior to our 3-year study period, it is clear that the study period

Figure 4

The magnitude of precipitation by seasons (winter/spring, summer, and fall) of each year and the seasonal average from the six weather stations located around the Rathbun Lake Watershed. The number of observations for each season of the year is 13 and for the total seasonal average is 39. Bars indicate standard error. The letters indicate significant differences in precipitation, $p < 0.10$. The Statistical Analysis Systems MIXED procedure was used to analyze the data. For significant differences, "lsmeans pdiff adjust tukey" was used.

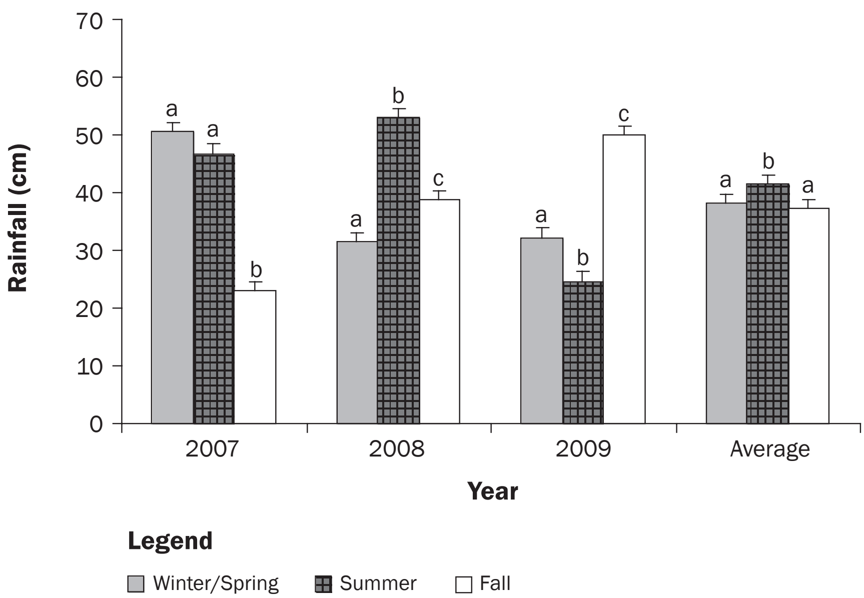
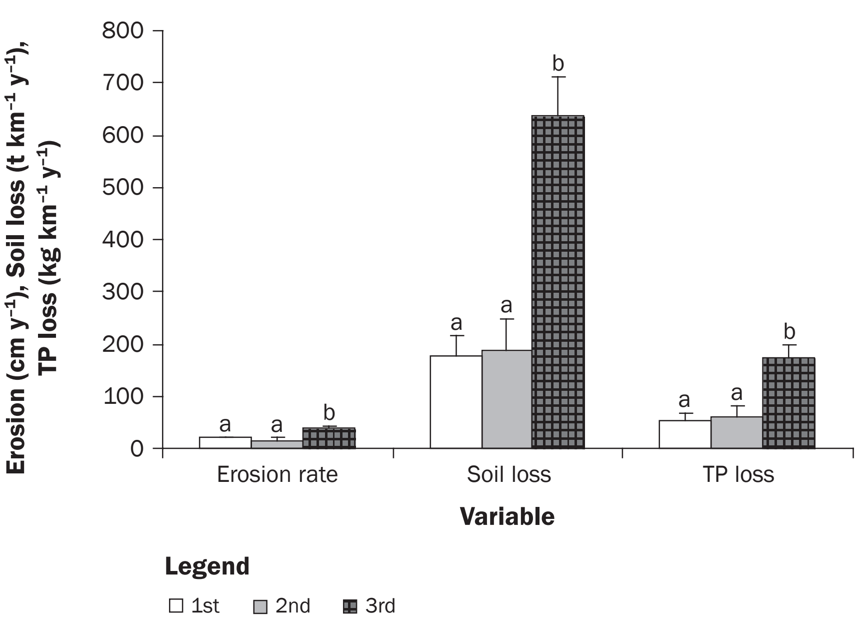


Figure 5

Differences in erosion rate, soil loss rate, and total phosphorus (TP) loss rate among 1st, 2nd, and 3rd order stream categories. The total number of observations for each variable is 13, including 8 for 1st order, 3 for 2nd order, and 2 for 3rd order streams. Bars indicate standard error. The letters indicate significant differences in erosion, soil loss, and total phosphorus loss by stream order, $p < 0.10$. The Statistical Analysis Systems MIXED procedure was used to analyze the data. For significant differences, "lsmeans pdiff cl" was used.

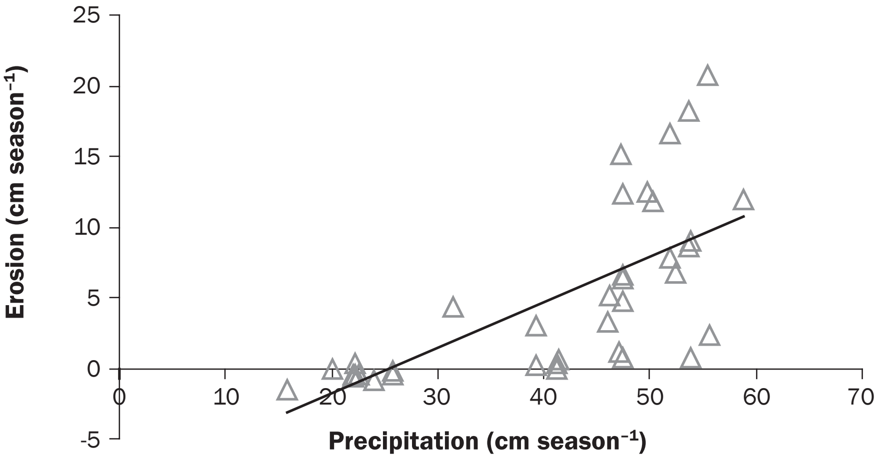


(2007 to 2009) had higher average annual rainfall and more intense rainfall events than the previous 13 years (1994 to 2006) (figure 7). The increase in precipitation in recent wet years was likely one of the main reasons for the greater bank erosion and soil loss recorded from the grazed pastures in the Rathbun Lake Watershed. Although higher erosion rates from the Rathbun study can be directly related to an increase in total precipitation in recent years, the differences in erosion rates between these two studies may also be related to the differences in frequency, timing, intensity, and duration of the rainfall events. These features could be important in explaining the spatial and temporal patterns in bank erosion due to their effects on stream power during individual runoff events. Because of greater variability in precipitation from year to year, it is essential to have long-term studies to accurately estimate the effects of land use on stream bank erosion. Also, in order to understand, especially for the winter/spring season when most of the bank erosion occurs, the effects of freeze-thaw cycle and rainfall characteristics on stream bank erosion, short time–scale (monthly) study of bank erosion should be conducted. Additionally, some bank soil physical characteristics (moisture, temperature, bulk density, texture, and shear stress) should also be measured to explain to variability on the bank erosion.

In this study, one of the challenges in trying to relate bank erosion rate responses to precipitation was the lack of precipitation data within the specific watersheds in which research was conducted. Rainfall data from six established weather stations that were some distance from the specific pasture sites had to be used. Stage or discharge data for any of the streams that could be directly correlated to precipitation in the specific watersheds were also unavailable. In addition, pasture sites were on different stream orders (1^{st}, 2^{nd} and 3^{rd}), which meant that these streams probably had different slopes and sinuosity equilibrium states and responded differently to discharge and sediment inputs. In other words, their bank soil resistance to the same amount of precipitation and/or discharge would be different which, in turn, would result in different bank erosion rates.

Soil Phosphorus Content and Losses of Soil and Total Phosphorus from Stream Banks. Stream bank soil TP content ranged from 0.246 to 0.349 kg t^{-1} (0.0039 to 0.0055 oz lb^{-1}) (table 2) and was lower than

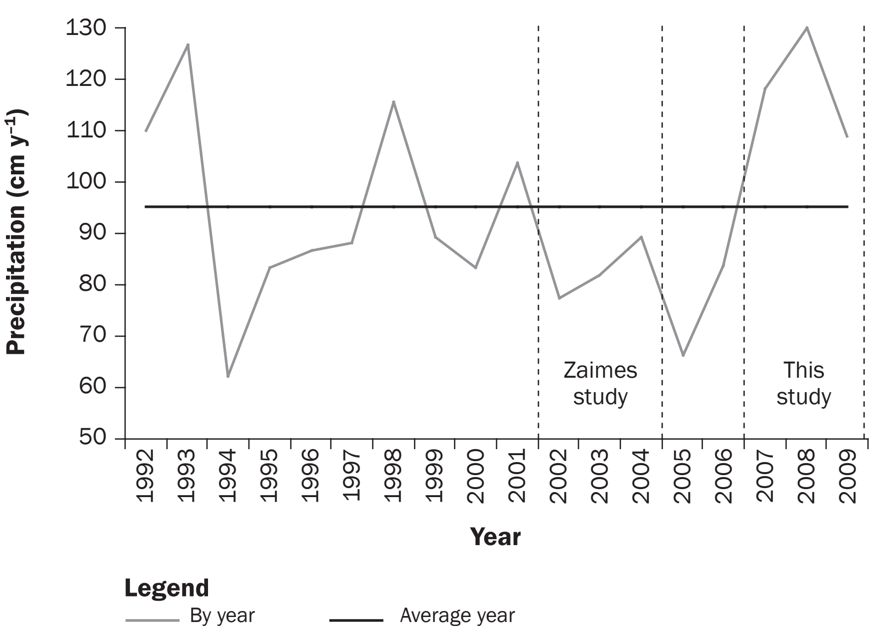
Figure 6
Relationship between seasonal (winter/spring, summer, and fall) erosion rate and seasonal precipitation in the year of 2007 ($y = -8.2 + 0.32x$; $r^2 = 0.48$; $p < 0.0001$). The number of observations for each variable is 39. The Statistical Analysis Systems REG procedure was used to analyze the data.



the range (0.360 to 0.555 kg t^{-1} [0.0057 to 0.0088 oz lb^{-1}]) observed from similar sites in the Southern Iowa Drift Plain by Zaimes et al. (2008b). Zaimes et al. (2008a) recorded stream bank soil loss rates of 197 to 264, 94 to 266, and 124 to 153 t km^{-1} y^{-1} (350 to 469, 167 to 472, and 220 to 272 t mi^{-1} yr^{-1}), from continuous, rotational, and intensive rotationally grazed pastures, respectively, located along 1st, 2nd and 3rd order streams in Iowa and 6 to 61 t km^{-1} y^{-1} (11 to 108 t mi^{-1} yr^{-1}) from other pastures where cattle were fenced out of streams banks. Since stocking rates were not correlated to bank erosion rates, there were also no significant correlations between stocking rates and both rates of soil and soil TP losses from the pasture reaches.

Erosion Rate and Soil and Total Phosphorus Losses Based on Strahler Stream Order Classification. Third order stream reaches had significantly higher stream bank erosion rates than both 2nd ($p = 0.0129$) and 1st order stream reaches ($p = 0.0184$) (figure 5). This difference could be the result of the fact that higher stream power can exert a greater amount of stress on stream banks during high flow events. Additionally, these taller banks are more likely to collapse in response to gravity when saturated by high flows or over-winter saturation because saturation increases soil bulk unit (specific) weight (Simon et al. 2000) and causes the taller 3rd order banks to collapse more readily than the shorter 2nd and 1st order banks that have not yet reached their critical height (Simon and Klimetz 2008). Similar to the trend in erosion rate, 3rd order stream reaches had a significantly higher stream bank soil loss rate than 1st ($p = 0.0002$) and 2nd ($p = 0.0008$) order stream reaches and also a higher soil TP loss rate than 1st ($p = 0.0013$) and 2nd ($p = 0.0045$) order stream reaches (figure 5).

Figure 7
Yearly total precipitation amounts from 1992 to 2009 compared to the average precipitation (horizontal line at 95 cm y^{-1}) at Chariton, Iowa, from National Oceanic and Atmospheric Administration weather records. Dashed lines represent study periods of both Zaimes et al. (2006, 2008a, 2008b) studies (from 2002 to 2004) and this (Rathbun) study (from 2007 to 2009).



Summary and Conclusions

Stocking rates of grazing livestock affect riparian areas and adjacent stream banks. The increase in percentage of eroded bank length and soil bulk density in the riparian areas was related to an increase in stocking rates. This relationship suggests that some of the proximate causative factors related to nutrient and soil losses from stream banks and riparian areas of grazed pastures can be directly related to the livestock stocking rates. Results from the study also imply that nutrient losses from stream banks and adjacent riparian areas could be reduced by improved riparian pasture management. Additionally, during the prolonged wet years, 3rd order stream channels produced greater amounts of sediment than 1st and 2nd order channels. This difference suggests that stream size, morphology, and some of the hydrologic characteristics of streams in response differences in precipitation are important causative factors driving sediment flux and may mask the impacts of improved riparian pasture management.

References

Agouridis, C.T., D.R. Edwards, S.R. Workman, J.R. Bicudo, B.K. Koostra, E.S. Vanzant, and J.L. Taraba. 2005. Stream bank erosion associated with grazing practices in the humid region. Transactions of the American Society of Agricultural Engineers 48(1):181-190.

Alexander, R.B., R.A. Smith, G.E. Schwarz, E.W. Boyer, J.V. Nolan, and J.W. Brakebill. 2008. Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River Basin. Environmental Science & Technology 42(3):822-830.

Allen, V.G. 1991. Terminology for Grazing Lands and Grazing Animals. Blacksburg, VA: Pocahontas Press.

Blake, G.R., and K.H. Hartge. 1986. Bulk density. *In* Methods of Soil Analysis, ed A. Clute, 363-375, Part 1. Physical and mineralogical methods, 2nd ed. Madison, WI: American Society of Agronomy and Soil Science Society of America.

Braster, M., T. Jacobson, and V. Sitzmann. 2001. Assessment and Management Strategies for the Rathbun Lake Watershed. http://www.iowadnr.gov/Portals/idnr/uploads/water/watershed/files/rathbunwmp1.pdf.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Application 8:559–568.

Correll, D.L. 1998. The role of phosphorus in the eutrophication of receiving waters: A review. Journal of Environmental Quality 27:261-266.

Crosland, A.R., F.J. Zhao, S.P. McGrath, and P.W. Lane. 1995. Comparison of *aqua regia* digestion with sodium carbonate fusion for the determination of total phosphorus in soils by inductively coupled plasma atomic emission spectroscopy ICP. Communications in Soil Science and Plant Analysis 26:1357-1368.

Dormaar, J.F., and W.D. Willms. 1998. Effect of forty-four years of grazing on fescue grassland soils. Journal of Range Management 51(1):122-126.

Downing, J.A., and J. Kopaska. 2001. Diagnostic study of Rock Creek Lake and its watershed: Recommendations for remediation. Des Moines, IA: Iowa Department of Natural Resources.

Evans, D.J., C.E. Gibson, and R.S. Rossell. 2006. Sediment loads and sources in heavily modified Irish catchments: A move towards informed management strategies. Geomorphology 79:93-113.

Haan, M.M., J.R. Russell, W.J. Powers, J.L. Kovar, and J.L. Benning. 2006. Grazing management effects on sediment and phosphorus in surface runoff. Rangeland Ecology Management 59:607-615.

Henderson, J.E. 1986. Environmental designs for stream bank protection projects. Water Resource Bulletin 22:549-558.

IDNR (Iowa Department of Natural Resources). 2008. 303d List of Impaired Waters. Iowa City, IA: Iowa Geological and Water Survey. http://www.igsb.uiowa.edu/wqm/ImpairedWaters/year2008/303dSC.htm.

Kumar, S., S.H. Anderson, and R.P. Udawatta. 2010. Agroforestry and grass buffer influences on macropores measured by computed tomography under grazed pasture system. Journal of Soil Science Society of America 74(1):203-212.

Laubel, A., B. Kronvang, A.B. Hald, and C. Jensen. 2003. Hydro-morphological and biological factors influencing sediment and phosphorus loss via bank erosion in small lowland rural streams in Denmark. Hydrological Processes 17(17):3443-3463.

Laubel, A., L.M. Svenden, B. Kronvang, and S.E. Larsen. 1999. Bank erosion in a Danish lowland stream system. Hydrobiologia 410:279-285.

Lawler, D.M. 1993. Needle ice processes and sediment mobilization on river banks: The River Ilston, West Glamorgan, UK. Journal of Hydrology 150:81-114.

Lyons, J., B.M. Weigel, L.K. Paine, and D.J. Undersander. 2000. Influence of intensive rotational grazing on bank erosion, fish habitat quality, and fish communities in southwestern Wisconsin Trout streams. Journal of Soil and Water Conservation 55(3):271-276.

Magner, J.A., B. Vondrack, and K.N. Brooks. 2008. Grazed riparian management and stream channel response in southeastern Minnesota (USA) streams. Environmental Management 42:377-390.

Murphy, J., and J.R. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta 27:31-36.

Mwendera, E.J., and M.A. Mohamed Saleem. 1997. Infiltration rates, surface runoff, and soil loss as influenced by grazing pressure in the Ethiopian highlands. Soil Use and Management 13:29-35.

Naeth, M.A., D.J. Pluth, D.S. Chanasyk, and A.W. Bailey. 1990. Soil compacting impacts on grazing in mixed prairie and fescue grassland ecosystems of Alberta. Canadian Journal of Soil Science 70:157-167.

Nagle, G.N., T.J. Fahey, J.C. Ritchie, and P.B. Woodbury. 2007. Variations in sediment sources and yields in the Finger Lakes and Catskills regions of New York. Hydrological Processes 21:828-838.

Nellesen, S.L., J.L. Kovar, M.M. Haan, and J.R. Russell. 2011. Grazing management effects on stream bank erosion and phosphorus delivery to a pasture stream. Canadian Journal of Soil Science 91:385-395.

Nguyen, M.L., G.W. Sheath, C.M. Smith, and A.B. Cooper. 1998. Impact of cattle treading on hill land: Soil physical properties and contaminant runoff. New Zealand Journal of Agricultural Research 41:279-290.

Odgaard, A.J. 1987. Streambank erosion along two rivers in Iowa. Water Resource Research 23:1225-1236.

Prior, J.C. 1991. Landforms of Iowa. Iowa City, IA: Iowa Department of Natural Resources University of Iowa Press.

Prosser, I.P., A.O. Hughes, and I.D. Rutherfurd. 2000. Bank erosion of an incised upland channel by subaerial processes; Tasmania, Australia. Earth Surface Processes Landforms 25(10):1085-1101.

Roseboom, D.P. 1987. Case studies of stream and river restoration. *In* Management of the Illinois River system: The 1990's and beyond. A Governor's Conference, Peoria, Illinois, April 1-3, 1987, 184-194. Illinois River Resource Management.

SAS (Statistical Analysis System Institute). 2003. SAS Release 9.1 ed. Cary, NC: SAS Institute Inc.

Schilling, K.E., and C.F. Wolter. 2000. Applications of GPS and GIS to map channel features in Walnut Creek, Iowa. Journal of American Water Resources Association 36(6):1423-1434.

Schumm, S.A., M.D. Harvey, and C.C. Watson. 1984. Incised channels. Morphology, Dynamics and Control. Littleton, CO: Water Resource Publication

Sekely, A.C., D.J. Mulla, and D.W. Bauer. 2002. Streambank slumping and its contribution to the phosphorus and suspended sediment loads of the Blue Earth River, Minnesota. Journal of Soil and Water Conservation 57(5):243-250.

Sharpley, A.N., S.J. Smith, and J.W. Naney. 1987. Environmental impact of agricultural nitrogen and phosphorus use. Journal of Agricultural and Food Chemistry 35:812-817.

Simon, A. 2008. Fine-sediment loadings to Lake Tahoe. Journal of the American Water Resources Association 44(3):618-639.

Simon, A., A. Curini, S.E. Darby, and E.J. Langendoen. 2000. Bank and near-bank processes in an incised channel. Geomorphology 35:193-217.

Simon, A., and L. Klimetz. 2008. Relative magnitudes and sources of sediment in benchmark watersheds of the Conservation Effects Assessment Project. Journal of Soil and Water Conservation 63(6):504-522, doi:10.2489/jswc.63.6.504.

Simon, A., N. Pollen, and E. Langendoen. 2006. Influence of two woody riparian species on critical conditions for streambank stability: Upper Truckee River, California. Journal of the American Water Resources Association 42(1):99-113.

Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology. Transaction of the American Geophysical Union 38(6):913-920.

Thoma, D.P., S.C. Gupta, M.E. Bauer, and C.E. Kirchoff. 2005. Airborne laser scanning for riverbank erosion assessment. Remote Sensing of Environment 95:493-501.

Trimble, S.W. 1994. Erosional effects of cattle on streambanks in Tennessee, USA. Earth Surface Processes and Landforms 19:451-464.

Tufekcioglu, M. 2006. Riparian land-use impacts on stream bank soil and phosphorus losses from grazed pastures. Master's thesis, Iowa State University.

USDA SCS (USDA Soil Conservation Service). 1971. Soil Survey, Wayne County, Iowa. Washington, DC: USDA Soil Conservation Service.

USDA Natural Resource Conservation Service (USDA NRCS). 1997. Grass filters. *In* Conservation Practice Standard, Code 393. Des Moines, IA: USDA Natural Resources Conservation Service.

USDA NRCS. 1998. Erosion and Sediment Delivery. Field Office Technical Guide Notice no. IA-198. Des Moines, IA: USDA Natural Resources Conservation Service.

United States Environmental Protection Agency (USEPA). 2003. Strategy for Water Quality Standards and Criteria: Setting Priorities to Strengthen the Foundation for Protecting and Restoring the Nation's Waters. EPA-823-R-03-010.

Wolman, M.G. 1959. Factors influencing erosion of a cohesive river bank. American Journal of Science 257:204-216.

Zaimes, G.N., R.C. Schultz, and T.M. Isenhart. 2006. Riparian land uses and precipitation influences on stream bank erosion in central Iowa. Journal of the American Water Resources Association 42(1):83-97.

Zaimes, G.N., R.C. Schultz, and T.M. Isenhart. 2008a. Streambank soil and phosphorus losses under different riparian land-uses in Iowa. Journal of the American Water Resources Association 44(4):935-947.

Zaimes, G.N., R.C. Schultz, and T.M. Isenhart. 2008b. Total phosphorus concentrations and compaction in riparian areas under different riparian land-uses of Iowa. Agriculture, Ecosystems and Environment 127:22-30.