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Carmen T. Agouridis
University of Kentucky, carmen.agouridis@uky.edu

Dwayne R. Edwards
University of Kentucky, dwayne.edwards@uky.edu

Stephen R. Workman
University of Kentucky, steve.workman@uky.edu

José R. Bicudo
CH2M Hill Canada, Ltd., Canada

Benjamin K. Koostra
University of Kentucky, ben.koostra@uky.edu

See next page for additional authors

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Authors
Carmen T. Agouridis, Dwayne R. Edwards, Stephen R. Workman, José R. Bicudo, Benjamin K. Koostra, Eric S. Vanzant, and Joseph L. Taraba

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STREAMBANK EROSION ASSOCIATED WITH GRAZING PRACTICES IN THE HUMID REGION

C. T. Agouridis, D. R. Edwards, S. R. Workman, J. R. Bicudo, B. K. Koostra, E. S. Vanzant, J. L. Taraba

ABSTRACT. *The effects of cattle grazing on stream stability have been well documented for the western portion of the U.S., but are lacking for the east. Stream and riparian damage resulting from grazing can include alterations in watershed hydrology, changes to stream morphology, soil compaction and erosion, destruction of vegetation, and water quality impairments. However, few studies have examined the successes of best management practices (BMPs) for mitigating these effects. The objective of this project was to assess the ability of two common BMPs to reduce streambank erosion along a central Kentucky stream. The project site consisted of two replications of three treatments: (1) an alternate water source and a fenced riparian area to exclude cattle from the stream except at a 3.7 m wide stream ford, (2) an alternate water source with free stream access, and (3) free stream access without an alternate water source (i.e., control). Fifty permanent cross−sections were established throughout the project site. Each cross−section was surveyed monthly from April 2002 until November 2003. Results from the project indicated that the incorporation of an alternate water source and/or fenced riparian area did not significantly alter stream cross−sectional area over the treatment reaches. Rather than exhibiting a global effect, cattle activity resulted in streambank erosion in localized areas. As for the riparian exclosures, changes in cross−sectional area varied by location, indicating that localized site differences influenced the processes of aggradation and/or erosion. Hence, riparian recovery within the exclosures from pretreatment grazing practices may require decades, or even intervention (i.e., stream restoration), before a substantial reduction in streambank erosion is noted.*

Keywords. *Alternate water source, Best management practices, Cattle, Riparian zone, Sediment.*

Over a quarter of the land area within the U.S. is used for grazing activities supporting nearly 100 million cattle and calves (USDA−NASS, 1997; Vesterby and Krupa, 1997). While these cattle are a major component of the U.S. agricultural trade, improperly managed grazing cattle can contribute significant pollutant loads to the nation's waterways. The U.S. Environmental Protection Agency (U.S. EPA, 2000) identified agriculture as the predominant source of nonpoint−source pollution (NPS), impairing 48% of the assessed rivers and streams. This value more than doubled the next leading source of NPS, hydrologic modifications. The two leading pollutants for rivers and streams were pathogens and sediment, constituents linked to cattle production (CAST, 2002; U.S. EPA, 2000; Belsky et al., 1999; Clark 1998). Cattle producers often use rivers and streams as the primary water source for their grazing livestock, resulting in increased activity along the water's edge. Streambank erosion occurs when livestock hooves trample banks and excessive grazing reduces riparian vegetation (Belsky et al., 1999).

Controlling or reducing agricultural NPS is an important step toward improving the quality of our nation's streams. A system of best management practices (BMPs) is the most likely means of achieving this goal in an effective and cost−efficient manner. However, developing a successful NPS pollution control program targeting grazing practices can be difficult, especially in the humid region of the U.S. The majority of research on the impacts of cattle grazing and the subsequent effect of BMPs to reduce these impacts has occurred in the western portion of the U.S., a region with a markedly different climate than the eastern U.S. (McInnis and McIver, 2001; Belsky et al., 1999; Clark, 1998; Magilligan and McDowell, 1997). While it is important to examine the individual effects of BMPs for reducing NPS associated with grazing activities, an understanding of the water quality benefits derived from multiple BMPs may provide insights that allow for more informed managerial decisions. Minimizing the impacts of grazing on stream health will likely necessitate the incorporation of both structural (i.e., riparian buffers) and cultural (i.e., managed grazing) BMPs (Logan, 1990).

Few studies in the humid region of the U.S. have examined the impacts of grazing BMPs on water quality (Line et al., 2000; Sheffield et al., 1997; Owens et al., 1989). Only isolated studies examined streambank erosion associated

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The authors are **Carmen T. Agouridis, ASAE Member Engineer,** Engineer Associate IV/Research for Water Resources, **Dwayne R. Edwards, ASAE Member Engineer,** Professor, **Stephen R. Workman, ASAE Member Engineer,** Associate Professor, **Benjamin K. Koostra, ASAE Member Engineer,** Engineer Associate, and **Joseph L. Taraba, ASAE Member Engineer,** Extension Professor, Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, Kentucky; **Eric S. Vanzant,** Associate Professor, Department of Animal Sciences, University of Kentucky, Lexington, Kentucky; and **José R. Bicudo, ASAE Member Engineer,** Environmental Engineer, CH2M Hill Canada, Ltd., Waterloo, Ontario, Canada. **Corresponding author:** Carmen T. Agouridis, Department of Biosystems and Agricultural Engineering, University of Kentucky, 128 C. E. Barnhart Bldg., Lexington, KY 40546−0276; phone: 859−257−3000; fax: 859−257−5671; e−mail: cagourid@bae.uky.edu.

with the use of a grazing BMP, although they yielded promising results. Sheffield et al. (1997) noted a 77% reduction in streambank erosion along a southwest Virginia stream following implementation of an off−stream water source. At a Tennessee stream, Trimble (1994) measured a six−fold increase in gross bank erosion along uncontrolled grazing sites as compared to reaches with exclusion fencing. While these studies provided useful information, they could not fill all the gaps in knowledge. Notably, these studies examined the effectiveness of a single BMP versus multiple controls more commonly implemented on farms, the erosive forces of cattle grazing and stream flow were not separated, and comparisons were not made between fenced and non−fenced treatments. As evident by these gaps in information, a need exists for additional information with regard to grazing BMPs, especially multiple BMPs, and their effectiveness in reducing streambank erosion. To fill the void, this project sought to determine the ability of an alternate water source with and without exclusion fencing (consisted of a 9.1 m wide riparian zone equipped with a 3.7 m wide stream ford) to reduce streambank erosion along a central Kentucky stream. Results from this project will provide stakeholders with necessary information regarding the effectiveness of these BMPs for reducing streambank erosion in central Kentucky and possibly within the humid region of the U.S.

METHODS

STUDY AREA

The study area is located on the University of Kentucky's Animal Research Center (ARC) in Woodford County, Kentucky, approximately 15 miles northwest of Lexington, Kentucky (38° 02' N, 84° 36' W). The climate is humid and temperate, with a mean monthly rainfall ranging from 66 mm in October to 118 mm in July and a mean annual rainfall of 1150 mm. Temperatures range from a mean monthly average of 0.3°C to 24.3°C, with a mean annual temperature of 12.6°C (University of Kentucky, 2004). The ARC is characterized by gently rolling hills, with elevations ranging from approximately 240 to 260 m above mean sea level. The valleys within the study area are narrow with a limited area for floodplain development. Valley slopes within the riparian area are approximately 5%, while valley slopes outside of the riparian area range from 12% to 17%. One stream drains much of the ARC through two second−order tributaries, Camden Creek and Pin Oak, whose confluence is near the property boundary of the ARC. Camden Creek originates outside of the boundaries of the ARC in horse−grazed pastures, while Pin Oak, and its headwaters, begin on the ARC. These streams flow over or near bedrock, each with a slope of about 0.5%. The entire study reach along both streams is characterized as a long run, devoid of perceivable riffles and pools. Camden Creek flows in a southwesterly direction, and Pin Oak flows in a northwesterly direction (fig. 1). The ARC is located in a significant karst terrain characterized by numerous shallow sinkholes. Previous surveys revealed that approximately 30% of the ARC drains to sinks (Fogle, 1998). Soils at the study site are derived from limestone and consist of the Hagerstown (fine, mixed, mesic Typic Hapludalf) and McAfee (fine, mixed, mesic Mollic Hapludalf) soil series along Pin Oak and the Hagerstown and Woolper (fine, mixed, mesic Typic Argiudoll) soils series along Camden Creek (Jacobs et al., 1994). The land use along the lowermost reaches of these tributaries is pasture. Land use within the subwatershed of Camden Creek consists primarily of pasture (hay and grazing) and crop (corn, wheat, and tobacco), while land use in the subwatershed of Pin Oak is predominately crop (corn, wheat, and tobacco). The pastures at the ARC, including those in the study area, are dominated by endophyte (*Neotyphodium coenophialum*) infected tall fescue (*Festuca arundinacea*).

TREATMENTS

Data collection involved two replications (one replicate was located on Camden Creek and the other on Pin Oak) of three treatments (i.e., pasture plots) listed in downstream order as: (1) an alternate water source and a fenced 9.1 m wide grassed riparian area to exclude cattle from the stream (equipped with a 3.7 m wide stream ford, which was constructed in accordance with USDA−NRCS specifications as outlined in Code 576), (2) an alternate water source with free stream access, and (3) free access without an alternate water source (i.e., control) (USDA−NRCS, 2004) (fig. 1). Treatments were ordered such that the anticipated severity of the treatment increased in the downstream direction. Selection of the treatment order followed work by Trimble (1994), who implemented a similar experimental design to assess the impacts of uncontrolled grazing on streambank erosion rates. Trimble (1994) reasoned that this treatment order would reduce the possibility of eroded bank sediments destabilizing down−gradient channel reaches through the formation of channel bars, which might alter flow patterns such that stresses would increase along stable banks. The pasture plots used for each treatment within a replication spanned the stream with similar stream frontage (table 1). The replication along Camden Creek contained pasture plots with an area of approximately 2 ha, while the pasture plots located along Pin Oak were nearly 3 ha. The difference in plot size for the replications resulted from the amount of land available for the study. Every attempt was made to ensure that other plot characteristics, such as topographical features, soils, existing shade, and riparian characteristics (if applicable), were as consistent as possible among the treatments.

The alternate water source consisted of insulated waterers installed on a concrete base with a geotextile−gravel pad. Located in the upland areas of the pasture plots, these waterers were between 87 to 121 m from the streams (table 1). High−tensile electrical fence was used to separate the pasture plots and to exclude cattle from the riparian areas. The excluded riparian areas consisted primarily of ungrazed tall fescue, as additional vegetation such as trees and shrubs were not planted. Stream crossings (i.e., fords) were constructed using geotextile, a 15 cm layer of riprap (approximately 10 cm dia.), and a 10 cm compacted layer of crushed rock, as outlined in Code 576 (USDA−NRCS, 2004). Fertilizer (ammonia nitrate) was applied annually to all pasture plots at a rate of 45 kg ha^{-1} prior to the start of the grazing season. Cattle stocking densities were varied throughout the grazing seasons based on the amount of available forage (table 2). However, the maximum practical level was used with the goal of maintaining the same stocking densities for all treatments within a replication. Initial stocking densities were set at 1300 kg ha^{-1} and were adjusted based on visual assessment of available forage. Cattle were weighed on a monthly basis during the grazing season

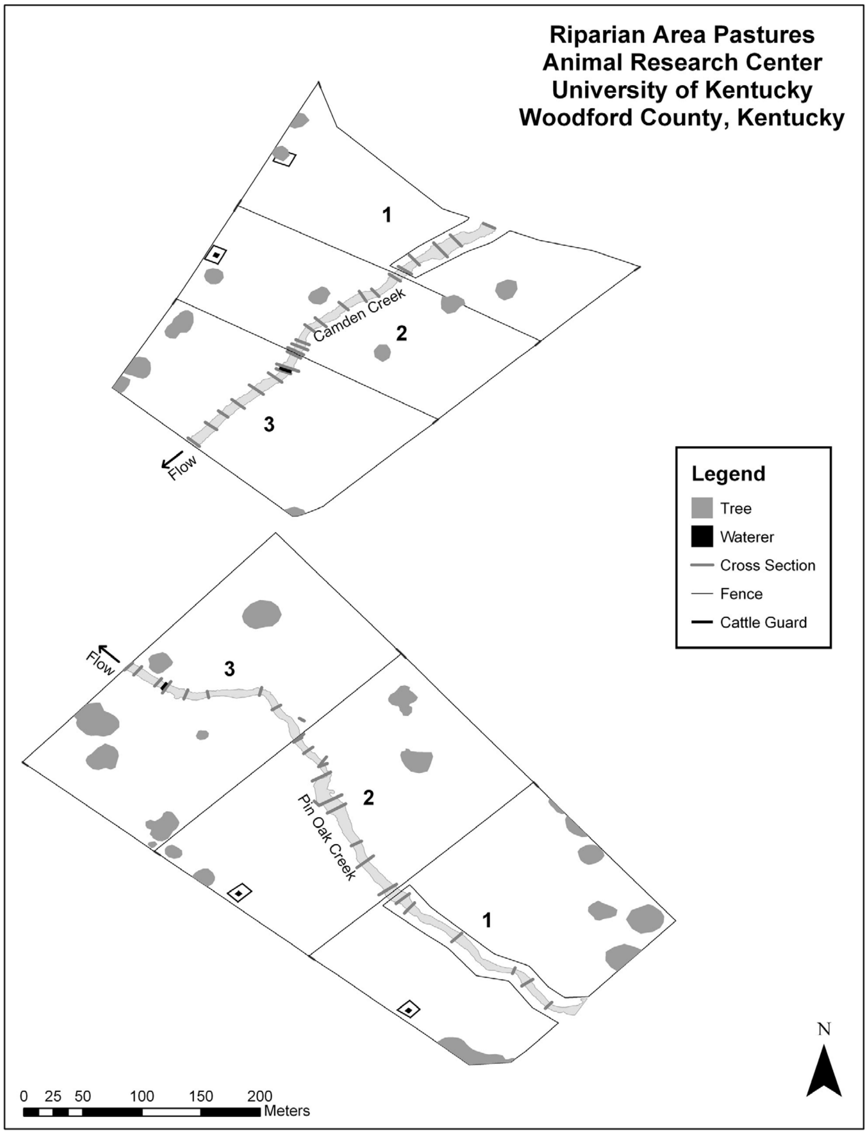

Figure 1. Base map of pasture plots: plot 1 treatment is the alternate water source and a fenced riparian area to exclude cattle from the stream except at a 3.7 m stream ford, plot 2 treatment is alternate water source with free stream access, and plot 3 is free stream access.

Table 1. Pasture plot characteristics.

Stream	Pasture Plot[a]	Area (ha)	Stream Frontage (m)	Distance to Alternate Water Source (m)[b]
Camden Creek	1	2.3	80	121
	2	2.3	100	87
	3	2.2	104	−−[c]
Pin Oak	1	3.2	155	98
	2	3.4	150	92
	3	3.4	142	−−

[a] Pasture plots are as follows: 1 = alternate water source and fence riparian zone, 2 = alternate water source with free stream access, and 3 = no alternate water source with free stream access (control).

[b] In relation to nearest streambank.

[c] No alternate water source present on the pasture plot.

(typically mid−April until late October). During the 2002 and 2003 grazing seasons, steers were grazed on the pastures, except during November and December 2002 when cows were placed on the pastures. During August and September of 2002, the stocking density was maintained by feeding hay (ad libitum) when forage supply became limited due to drought conditions. Supplemental hay was located in the upland areas away from the streams and on the opposite side of the pasture plots in comparison to the alternate water sources. All animal protocols were approved by the University of Kentucky Institutional Animal Care and Use Committee (Protocol 00245A2001).

CROSS-SECTIONAL AREAS

Using guidelines set forth by Harrelson et al. (1994), 50 permanent cross−sections (23 along Camden Creek and 27 along Pin Oak) were established for surveying erosion levels. Cross−sections were erected at both random locations and near areas anticipated as frequent travel paths for cattle. Along Pin Oak, one cross−section was established at the confluence of Pin Oak with an unnamed ephemeral channel. Each cross−section was established perpendicular to stream flow. Cross−sectional surveys were conducted monthly from April 2002 until November 2003, resulting in a total of

Table 2. Stocking densities (kg ha^{-1}) for each pasture plot and each sampled period.[a]

	Camden Creek			Pin Oak		
Period	1	2	3	1	2	3
June 2002	1429.7	1428.2	1430.6	1394.5	1420.9	1431.3
July 2002	1521.1	1613.8	1554.0	1543.8	1551.3	1519.7
Aug. 2002	829.4	846.0	777.1	802.5	833.3	814.9
Sept. 2002	829.0	825.9	783.9	808.1	846.2	834.8
Oct. 2002	820.6	824.5	776.0	806.3	826.4	722.4
Nov. 2002	−−[b]	−−	−−	−−	−−	−−
Dec. 2002	1040.5	1005.0	972.8	790.7	949.7	885.5
Jan. 2003	0.0[c]	0.0	0.0	0.0	0.0	0.0
Feb. 2003	0.0	0.0	0.0	0.0	0.0	0.0
March 2003	0.0	0.0	0.0	0.0	0.0	0.0
April 2003	0.0	0.0	0.0	0.0	0.0	0.0
May 2003	1338.2	1332.6	1304.6	1277.5	1263.3	1263.4
June 2003	1462.7	1443.8	1410.2	1361.9	1358.8	1340.1
July 2003	1482.1	1465.8	1427.9	1342.3	1350.6	1326.6
Aug. 2003	1508.4	1502.5	1451.8	1298.1	1377.5	1364.4
Sept. 2003	1546.7	1574.7	1497.0	1443.3	1470.6	1435.2
Oct. 2003	769.9	782.7	782.3	737.2	764.7	738.9

[a] Treatments are as follows: 1 = alternate water source and fence riparian zone, 2 = alternate water source with free stream access, and 3 = no alternate water source with free stream access (control).

[b] No data available because scale malfunctioned.

[c] No cattle were present on the pasture plots.

18 surveys of each cross−section. Conventional leveling techniques, as outlined in Harrelson et al. (1994), were employed, and elevation measurements were taken at 0.3 m horizontal intervals. Data from all of the cross−sectional surveys were used in the analysis except for those collected during January 2003 (when the alluvial material was frozen).

Computation of changes in cross−sectional area with subsequent surveys was a multi−step process. Each recorded elevation within a cross−section was subtracted from an upper plane (i.e., constant elevation) that was greater than all of the measured elevations for that cross−section to obtain a cross−sectional area at that location and time period. This step was performed for all 50 cross−sections and for all 17 periods. The cross−sectional areas ($A_{T,\,j,k}$) for each cross−section and for each sample period were computed using:

$$A_{T,\,j,k} = \Sigma A_i = \left(x_i - x_{i-1}\right)\left(\frac{y_i + y_{i-1}}{2}\right) \tag{1}$$

where x is the lateral station along the cross−section, and y is the elevation at the corresponding lateral station. Lateral station is represented by the subscript i, sample period is represented by the subscript j, and cross−section location is represented by the subscript k. Differences in cross−sectional area were computed for each cross−section by subtracting the cross−sectional area for the previous period ($j - 1$) from the cross−sectional area for the current period (j). At each individual cross−section, increased values of $A_{T,\,j,k}$ from one cross−sectional survey period to the next indicated alluvium loss or erosion, while decreased values of $A_{T,\,j,k}$ from one cross−sectional survey period to the next indicated alluvium gain or aggradation. A total of 16 cross−sectional area differences were computed for each cross−section. For a given sampling period, all cross−sectional area differences computed for the cross−sections within a treatment and replication were averaged to obtain an overall mean for the respective pasture plot (table 3).

CATTLE POSITION

Understanding the impact of grazing activity on streambank erosion required knowledge of animal position. Global positioning system (GPS) collars (GPS_2200 Small Animal GPS Location Systems, Lotek Engineering, Inc., Newmarket, Ontario) were used to collect position information on a sample of cattle from each pasture plot (table 4) Detailed descriptions of the GPS collars were presented in Turner et al. (2000) and Agouridis et al. (2004). Position information was collected over seven 18−day periods during May, August, and November of 2002 and April, June, July, and October of 2003. A 5 min sample interval, the smallest permitted with the GPS collars, was selected. Data from the

Table 3. Means[a] and standard deviations for changes in cross−sectional areas (m^2) for each pasture plot and each sampled period.[b]

	Camden Creek			Pin Oak		
Period	1	2	3	1	2	3
June 2002	−0.07 ±3.10	0.00 ±0.54	0.12 ±2.35	−0.15 ±1.52	0.03 ±1.41	0.03 ±1.37
July 2002	−0.09 ±0.55	0.05 ±0.46	−0.01 ±2.05	−0.07 ±0.49	−0.01 ±0.90	−0.02 ±0.97
August 2002	0.09 ±1.70	0.02 ±0.48	−0.01 ±1.05	0.05 ±0.38	−0.01 ±1.19	0.01 ±0.51
September 2002	−0.08 ±0.82	0.00 ±0.93	0.04 ±1.86	0.06 ±1.06	−0.01 ±1.04	0.01 ±1.44
October 2002	0.11 ±0.99	0.02 ±0.55	0.09 ±1.08	0.00 ±0.94	0.00 ±1.02	0.01 ±1.19
November 2002	0.02 ±0.90	0.03 ±0.39	0.04 ±1.18	0.01 ±0.92	0.06 ±0.71	0.06 ±0.47
December 2002	0.00 ±0.75	0.01 ±0.76	−0.02 ±1.08	0.02 ±0.96	0.02 ±0.93	−0.03 ±0.38
February 2003	−0.01 ±0.45	0.04 ±0.84	−0.17 ±1.82	0.10 ±0.77	−0.02 ±1.17	0.06 ±0.26
March 2003	0.04 ±1.37	0.00 ±0.36	0.13 ±0.88	−0.02 ±0.32	−0.01 ±0.67	−0.02 ±0.55
April 2003	−0.04±0.90	−0.02 ±1.00	−0.06 ±2.43	−0.11 ±0.79	−0.05 ±0.69	−0.06 ±0.24
May 2003	−0.06 ±1.04	0.05 ±1.03	−0.01 ±3.99	0.06 ±0.68	0.06 ±1.05	0.00 ±1.65
June 2003	−0.02 ±0.92	0.00 ±0.44	0.04 ±1.95	−0.13 ±1.48	−0.02 ±1.33	0.04 ±0.82
July 2003	0.01 ±0.89	0.00 ±0.67	0.01 ±2.82	−0.12 ±1.88	0.02 ±1.10	−0.04 ±0.96
August 2003	−0.03 ±0.56	0.03 ±0.64	0.02 ±1.41	0.09 ±1.01	−0.05 ±1.04	0.04 ±1.82
September 2003	−0.06 ±0.57	−0.04 ±0.68	−0.13 ±1.48	−0.03 ±0.93	−0.06 ±1.04	0.03 ±1.27
October 2003	0.04 ±0.47	0.00 ±0.97	−0.01 ±0.81	0.05 ±1.13	−0.02 ±1.06	−0.05 ±1.94

[a] A positive value indicates an increase in cross−sectional area (i.e., erosion), while a negative value indicates a decrease in cross−sectional area (i.e., aggradation).

[b] Treatments are as follows: 1 = alternate water source and fence riparian zone, 2 = alternate water source with free stream access, and 3 = no alternate water source with free stream access (control).

Table 4. Percentage of cattle equipped with GPS collars during each sampled event.[a]

	Camden Creek			Pin Oak		
Sampling Event	1	2	3	1	2	3
May 2002	22	33	33	20	13	20
August 2002	50	75	50	38	38	25
November 2002	67	100	100	75	75	75
April 2003	38	25	25	25	25	25
June 2003	25	25	25	17	25	17
July 2003	25	25	25	25	25	25
October 2003	50	50	50	33	50	33

[a] Treatments are as follows: 1 = alternate water source and fence riparian zone, 2 = alternate water source with free stream access, and 3 = no alternate water source with free stream access (control).

Table 5. Percentage of filtered GPS position points for each pasture plot (total) and within 5 m of streambanks.[a]

	Camden Creek			Pin Oak		
Sampling Event	1	2	3	1	2	3
	Total					
May 2002	85.7	86.4	76.1	85.5	86.7	86.6
August 2002	96.2	95.8	90.3	87.5	93.9	95.7
November 2002	77.6	77.6	77.2	77.5	77.5	78.6
April 2003	88.6	86.9	87.1	86.3	89.5	88.1
June 2003	97.3	95.1	89.2	98.1	98.1	98.2
July 2003	88.1	90.5	87.4	87.5	88.7	89.0
October 2003	97.6	97.0	96.4	96.6	97.3	97.0
	Streambanks					
May 2002	81.6	79.7	93.5	84.4	88.2	87.0
August 2002	97.6	97.9	94.7	82.7	95.6	96.5
November 2002	72.8	75.4	81.1	77.3	77.1	82.8
April 2003	91.0	92.4	90.8	91.3	86.7	89.2
June 2003	97.9	98.7	93.2	99.1	96.8	99.4
July 2003	90.9	94.0	91.9	86.3	87.3	87.8
October 2003	99.6	98.6	99.6	99.7	97.5	99.2

[a] Treatments are as follows: 1 = alternate water source and fence riparian zone, 2 = alternate water source with free stream access, and 3 = no alternate water source with free stream access (control).

GPS collars were filtered and differentially corrected, allowing use of the most accurate position points in the analysis (Agouridis et al., 2004). To ensure that the filtering process did not skew the data, one−way repeated measures analysis of variance (ANOVA) tests ($\alpha = 0.05$) were conducted to compare the percentage of usable (i.e., non−filtered) position points between each pasture plot in its entirety and between each pasture plot along the streambanks (table 5). No statistical difference was detected between the usable position points collected in the pasture plot and those along the streambanks. Additionally, no statistical differences were noted between pasture plots for the percentage of usable points along the streambanks (i.e., the position points used in the streambank erosion analysis).

Prior to the start of the project, a base map identifying key pasture features was created using a real−time kinematic global positioning system (RTK−GPS) with a published horizontal accuracy of 20 mm. Key pasture features included the streambanks of Camden Creek and Pin Oak, fences, trees, alternate water sources, fenced riparian areas, and stream crossings. The base map was used in conjunction with data collected from the GPS collars during the seven cattle−monitoring periods to characterize cattle position along the streambanks. A 5 m buffer from the edge of the streambanks was created in ArcView for each pasture plot. The 5 m buffer was selected because it represents the estimated maximum horizontal error associated with the GPS collars in an open−field environment (Agouridis et al., 2004). Separation of in−stream and near−stream cattle positioning was not performed because technological limitations with the GPS collars (i.e., accuracy level) prohibited specific identification of in−stream versus near−stream position. For each GPS collar−monitoring period, all GPS collar data points that fell within this buffer were totaled ($GPS_{s,p,j}$). A 5 m buffer around each cross−section was overlaid on the 5 m stream buffer, and all of the GPS collar data points that fell within this overlay were totaled ($GPS_{ov,p,j}$). Finally, the percentage of cattle activity within 5 m of the stream associated with each cross−section and each GPS monitoring period was computed using:

Table 6. Means and standard deviations for cross−sectional cattle positions (%) for each pasture plot and each sampled period.[a]

	Camden Creek			Pin Oak		
Period	1	2	3	1	2	3
June 2002	5.10 ±7.95	10.53 ±5.14	7.26 ±10.06	5.50 ±10.65	8.02 ±8.47	6.08 ±4.15
July 2002	−−[b]	−−	−−	−−	−−	−−
August 2002	−−	−−	−−	−−	−−	−−
September 2002	4.22 ±6.82	9.32 ±4.37	9.42 ±4.39	6.90 ±16.42	8.06 ±16.05	7.39 ±11.86
October 2002	−−	−−	−−	−−	−−	−−
November 2002	5.47 ±10.07	9.92 ±4.73	9.33 ±6.23	5.87 ±12.61	9.18 ±12.10	5.39 ±5.69
December 2002	−−	−−	−−	−−	−−	−−
February 2003	0.0[c]	0.0	0.0	0.0	0.0	0.0
March 2003	0.0	0.0	0.0	0.0	0.0	0.0
April 2003	0.0	0.0	0.0	0.0	0.0	0.0
May 2003	1.92 ±2.64	10.02 ±7.42	9.01 ±4.30	5.13 ±10.85	8.33 ±7.41	6.08 ±3.00
June 2003	7.51 ±16.32	9.56 ±6.65	9.06 ±5.18	3.44 ±7.91	9.75 ±16.87	4.51 ±3.85
July 2003	3.80 ±4.19	8.66 ±4.28	8.34 ±7.93	4.60 ±10.96	8.33 ±15.47	7.02 ±11.22
August 2003	−−	−−	−−	−−	−−	−−
September 2003	−−	−−	−−	−−	−−	−−
October 2003	6.47 ±5.18	8.53 ±4.65	8.29 ±6.87	2.99 ±6.22	9.52 ±14.99	7.19 ±13.99

[a] Treatments are as follows: 1 = alternate water source and fence riparian zone, 2 = alternate water source with free stream access, and 3 = no alternate water source with free stream access (control).
[b] Indicates that no data were collected for this period.
[c] Cattle were not present on the pasture plots.

$$\mathrm{GPS}_{j,k} = \left(\frac{\mathrm{GPS}_{ov,p,j}}{\mathrm{GPS}_{s,p,j}} \right) \times 100 \qquad (2)$$

where the subscript *s* denotes the 5 m stream buffer around the stream, the subscript *ov* denotes the overlay of the 5 m stream buffer around the stream and the 5 m cross−section buffer around the cross−section, and the subscript *p* denotes the pasture plot that contained the cross−section. As with differences in cross−sectional areas, all cross−sectional cattle position values within each treatment and replication were averaged to obtain an overall mean for the respective pasture plots for each sampled period (table 6).

STOCKING DENSITIES

All cattle on each of the pasture plots were weighed at 28−day intervals during the grazing season for both years of the project. The final weights and cattle numbers for each pasture plot and for each period were used to compute stocking densities (table 2). Every attempt was made to maintain equivalent stocking densities across the pasture plots within a replicate for a given period. Stocking densities varied with available forage, ranging from 1670 kg ha^{-1} at the early stages of the grazing seasons to 720 kg ha^{-1} during the latter part of the grazing seasons.

STREAM DISCHARGES

Stream discharge data were collected at the most downstream edge of each replication (i.e., Camden Creek and Pin Oak) using compound 90° V−notch weirs and ISCO 4220 flowmeters (pressure transducers) (fig. 1). Discharge data were collected at 10 min intervals at the two weirs for the duration of the study. Each weir was located approximately 5 m downstream from the respective most downstream treatments. Average discharges were computed from flow values collected during the period prior to each cross−sectional survey. For example, if a cross−sectional survey was performed on September 3, 2002, and the subsequent survey was conducted on October 2, 2002, then the average discharge for the period was assigned to the October survey. Since flow data were not available at each cross−section, ArcView was used to prorate the outlet flow contributions to each cross−section based on the cross−section's watershed area:

$$Q_{j,k} = \left(\frac{Q_{w,j}}{WS_w} \right) WS_k \qquad (3)$$

where *Q* represents discharge (m^3 s^{-1}), *WS* represents watershed area, and the subscript *w* represents the weir. Flow data were not available for the ephemeral channel that flows into Pin Oak. As with differences in cross−sectional areas, all cross−sectional stream discharge values within a treatment and replication were averaged to obtain an overall mean for the respective pasture plots for each sampled period (table 7).

Table 7. Mean stream discharges (m^3 s^{-1}) for each pasture plot and each sampled period.[a]

	Camden Creek			Pin Oak		
Period	1	2	3	1	2	3
June 2002	0.12	0.12	0.12	0.15	0.16	0.16
July 2002	0.02	0.02	0.02	0.01	0.01	0.01
Aug. 2002	0.00	0.00	0.00	0.00	0.00	0.01
Sept. 2002	0.00	0.00	0.00	0.00	0.00	0.00
Oct. 2002	0.00	0.00	0.00	0.01	0.01	0.01
Nov. 2002	0.15	0.15	0.15	0.08	0.09	0.09
Dec. 2002	0.09	0.09	0.09	0.05	0.06	0.06
Feb. 2003	0.15	0.15	0.16	0.10	0.10	0.11
March 2003	0.22	0.23	0.23	0.19	0.20	0.20
April 2003	0.10	0.10	0.10	0.06	0.06	0.06
May 2003	0.26	0.26	0.26	0.13	0.14	0.14
June 2003	0.18	0.19	0.19	0.13	0.14	0.14
July 2003	0.03	0.03	0.03	0.03	0.03	0.03
Aug. 2003	0.02	0.02	0.02	0.01	0.02	0.02
Sept. 2003	0.06	0.06	0.06	0.02	0.03	0.03
Oct. 2003	0.02	0.02	0.02	0.02	0.02	0.02

[a] Treatments are as follows: 1 = alternate water source and fence riparian zone, 2 = alternate water source with free stream access, and 3 = no alternate water source with free stream access (control).

TIME

The parameter time was defined as the time lapse or interval from the start of cross−sectional data collection (i.e., prior to cattle introduction in April 2002) until the end of the project (i.e., following cattle removal in November 2003). A time value in relation to the original cross−sectional survey was computed for each subsequent cross−sectional survey, and ranged from 59 days in June 2002 to 571 days in November 2003.

STATISTICAL ANALYSIS

In this study, the experimental unit and blocking unit were stream (i.e., Camden Creek and Pin Oak), and cross−sections were subsamples within the experimental unit. For each sampled period, the cross−sectional area differences within each treatment and replication were averaged to obtain an overall mean. Multivariate repeated measures analysis techniques were conducted using the mixed model in SAS (PROC MIXED) to determine the effects that treatment, time, stream, stocking density, cross−sectional cattle positions, and cross−sectional stream flow had on changes in cross−sectional area (SAS, 1985). Because the number of cross−sections or subsamples differed among the pasture plots, the subsamples were weighted for unequal sizes in the mixed model. The Akaike information criterion (AIC) and Bayesian information criterion (BIC) were used to evaluate the covariate structure of the model. Construction of the model occurred by first eliminating nonsignificant continuous variables (i.e., stocking density, cross−sectional cattle positions, and cross−sectional stream flow) at α = 0.05, followed by categorical variables without interaction (i.e., stream and time). Since the objective of the study was to assess the ability of treatment (i.e., BMPs) to reduce streambank erosion, treatment and variables interacting with treatment remained in the model during the model reduction process.

RESULTS AND DISCUSSION

Three iterations of the mixed model were conducted to assess the effects of the categorical and continuous variables on changes in cross−sectional areas. Results of these iterations indicated that none of the examined variables (stream, treatment, time, stocking density, cross−sectional cattle position, and cross−sectional stream flow) were significant predictors of changes in cross−sectional area at the $\alpha = 0.05$ level of significance. Only one variable, cross−sectional cattle position, was significant at $\alpha = 0.10$ ($P = 0.06$).

CATTLE POSITION AND ACTIVITY

Based on previous research into the impacts of cattle grazing on streambanks, it was expected that cross−sectional cattle positions would be a stronger predictor of change in cross−sectional area (Belsky et al., 1999; Sheffield et al., 1997; Trimble, 1994; Kauffman et al., 1983). The moderate nature of the trend was likely due to the position accuracy limitations of the GPS collars, coupled with a lack of information regarding actual cattle activity associated with the position points. While the GPS collars were equipped with two−axis activity sensors, these sensors provided a poor sense of animal activity because: (1) collar fit, which differed for each animal, impacted sensitivity, (2) orientation of the collar on the animal impacted sensor performance (i.e., which side of the collar was facing outward), and (3) movement of the animal's head alone could not be readily differentiated from movement of the entire animal (i.e., drinking or grazing versus walking). As such, the nature of the position points (i.e., active or static) was not differentiated, meaning that all cross−sectional cattle positions were treated equally in the model, regardless of the level of activity. In actuality, a large number of position points may have been associated with low levels of cattle movement (i.e., cattle loitering in the stream) and relatively small changes in cross−sectional area, while a small number of position points with high levels of cattle movement (i.e., cattle walking along the streambanks) may have been linked to relatively large changes in cross−sectional area (table 8).

Table 8. Cross−sectional area linear trends and cattle activity.

Cross Section[a]	Treatment[b]	Trend[c]	R^2	Cattle Positions[d]
C1	1	D	0.17	0.00
C2	1	D	0.01	1.61
C3	1	I	0.12	2.30
C4	1	I	0.78	0.84
C5	1	I	0.58	19.98
C6	2	D	0.60	18.49
C7	2	D	0.67	5.03
C8	2	−−	0.00	7.53
C9	2	−−	0.00	7.27
C10	2	D	0.01	9.47
C11	2	D	0.38	14.76
C12	3	D	0.27	8.97
C13	3	D	0.79	10.38
C14	3	D	0.08	5.60
C15	3	D	0.32	9.75
C16	3	I	0.12	9.15
C17	3	I	0.07	14.31
C18	3	I	0.40	5.04
C19	3	I	0.35	4.19
C20	2	D	0.84	9.37
C21	2	D	0.57	6.58
C22	3	D	0.36	14.69
C23	2	D	0.74	8.25
P1	1	I	0.37	0.31
P2	1	I	0.38	0.32
P3	1	I	0.22	0.17
P4	1	I	0.11	0.97
P5	1	I	0.41	0.43
P6	1	−−	0.00	24.68
P7	2	I	0.03	1.75
P8	2	D	0.24	45.08
P9	2	D	0.43	33.49
P10	2	D	0.02	1.91
P11	2	D	0.09	1.49
P12	2	D	0.07	5.84
P13	2	I	0.01	1.19
P14	3	D	0.65	1.96
P15	3	D	0.21	3.10
P16	3	D	0.04	7.23
P17	3	D	0.02	3.82
P18	3	D	0.56	23.95
P19	3	−−	0.00	2.43
P20	3	I	0.04	3.27
P21	2	D	0.06	1.31
P22	2	D	0.11	1.34
P23	3	D	0.60	2.03
P24	2	I	0.35	9.32
P25	2	I	0.28	2.21
P26	3	I	0.59	10.43
P27	2	I	0.19	2.54

[a] Averaging time since cattle started grazing would have no meaning. The time intervals were 59, 87, 116, 144, 173, 222, 249, 314, 343, 371, 399, 434, 466, 500, 529, and 571 days. The letter before the number indicates the stream on which the cross−section was located. C = Camden Creek and P = Pin Oak.

[b] Treatments are as follows: 1 = alternate water source and fenced riparian zone, 2 = alternate water source with free stream access, and 3 = no alternate water source with free stream access (control)

[c] I = increasing cross−sectional area, D = decreasing cross−sectional area, and −− = no change in cross−sectional area.

[d] Percentage of position points within 5 m of cross−section in relation to position points within 5 m of streambanks for all seven sampled periods combined.

Examination of changes in cross−sectional areas over the course of the study, with respect to cross−section location in the pasture plots, revealed interesting aspects. Cross−sections that demonstrated some of the strongest increasing trends with respect to cross−sectional area did not necessarily have the greatest percentage of cattle position points and were often located along or near preferred stream crossing points (i.e., locations of active movement). For example, cross−sections C6, C7, C13, C20, C21, P14, P18, and P26 were all located near fencelines (i.e., newer cattle stream crossings or paths) or near former cattle guards marking former fencelines (i.e., old cattle stream crossings or paths) (fig. 1). Similarly, not all cross−sections that demonstrated a strong decreasing trend in cross−sectional area had a small percentage of cross−sectional cattle position points (i.e., C5). Higher levels of cattle position points were associated with cross−sections adjacent to the stream fords, which was due (in part for the non−fenced riparian area cross−sections, and entirely for the fenced riparian area cross−sections) to the accuracy level of the collars. For the pasture plots with fenced riparian areas, cattle were excluded from the riparian areas, and as such cattle position points should not have been recorded in relation to cross−sections located in these excluded areas. Furthermore, the two cross−sections with the highest number of recorded cattle positions (P8 and P9) demonstrated weak to moderate decreasing cross−sectional area trends ($R^2 = 0.24$ and 0.43, respectively). These cross−sections were located in areas where cattle frequently loitered, as determined by numerous visual observations, thus highlighting the greater importance of cattle activity rather than cattle position in erosion processes.

The incorporation of a fenced riparian zone into a grazing BMP program may prove beneficial in the reduction of erosion rates, but a significant period of time may be required if these benefits are to be realized. The lack of significance of the variable treatment is likely the result of the geomorphologic nature of the stream and the length of the study. Throughout the study reach, as well as the reaches upstream of the study area, the discharge from both Camden Creek and Pin Oak flows over or near bedrock. Therefore, sediment supply to the streams is limited to contributions from runoff and the streambanks. Previous geological research at the ARC revealed the importance of groundwater, as Gremos (1994) discovered nearly 80 sinkholes and sinks (rounded depressions) on the ARC. Maury and McAfee, the dominant soil series at the ARC, are in the hydrologic soil group B, which is characterized by moderate infiltration rates (Haan et al., 1994; Jacobs et al., 1994). With limited amounts of runoff contributing to the flow in Camden Creek and Pin Oak, the majority of the in−stream sediments are produced from streambank erosion processes (i.e., cattle activity and discharge). The lack of significance for the variable discharge is indicative of the potentially lengthy period of time required for notable changes in the cross−sectional areas (i.e., channel narrowing) to occur under the influence of discharge alone. Furthermore, the sampling period to sampling period oscillation between increases in cross−sectional area and decreases in cross−sectional area for certain cross−sections was likely the result of varying sediment supplies (i.e., degree of streambank trampling by cattle) and transport rates (i.e., stream discharge). With regard to sediment supply, no notable degradation of the stream fords was perceived over the course of the study, meaning that no rills formed along the stream fords and loss of rock along the top layer was minimal.

ELIMINATED VARIABLES

The variables identified as nonsignificant in the mixed model (i.e., stream, treatment, time, stocking density, and discharge) were as interesting as the significance of cattle position (P = 0.06). The nonsignificant nature of the variable stream indicates that the results of this study are applicable to other areas within central Kentucky and possibly similar bedrock streams in the humid region of the U.S. With regard to treatment, the flawed assumption was that the rate of both streambank erosion for the unfenced treatments and the recovery phase for the fenced treatments from pre−study grazing pressures would be similar. In actuality, Camden Creek and Pin Oak resembled a broken−leg model, in which recovery occurs at a slow rate following removal of grazing pressures; it takes a much longer time for the stream to reach a state of equilibrium (Sarr, 2002). The low potential for upstream sediment influxes, due to the nature of the streams and watersheds, coupled with the low potential for sediment deposition, due to the straightness of the channels, indicates that grazing recovery within the study reach may require several years, and may in fact require intervention (i.e., stream restoration). Costa (1974) noted that straight channel reaches are slow to recover because of the minimal occurrence of flow restrictions, which promote sediment deposition. Magilligan and McDowell (1997) noted that channel adjustment on four alluvial streams in Oregon occurred in part by sediment deposition following the exclusion of cattle. Trends of decreasing cross−sectional area were noted for some cross−sections (i.e., C18, C19, and P26) in close proximity to the backwaters created by the weirs. The weirs can be characterized as small dams that promoted the settling of suspended sediments, which probably originated from the streambanks. As for the alternate water source, its presence alone did not reduce streambank erosion. Although not directly measuring streambank erosion rates, Line (2003) noted that significant decreases in suspended sediment concentrations did not occur with an alternate water source alone but did occur following exclusion fencing.

A basic assumption made with regard to streambank erosion over the course of the study at Camden Creek and Pin Oak, and that helped to explain the insignificance of time, was that following the introduction of cattle, erosion would occur steadily over time until cattle were removed, and little recovery would take place after their removal during the off−grazing season. Following cattle removal, erosion rates would continue slowly and possibly plateau, and then increase again following the re−introduction of cattle. The basic flaw with this assumption was that cattle position, and hence cattle activity, within a cross−section would be constant throughout the time that the animals were in the pasture. Plots of GPS collar data revealed that while cattle favored certain sections of the stream, the rates at which they frequented these sections varied throughout the study (fig. 2). Furthermore, the level of activity within a cross−section was a more important indicator of erosion than merely cattle presence in the cross−section (table 8). The pressure exerted on streambanks by cattle hooves can result in bank shear and bank sloughing (CAST, 2002; Warren et al, 1986). Cattle frequently standing on the bedrock bottom of the stream, as visually confirmed with cross−section P8 and P9, had a lesser impact on cross−sectional areas (i.e., decreasing trends) when compared to cross−sections located near new or established cattle stream crossings or paths near fencelines. This observation indicates that erosion can happen quickly in areas associated with frequent cattle movement but may occur more slowly in reaches noted for cattle loitering.

In addition to time and treatment, stocking density was not found to be a significant predictor of change in cross−sectional area. Stocking density was greatest during the early cooler months of the grazing season when forage was plentiful. As the grazing season continued, stocking densities in the pasture plots generally decreased as forage availability decreased. By fluctuating stocking densities based on available forage, as determined by visual observation, and supplementing forage (i.e., hay) during August and September 2002 during drought conditions, stocking densities were essentially a managerial BMP. Zobisch (1993) noted that soil loss increased with stocking density, but that reductions in soil loss occurred when stocking densities were managed to maintain at least a 40% foliage cover level. Furthermore, these managed stocking densities did not affect increasing trends in cross−sectional area (i.e., erosion) for high−traffic locations, such as along fencelines, indicating that erosion can occur with a small number of animals. If stocking density had remained constant throughout the grazing seasons, particularly the 2002 grazing season, then the level of erosion may have been greater in these high−traffic areas.

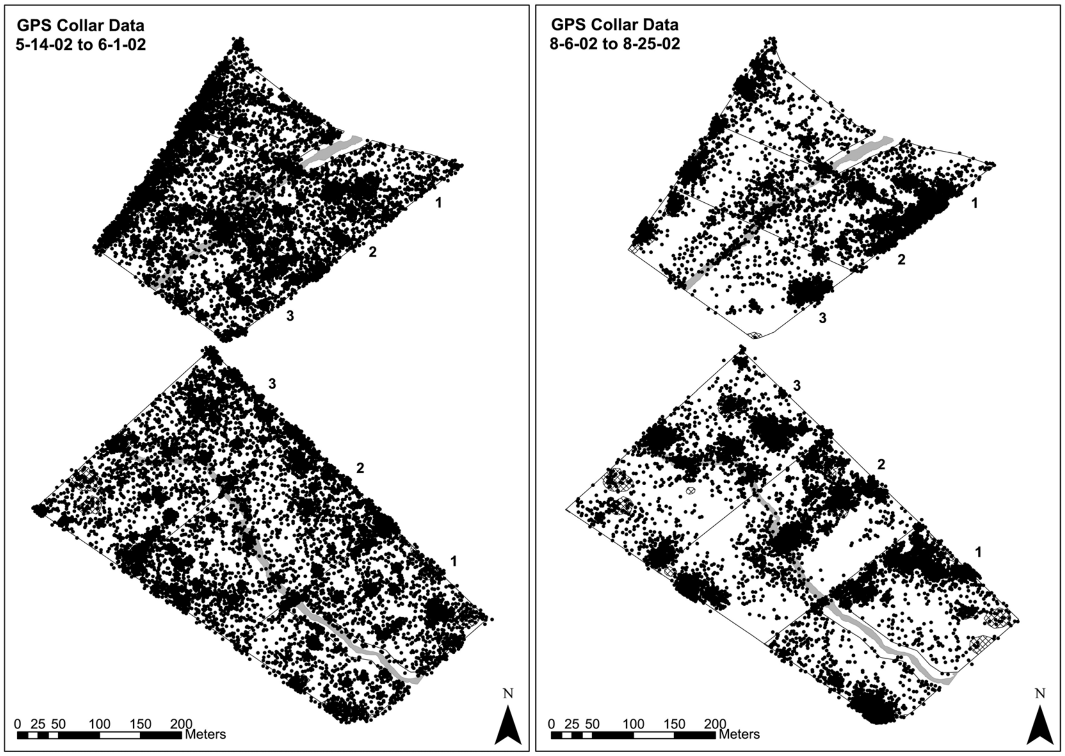

Figure 2. Example of spatial variability in GPS collar position data between sampled periods: plot 1 treatment is the alternate water source and a fenced riparian area to exclude cattle from the stream except at a 3.7 m stream ford, plot 2 treatment is alternate water source with free stream access, and plot 3 is free stream access.

Surprisingly, cross−sectional discharge was not significantly related to change in cross−sectional area. Lane (1955) indicated that increases in flow produce increases in sediment, assuming that median particle size and slope remain constant. As such, the expectation was that increased discharge levels would result in increased rates of streambank erosion, especially in the unfenced treatments that lacked substantial riparian vegetation. The lack of a significant relationship between discharge and change in cross−sectional area is likely due to: (1) the nature of the streambank materials, and (2) the overriding influence of cattle position (i.e., activity) on change in cross−sectional area. Soils along the study reaches are from the Maury and McAfee soil series, which are silt loams. Cohesive banks, such as those in the study reaches, are generally resistant to high fluid shear, which is present with elevated discharges. Additionally, these soils have low shear strength, making them more susceptible to mass failure, which may be influenced by cattle activity (Lawler et al., 1997). Lawler et al. (1997) noted that cohesive banks rarely experience mass failures during periods of high discharge, but that these banks are more susceptible to such events within hours to days after the recession of higher flows. While these banks may have been more susceptible to erosion as a result of greater discharges, a time lag likely preceded any mass failures, provided that these mass failures occurred at the study site.

CONCLUSIONS

Streambank erosion along two bedrock−bottom, second−order perennial streams was positively correlated with cattle position within the cross−section (P = 0.06). While knowledge regarding cattle position was useful, information pertaining to specific cattle activity (i.e., walking versus loitering) would have been of greater assistance, as the number of position points within a cross−section did not readily relate to high levels of cattle movement (i.e., streambank trampling). Cross−sections that demonstrated the highest erosional trends did not have the highest number of position points, but rather were located in areas typical of greater cattle movement, such as preferred stream crossings or paths. Cattle continued to impact the stream if allowed access, indicating that the use of an alternate water source alone did not reduce streambank erosion rates. The trend of decreasing cross−sectional area for locations within the exclusion areas, while not significant, suggests that the inclusion of a fenced riparian zone into a grazing BMP program may prove beneficial, but years may be required before any morphological benefits are apparent. While some systems may recover quickly, the low supply of upstream sediments to the study reaches on Camden Creek and Pin Oak likely means that several years of rest or even intervention (i.e., stream restoration) may be required before pre−grazed conditions are realized.

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