

Grazed Riparian Management and Stream Channel Response in Southeastern Minnesota (USA) Streams

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Received: 4 May 2007 / Accepted: 13 April 2008 / Published online: 15 May 2008
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Abstract The U.S. Department of Agriculture-Natural Resources Conservation Service has recommended domestic cattle grazing exclusion from riparian corridors for decades. This recommendation was based on a belief that domestic cattle grazing would typically destroy stream bank vegetation and in-channel habitat. Continuous grazing (CG) has caused adverse environmental damage, but along cohesive-sediment stream banks of disturbed catchments in southeastern Minnesota, short-duration grazing (SDG), a rotational grazing system, may offer a better riparian management practice than CG. Over 30 physical and biological metrics were gathered at 26 sites to evaluate differences between SDG, CG, and nongrazed sites (NG). Ordinations produced with nonmetric multidimensional scaling (NMS) indicated a gradient with a benthic macroinvertebrate index of biotic integrity (IBI) and riparian site management; low IBI scores associated with CG sites and higher IBI scores associated with NG sites. Nongrazed sites were associated with reduced soil compaction and higher bank stability, as

measured by the Pfankuch stability index; whereas CG sites were associated with increased soil compaction and lower bank stability, SDG sites were intermediate. Bedrock geology influenced NMS results: sites with carbonate derived cobble were associated with more stable channels and higher IBI scores. Though current riparian grazing practices in southeastern Minnesota present pollution problems, short duration grazing could reduce sediment pollution if managed in an environmentally sustainable fashion that considers stream channel response.

Keywords Short duration grazing · Channel stream bank · Channel stream bed · Habitat · Benthic IBI

Introduction

Agricultural practices in northeast Iowa, southeastern Minnesota, and southwestern Wisconsin inspired Aldo Leopold to speak about society's need to conserve our natural resources, primarily the productive silt-derived soils (Tanner 1995) that were transported into stream channels. In a chronicle of Driftless Ecoregion landscape changes, Trimble (1983) documented stream changes that occurred from 1853 to 1977 in Coon Creek (Wisconsin) and found a strong linkage between stream bank erosion, channel stability and catchment land use practices. Stream bank erosion is common throughout many southeastern Minnesota streams, and can be linked to the hydrology associated with catchment land use, geology (both hydrologic response and material resistance), and riparian management (material resistance to erosion) (Odgaard 1987; Thurow 1991; Waters 1995; Wang and others 1997; Sovell and others 2000). This article focuses on riparian management and associated channel response, particularly cattle grazing and fluvial geomorphology.

Minnesota Cooperative Fish and Wildlife Research Unit is jointly sponsored by the U.S. Geological Survey, the University of Minnesota, the Minnesota Department of Natural Resources, and the Wildlife Management Institute.

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Channel stability, stream bank erosion, and sediment transport, are influenced by riparian vegetation, which is affected by cattle grazing (Kondolf 1993; Trimble and Mendel 1995). Poorly protected silt-derived soil in southeastern Minnesota becomes detached and transported via rills, gullies, and eroding banks into stream channels. A gully forms or a channel erodes when flow and resistance to flow are in disequilibrium (Schumm and others 1984; Simon and Hupp 1986). Lane (1955) described channel equilibrium in terms of a balance between flow (force) and the resistance to flow (friction). Flow is determined by total stream power and the resistance to flow by the proportion of sediment size and load. Southeastern Minnesota stream bank soils contain weak intrinsic critical shear strength and offer little resistance to streamflow force (Trimble 1983); robust vegetation, however, strengthens silt-derived soils (Simon and Collison 2002). Stream bank vegetation must be incorporated down to the bed with respect to flow vector direction when diagnosing channel stability (Montgomery and MacDonald 2002). Stream channel instability can be described in terms of excess shear stress or boundary shear stress (τ_o) and critical shear resistance (τ_c) or ($\tau_o - \tau_c$) of the bed and/or bank material (Simon and others 2000; Simon and Collison 2001). Critical shear resistance is a function of intrinsic soil properties and vegetation (Simon and Rinaldi 2000). Force associated with boundary shear stress is a function of the channel hydraulics driven by unit stream power (velocity and channel slope). Factors that drive erosion and deposition are important to understand for limiting stream channel habitat loss which adversely influences the benthic community (Nerbonne and Vondracek 2001; Vondracek and others 2005).

Most literature related to domestic cattle grazing along streams indicates negative consequences to stream bank stability because of hoof shear and inadequate vegetative cover (Buckhouse and others 1981; Kauffman and Krueger 1984; Bohn and Buckhouse 1985; Elmore 1992; Trimble and Mendel 1995; Stewart and others 2001). However, few data have been collected in the upper Midwestern United States on stream bank and bed condition along grazed cohesive-sediment riparian stream corridors. Domestic cattle grazing in the upper Midwestern United States typically occurs in marginal landscapes that do not support a corn-soybean rotation.

Few studies have examined the linkage between riparian management, benthic macroinvertebrates, and stream geomorphic changes due to implementation of best management practices (BMPs), yet the U.S. Department of Agriculture (USDA), via the Environmental Quality Incentive Program (EQIP), and land owners have spent over 2.5 billion dollars from 1997–2001 on nonpoint source BMP implementation (Agouridis and others 2005). The USDA has identified rotational animal stocking as a

BMP (Minnesota Natural Resources Conservation Service [NRCS] conservation practice standard, code 528) and has assisted landowners by developing grazing plans in Minnesota. The goal of this study was to examine the effectiveness of short-duration grazing (SDG), a rotational grazing system (Holechek and others 2001), along riparian corridors of southeastern Minnesota streams.

In this article, we examined catchment characteristics, the riparian corridor, stream channel (bed and bank) morphology, and benthic macroinvertebrates of selected southeastern Minnesota streams. Objectives of this research were: (1) examine and quantify the effects of different riparian grazing practices on the stream channel and associated soil and vegetative response, (2) examine and quantify stream morphological metrics adjacent to riparian grazing management systems, and (3) measure the biological response via benthic macroinvertebrate index of biotic integrity (IBI).

Methods

Study Sites

Three riparian grazing management treatments (26 sites) located in cohesive-sediment, riparian stream channels (Fig. 1) were selected for this study: nongrazing (NG), continuous grazing (CG), and short-duration grazing (SDG). Over 12,000 individual measurements were made once at each site during the summer (June, July, or August) in 2004 or 2005. A study site consisted of a riparian floodplain and/or terrace area between stream valley walls for a length of 20–30 stream channel bankfull widths. Silt-derived soils (loess and/or colluvium) were present at all 26 study sites in the floodplains and terraces. Underlying geology consisted of till, coarse-grained alluvium/bedrock derived colluvium, sandstone, or carbonate bedrock. Land use in the basins of our study sites was 63% cultivated row crops, 14% hay/pasture, and 21% wooded or forested.

Nonimpacted catchments with nonimpacted reference channels do not exist in southeastern Minnesota, thus we chose nine NG sites that had no livestock present in the riparian zone for at least 3–5 km upstream and had minimal grazing, less than 10, 455 kg animals/ha/year in the up-gradient portions of the catchment. Further, within the past 25 years, the riparian zones were not intensively managed (in terms of vegetation and/or cattle) but contained a variety of trees, shrubs, and forbs. Four of the eight NG sites were located in a state or local park.

Nine CG sites had varying numbers of cattle, both beef and dairy that grazed in the riparian corridor with no attempt to keep cattle from the stream channel (Table 1). Typically, CG sites were grazed throughout the year;

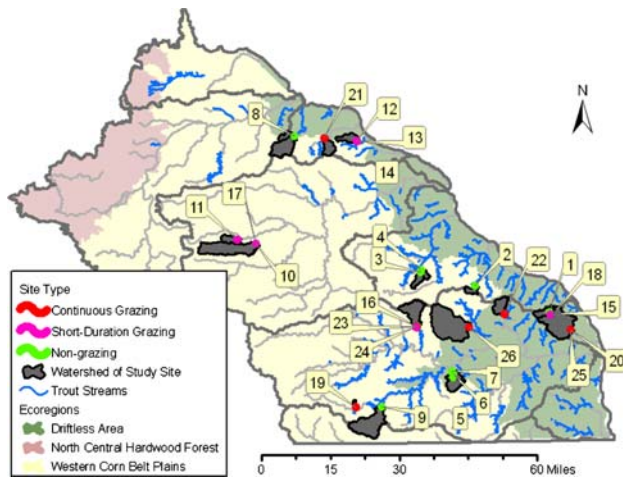


Fig. 1 Location, treatment type, and drainage area by ecoregion in Southeastern Minnesota

however, days in late December into March (85 days) when the ground was frozen and covered with snow, were not considered grazing days for purposes of calculating an overall exposure impact. Cattle were fed hay supplements typically between late December into March based on 85 estimated days of nongrazing for an average year and average number of frost days in southeastern Minnesota.

The key distinction between CG and SDG sites was temporal and spatial access to the riparian corridor and stream channel. Because off-channel water was not provided, cattle at CG sites were allowed daily stream access.

Typically, cattle grazed all portions of the riparian corridor including the stream bank. Table 1, presents more quantitative information about stocking rate, duration and the overall annual animal exposure per length of stream. A range of stocking rates (0.16–1.6 animal units/ha) were determined for all 17 grazed sites. A full grown animal was considered an animal unit (AU) equal to 455 kg (Holechek and others 2001). Animal density was then divided by the length (km) of stream available for grazing access.

Eight SDG sites were defined as a short duration, rotational grazing system utilizing fencing with specified watering location and stocking rates generally over one AU/ha. SDG follows the Minnesota NRCS code 528 as the controlled harvest of vegetation with grazing or browsing cattle, managed with the intent to achieve a specified objective. Objectives of the code include: “(a) improving the quality and quantity of forages for the benefit of the producer, livestock, wildlife and environment; (b) protecting water quality; (c) improving and maintaining the health of livestock, plants, and soil; and (d) reducing soil erosion.” Cattle did not have open access to the riparian corridor year-round; dairy cattle were moved between paddocks as often as every 12 hours, whereas beef cattle were moved every 3–30 days. The intent is to allow vegetation to be cropped and then regenerate. A paddock is a configured fenced area designed to force cattle to consume the vegetation within the fenced area for a specified time (Bellows 2003). Dairy operations have enough paddocks to limit the duration of exposure to 12 days/year. More than

Table 1 Stocking rate (AU/ha of pasture or paddock; where 1 AU = a 455-kg animal), length of stream adjacent to the pasture or paddock (km), stocking rate per length of stream (AU/ha/km), annual duration (days/year), grazing impact per length of stream (density/km/year), and mean grazing impact (AU/ha/km/year)

Site	Stocking rate	Stream length	Stocking rate/length	Duration	Impact range	Cattle impact
10	1.1–1.6	0.13	8.5-to-12.3	12	102–148	125
11	1.1–1.6	0.15	7.3-to-10.7	12	88–128	108
12	0.6–1.1	0.15	4-to-7.3	39	156–289	223
13	1.1–1.6	0.1	11-to-16	3	33–48	41
14	1.1–1.6	0.1	11-to-16	5	55–80	68
15	0.6–1.1	0.5	1.2-to-2.2	60	72–132	102
16	0.6–1.1	0.2	3-to-5.5	30–90	90–495	292
17	1.1–1.6	0.2	5.5-to-8	12	66–96	81
18	0.6–1.1	0.05	12-to-22	280	3,360–6,160	4,760
19	0.16–0.6	0.15	1.1-to-4.4	280	308–1,232	770
20	0.16–0.6	0.25	0.6-to-2.7	280	168–765	466
21	0.16–0.6	0.3	0.5-to-2.2	280	140–616	378
22	0.6–1.1	0.4	1.5-to-3	280	420–840	630
23	1.1–1.6	0.1	1-to-1.6	280	280–448	364
24	0.16–0.6	0.2	1-to-3.3	280	280–924	602
25	0.16–0.6	0.4	0.4-to-1.7	280	112–476	294
26	0.16–0.6	0.5	0.3-to-1.3	280	84–364	224

one SDG site was established on a single farm in this study because of the limited number of landowners practicing SDG along streams in southeastern Minnesota. Six months were spent in cooperation with the regional NRCS grazing specialist collecting initial site information prior to final site selection. One farm had three SDG sites (sites 12, 13, and 14), each with slightly different management and limited cattle access to the stream based on soil and vegetative quality goals.

Catchment, Riparian, and Channel Characteristics

This study examined four catchment metrics (drainage area, % cultivated, % hay/pasture, and % forested), six riparian metrics (cattle impact, soil compaction, vegetation height, % grass, % forb, and % tree), seven channel facet ratios (bankfull width/depth, pool/rifle depth, entrenchment, pool spacing, pool length, channel shear, and stable channel width), nine stream bed metrics (stream bed sediment, channel slope, % silt-clay, % sand, % gravel, % cobble, mean particle size, D_{84} , and D_{84} over the mean bankfull depth), a physical channel stability index (PSI), index of biotic integrity (IBI) and two channel classification schemes (channel evolution model and Rosgen). Catchment metrics included the drainage area above a site (determined using GIS to the site channel cross-section); areas ranged from $<1 \text{ km}^2$ to $>120 \text{ km}^2$. The three management types had equal numbers of large and small catchments (Table 2). Land use categories (% cultivation, % forested, and % hay-pasture) in each catchment were based on Minnesota Land Use and Cover, 1990s Census of the Land (LMIC 2005). A regional hydraulic geometry curve (Magner and Brooks 2007) was used to locate and characterize the bankfull stage for subsequent stream classification and to assign the appropriate channel evolutionary stage (Schumm and others 1984).

Riparian metrics quantified several vegetation characteristics. Stream bank and riparian vegetation was quantitatively measured using a modified relevè sampling method to establish vegetative type and pattern (Mueller-Dombois and Ellenberg 1974). The height of the nearest forb or grass at 20 locations along 10 transects, 5 on each side of the stream was measured once from the stream channel extending 20 m into the floodplain or terrace. Additionally, at each point, the proportion of trees, shrubs, grasses, and forbs were noted.

At each site, a longitudinal profile (100–400 m) and a riffle cross-section were conducted to classify the stream by Rosgen stream type (Rosgen 1996). In addition to the Rosgen stream type, stream reaches were classified using Schumm's channel evolution model (CEM) (Schumm and others 1984). At Rosgen classification cross-sections, soil compaction measurements (14–20 locations times 5–7 measurements

with depth) were made once along both sides of the channel, using a SC-900 compaction meter with an attached cone penetrometer (2-cm diameter) to measure the relative soil density of the terrace and floodplain.

A Wolman pebble count was conducted along each stream reach (Bevenger and King 1995). A modified approach of Lisle and Hilton (1999) and Walser and Bart (1999) was used to measure bed mechanical resistance and sediment accretion in selected pools of the study reaches by applying a constant force with two hands to a 2.5-m copper rod into bed sediment until resistance prevented further penetration. The depth of penetration was measured (cm) along with an estimate of particle packing; these data were defined as stream bed sediment in Table 2. Sub-pavement layers and ground water pore pressure zones were noted and rod penetration that occurred as a result of these hydrogeologic features was excluded from the final measurement results. Measurements were made in the largest pool in the channel at 5 locations with a minimum of 5 transects per pool. A Pfankuch (1975) channel stability index (PSI) assessment was conducted to characterize each study reach. The PSI rates channel stability from 38–150 with lower scores indicating higher stability.

Stream morphological data were entered into the STREAMS Module (SM) (Mecklenburg and Ward 2004). The SM calculated channel slope, mean depth, maximum depth, pool spacing ratio (PSR), pool length ratio (PLR), bankfull width/depth (W/D), and Rosgen's (1996) channel entrenchment ratio (ER); W/D is presented as Depth ratio in Tables 3 and 4 and Figs. 2 and 3. An elevation to obtain the bankfull cross-sectional area was selected based on field observations to properly identify the bankfull width (W_{bf}), which was then used to determine the ER (W_{fp}/W_{bf}), where (W_{fp}) is the floodprone width. To verify the bankfull cross-sectional area calculated by SM, the results were compared with southeastern Minnesota regional hydraulic geometry curves (Magner and Brooks 2007). A maximum pool depth to mean riffle depth ratio (P/RDR) was created to compare pool depths between management treatments. The SM also plotted a cumulative distribution of particle sizes (e.g., D_{84}) and provided values for the mean particle size and curve skewness. Additionally, the % silt-clay, % sand, % gravel, and % cobble were calculated by the SM. D_{84} was divided by the mean bankfull channel depth (d) to provide a scaled estimate of entrainment potential. Channel boundary shear was calculated by the SM. A channel shear ratio (CSR) was determined by dividing the channel shear of the Rosgen floodprone width (W_{fp}) by the channel shear of the bankfull width. A stable channel width (SCW) was determined by dividing the valley belt width (B_w) by the Rosgen floodprone width (W_{fp}). The (B_w) was determined by measuring the distance between the left first terrace toe slope to the right first terrace toe slope using a tape measure or a Bushnell 500 YardagePro range finder.

Table 2 Catchment, riparian, and channel characteristics at study sites in Southeastern Minnesota

Site	Drainage area (km ²)	Vegetation ^a height (cm)	Soil ^a compaction	Streambed sediment ^a (cm)	Pfankuch index (PSI)	Slope of ^a streambed	% Silt-clay	% Sand				
<i>Nongrazing (NG)</i>												
1	15.4	42	432	21.0	49	0.012	10	10				
2	10.3	48	341	11.1	55	0.008	4	12				
3	12.9	83	546	13.5	64	0.010	12	8				
4	19.6	48	569	7.5	63	0.006	10	8				
5	20.3	66	536	18.0	65	0.007	6	5				
6	25.1	39	427	5.8	57	0.011	3	4				
7	33.2	67	502	6.0	78	0.009	0	0				
8	51.9	71	667	15.5	80	0.003	11	19				
9	74.1	67	426	10.6	49	0.003	6	8				
<i>Short duration grazing (SDG)</i>												
10	2.4	14	747	9.6	87	0.006	18	30				
11	16.2	31	983	14.6	73	0.005	0	13				
12	16.5	18	850	17.0	108	0.006	62	13				
13	16.7	60	830	18.0	79	0.008	37	25				
14	16.8	39	628	5.0	86	0.004	38	40				
15	17.9	42	824	4.0	62	0.011	0	4				
16	45.1	29	1,807	7.0	53	0.005	5	4				
17	71.3	58	445	11.0	51	0.006	3	11				
<i>Continuous grazing (CG)</i>												
18	0.7	22	1,410	9.5	69	0.009	21	49				
19	2.3	8	1,060	29.0	87	0.006	69	21				
20	16.2	19	1,288	18.4	93	0.002	7	45				
21	19.1	23	1,094	64.0	87	0.003	10	31				
22	24.5	11	1,020	157.0	83	0.007	4	7				
23	45.3	12	1,393	8.4	122	0.001	0	4				
24	45.6	18	760	10.3	77	0.004	26	10				
25	100.5	17	1,133	50.0	101	0.001	35	53				
26	119.6	11	1,434	20.0	119	0.002	15	22				
Site	% Gravel	% Cobble	D ₈₄ ^b	Mean particle size	D ₈₄ /depth	Width depth ratio	P/RDR	ER	PSR	PLR	CSR	SCW
<i>Non-grazing (NG)</i>												
1	43	35	110	5.8	32	14.9	1.7	21.7	1.4	0.4	2.5	1.0
2	40	39	130	16.1	130	38.0	2.7	12.0	1.5	0.1	2.3	1.0
3	37	42	99	4.3	99	19.1	4.5	1.9	1.2	0.1	1.6	7.2
4	31	51	99	6.4	99	23.7	3.3	4.2	2.2	0.3	1.1	1.5

Table 2 continued

Site	% Gravel	% Cobble	D ₈₄ ^b	Mean particle size	D ₈₄ /depth	Width depth ratio	P/RDR	ER	PSR	PLR	CSR	SCW
5	44	44	140	32.6	127	21.0	4.7	2.3	1.2	0.2	2.0	6.0
6	54	34	140	39.2	78	10.6	6.0	5.2	1.8	0.4	1.3	1.0
7	52	48	87	57.5	58	12.0	3.7	8.0	1.9	0.5	1.0	4.7
8	56	13	56	3.4	31	24.0	3.4	2.3	0.6	0.1	2.1	1.0
9	60	26	85	15.4	53	25.0	2.4	17.3	1.4	0.3	1.6	1.2
<i>Short duration grazing (SDG)</i>												
10	29	22	81	2.2	135	16.5	3.8	2.2	2.4	0.5	2.2	1.8
11	68	19	70	23.7	78	31.6	1.8	3.4	0.3	0.3	2.6	1.0
12	24	1	13	0.9	9	17.8	1.4	2.7	1.2	0.2	2.0	1.2
13	36	2	16	1.0	11	18.3	1.2	2.5	0.7	0.1	2.2	5.0
14	22	0	4.9	0.6	2	8.0	2.0	2.7	2.3	0.3	1.3	1.0
15	67	28	86	28.4	86	30.0	2.6	2.7	1.5	0.2	1.8	1.8
16	46	36	170	45.2	81	15.4	2.4	6.8	0.5	0.1	1.3	1.0
17	32	40	180	21.6	106	18.8	1.7	3.1	1.0	0.3	1.3	1.0
<i>Continuous grazing (CG)</i>												
18	18	12	45	1.7	150	15.4	1.1	20.0	7.9	1.8	2.5	1.0
19	8	2	0.47	0.2	0.6	9.5	1.4	7.5	2.4	0.4	1.9	1.0
20	48	0	19	1.6	15	15.9	1.0	2.8	1.1	0.4	1.9	1.5
21	54	5	22	1.6	11	9.9	3.1	2.5	0.9	0.2	1.9	1.5
22	47	42	90	47.4	47	12.7	3.2	21.0	2.8	0.2	1.9	1.0
23	71	23	83	30.2	31	22.2	1.6	7.5	1.3	0.1	1.5	1.0
24	33	27	130	2.8	46	12.6	1.3	3.3	1.1	0.6	1.2	2.1
25	13	0	0.33	0.1	0.1	12.1	2.3	15.0	0.6	0.3	1.6	1.0
26	56	7	44	1.8	24	29.4	2.2	3.9	0.8	0.1	1.9	1.2
Site	% Cultivated	% Hay-grazed	% Forested	% Tree	% Forb	% Grass	Benthic IBI ^c	CEM	Rosgen class			
<i>Non-grazing (NG)</i>												
1	57	15	26	76	97	40	6.7	2	C4			
2	70	7	20	96	95	17	41.6	2	C4			
3	81	8	9	91	96	11	18.3	2	B4c			
4	78	7	13	91	90	21	18.3	3	C3			
5	50	18	29	71	82	37	25.8	2	C4			
6	47	18	32	90	99	16	22.5	2	E4			
7	46	20	31	54	99	75	34.2	2	E4			
8	79	9	9	85	98	13	n/a	2	C4			
9	82	7	8	100	97	30	31.6	2	C4			

Table 2 continued

Site	% Cultivated	% Hay-grazed	% Forested	% Tree	% Forb	% Grass	Benthic IBI ^f	CEM	Rosgen class
<i>Short duration grazing (SDG)</i>									
10	96	2	1	0	90	100	18.3	2	C4
11	87	3	2	42	94	100	21.6	2	C4
12	48	12	37	8	80	98	13.3	2 or 4	C6
13	48	12	37	15	92	100	16.6	2 or 4	C5
14	47	13	37	62	87	32	11.6	2	E5
15	59	14	24	77	97	90	21.7	3	C4
16	58	26	11	0	100	100	13.3	2	C4
17	93	3	2	58	62	72	31.7	2	C3
<i>Continuous grazing (CG)</i>									
18	58	15	25	1	90	100	n/a	2	C5
19	73	21	4	1	88	99	11.6	2	E6
20	33	14	51	0	58	100	11.6	2	C5
21	73	10	14	0	75	95	n/a	5	E4
22	50	20	29	19	44	99	25.0	2	E4
23	57	28	12	1	58	79	3.3	4	C4
24	54	30	13	75	65	43	5.0	3	E4
25	39	16	43	0	100	100	6.7	2	E5
26	67	14	17	0	45	91	20.0	4	C4

^a These are mean values derived from measurements described in the section "Methods."

^b % values were determined by pebble count

^c The channel metrics presented are calculated from the SM module

^d % values were determined by GIS

^e IBI is a calculated score from metrics described in text

^f CEM and Rosgen class were determined by channel metric data

Table 3 Pearson and Kendall correlations for channel, riparian, and watershed characteristics with ordination axes for sites with benthic macroinvertebrate IBI scores ($n = 23$)

Axis:	1			2			Total
	<i>r</i>	<i>r</i> -sq	tau	<i>r</i>	<i>r</i> -sq	tau	
% Tree	0.877	0.769	0.676	-0.294	0.087	-0.166	0.856
Vegetation height	0.747	0.558	0.548	-0.220	0.048	-0.164	0.606
% Cobble	0.637	0.405	0.375	0.336	0.113	0.2000	0.518
D ₈₄ /depth	0.595	0.354	0.417	0.281	0.079	0.210	0.433
Slope	0.595	0.354	0.414	-0.269	0.072	-0.167	0.426
D ₈₄	0.582	0.339	0.421	0.500	0.250	0.278	0.589
Depth ratio	0.485	0.235	0.341	0.046	0.002	0.063	0.237
% Forb	0.344	0.118	0.281	-0.150	0.022	-0.104	0.140
% Cultivated	0.308	0.095	0.155	0.030	0.001	0.044	0.096
SCW	0.247	0.061	0.086	-0.213	0.046	-0.240	0.107
PSR	0.210	0.044	0.208	-0.359	0.129	-0.224	0.173
Mean particle size	0.196	0.038	0.265	0.527	0.278	0.407	0.316
PLR	0.179	0.032	0.148	-0.406	0.165	-0.304	0.197
Width/depth	0.171	0.029	0.083	0.325	0.106	0.241	0.135
ER	0.140	0.020	-0.004	0.087	0.007	0.195	0.027
% Gravel	0.112	0.013	0.051	0.450	0.203	0.383	0.216
CSR	-0.085	0.007	0.000	-0.065	0.004	-0.072	0.011
% Forested	-0.135	0.018	-0.104	-0.199	0.040	-0.112	0.058
DA (km ²)	-0.232	0.054	-0.067	0.358	0.128	0.233	0.182
Streambed sediment	-0.279	0.078	-0.269	0.121	0.015	0.000	0.093
% Silt/clay	-0.325	0.105	-0.230	-0.515	0.266	-0.448	0.371
% Hay/grazing	-0.371	0.138	-0.246	0.261	0.068	0.157	0.206
% Sand	-0.454	0.206	-0.242	-0.309	0.095	-0.251	0.301
PSI	-0.764	0.584	-0.599	-0.019	0.000	-0.036	0.584
% Grass	-0.784	0.614	-0.535	0.234	0.055	0.102	0.669
Impact	-0.856	0.733	-0.647	0.212	0.045	0.176	0.778
Soil compaction	-0.909	0.826	-0.921	0.595	0.354	0.217	1.180

Note that the ordination was rotated to maximize the gradient in IBI scores

Within each stream reach, a kick net procedure (Barbour and others 1999) was used to collect benthic macroinvertebrates during base stream flow conditions. The macroinvertebrates were identified to the lowest taxonomic level possible, usually species or genus. An index of biotic integrity (IBI) developed for benthic macroinvertebrates developed for southeast Minnesota was calculated at 23 sites (Table 5, additional information at: <http://www.bio.wisconsin.edu/mundahl/hp/documents/WittmanMundahl.pdf>).

We used a Multi-Response Permutation Procedures (MRPP) with PC-ORD version 5 (McCune and Mefford 1999) with Sorensen's distance to compare all variables across riparian management treatments (NG, SDG, and CG) for all 26 sites. MRPP is a nonparametric procedure that can address the same types of questions as Multivariate Analysis of Variance to compare two or more pre-existing groups of variables. However, MRPP does not require

multivariate normality and homogeneity of variances (McCune and Mefford 1999).

Nonmetric multidimensional scaling (NMS) (Kruskal 1964; Mather 1976) with PC-ORD version 5 (McCune and Mefford 1999) was used to ordinate cattle impact, channel, riparian, and catchment characteristics. NMS is an ordination technique suited to data that are nonnormal or are expressed on arbitrary scales (McCune and Grace 2002). NMS does not assume a linear relationship among variables and allows the use of various distance measures. NMS calculates "stress" and "instability" to evaluate the ordination. Stress measures the disparity between the original distance matrix and the distances in ordination space. Lower stress values indicate more interpretable ordinations. Instability is calculated as the standard deviation in stress over the preceding 10 iterations. Instability is calculated as the standard deviation in stress over the

Table 4 Pearson and Kendall correlations for channel, riparian, and watershed characteristics with ordination axes for all 26 sites

Axis:	1			2			Total
	<i>r</i>	<i>r</i> -sq	tau	<i>r</i>	<i>r</i> -sq	tau	
Soil compaction	0.894	0.800	0.852	0.726	0.527	0.385	1.327
Impact	0.843	0.711	0.621	0.433	0.188	0.353	0.899
% Grass	0.774	0.600	0.513	0.413	0.171	0.284	0.771
PSI	0.733	0.537	0.560	0.046	0.002	0.022	0.539
% Sand	0.523	0.273	0.319	-0.04	0.002	-0.044	0.275
% Silt/clay	0.343	0.118	0.279	-0.343	0.118	-0.298	0.236
% Hay/grazing	0.342	0.117	0.269	0.260	0.068	0.113	0.185
Streambed Sediment	0.306	0.094	0.247	0.084	0.007	0.018	0.101
CSR	0.160	0.026	0.047	0.066	0.004	0.059	0.030
% Forested	0.151	0.023	0.127	-0.136	0.019	-0.090	0.042
DA (km ²)	0.123	0.015	0.003	0.166	0.028	0.028	0.043
PLR	0.122	0.015	-0.074	0.152	0.023	-0.148	0.038
PSR	0.099	0.010	-0.122	0.177	0.031	-0.059	0.041
ER	-0.049	0.002	0.059	0.160	0.025	0.189	0.027
% Gravel	-0.147	0.022	-0.059	0.194	0.038	0.188	0.060
Width/depth	-0.240	0.058	-0.142	0.213	0.045	0.160	0.103
SCW	-0.254	0.065	-0.093	-0.203	0.041	-0.179	0.106
Mean particle size	-0.261	0.068	-0.351	0.331	0.110	0.228	0.178
% Cultivated	-0.293	0.086	-0.158	-0.018	0.000	0.016	0.086
% Forb	-0.348	0.121	-0.287	-0.186	0.035	-0.212	0.156
D ₈₄ /depth	-0.479	0.230	-0.389	0.354	0.126	0.266	0.356
Depth ratio	-0.496	0.246	-0.376	-0.102	0.010	-0.074	0.256
Slope	-0.523	0.273	-0.356	-0.179	0.032	-0.115	0.305
D ₈₄	-0.637	0.406	-0.495	0.323	0.104	0.155	0.510
% Cobble	-0.665	0.442	-0.434	0.192	0.037	0.093	0.479
Vegetation-height	-0.728	0.530	-0.525	-0.388	0.151	-0.264	0.681
% Tree	-0.873	0.762	-0.66	-0.468	0.219	-0.311	0.981

Note that the ordination was rotated to maximize the gradient across riparian management

preceding 10 iterations. A final stress <10 suggests a “good” ordination (Clarke 1993).

Two types of NMS analysis were performed: (1) an ordination of channel, riparian, and catchment characteristics for the 23 sites for which we had IBI scores for benthic macroinvertebrates and for all 26 sites, and (2) a correlation of each catchment, riparian, and channel variable in Table 2, except the CEM stage, Rosgen classification, and IBI score, with each ordination axis for both ordinations. Channel, riparian, and catchment characteristics were considered to have a strong relationship with the ordination axes if Pearson’s correlation coefficient *r* was > ±0.404 or Kendall’s rank correlation coefficient *tau* was > ±0.307. We rotated the ordinations to maximize the influence of the IBI scores for the ordination of the 23 sites that contained IBI scores and riparian management treatment (NG, SDG, and CG) for all 26 sites. Variables listed as percentages in Table 2 were converted to

proportions and transformed using arcsine-square root transformation. For the NMS analysis, we used a Sorenson distance measure. We used the autopilot mode in PC-ORD with a random starting configuration; and specified the maximum number of ordinations = 6 and the maximum number of iterations = 200.

Results

Riparian treatment groups were significantly different based on MRPP. Chance-corrected within-group agreement, *a* = 0.349 across riparian treatment groups (*t* = -10.881, *p* < 0.001). Pair-wise comparisons of riparian treatments indicated differences between groups: NG versus SDG (*a* = 0.199, *t* = -7.056, and *p* < 0.001), NG versus CG (*a* = 0.453, *t* = -10.977, and *p* < 0.001), and SDG versus CG (*a* = 0.103, *t* = -6.581, and *p* < 0.001).

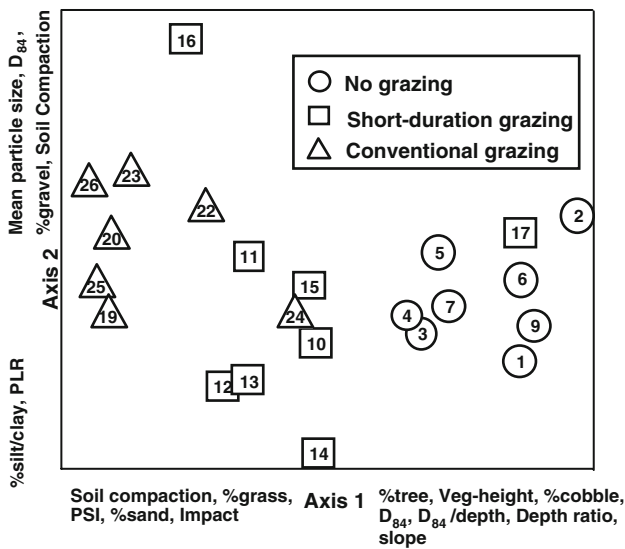


Fig. 2 Ordination of catchment, riparian, and channel characteristics for 23 stream sites in Southeastern Minnesota rotated to maximize the influence of the IBI scores. Numbers within the symbols indicate site numbers in Table 2. Axis 1 explained 85.9% of the variance and axis 2 explained 11.2% of the variance. Final stress = 6.334, final instability = 0.00001, and number of iterations = 94

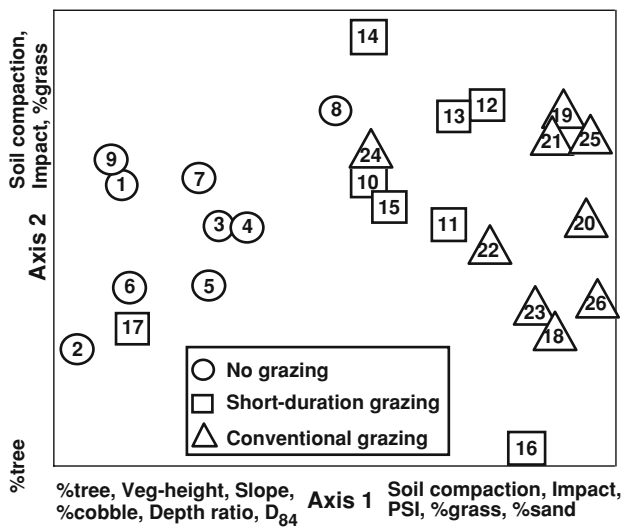


Fig. 3 Ordination of catchment, riparian, and channel characteristics for 26 stream sites in Southeastern Minnesota rotated to maximize the influence of the riparian management. Numbers within the symbols indicate site numbers in Table 2. Axis 1 explained 88.2% of the variance and axis 2 explained 9.1% of the variance. Final stress = 6.440, final instability = 0.00001, and number of iterations = 56

The NMS analysis for the sites with IBI scores explained 85.9% of the variance along axis 1 and 11.2% along axis 2. Final stress was 6.334, indicating a good fit (Clarke 1993) and final instability was 0.00001. The highest IBI scores were associated with NG and the lowest with CG. The SDG sites that were generally intermediate

Table 5 Metrics and rating guidelines for an index of biotic integrity (IBI) developed for benthic macroinvertebrates developed for Southeastern Minnesota (Neal Mundahl personal communication, Feb 2008)

Metric	0	5	10
Number of taxa	0–6	7–12	>12
Number of plecoptera	0	1	>1
Number of trichoptera	0–1	2–3	>3
Number of diptera	0–2	3–4	>4
Number of long-lived taxa	0	1	>1
Number of intolerant taxa	0–1	2–3	>3
Number of filterer taxa	0–2	3–4	>4
Percent plecoptera individuals	<6	6–12	>12
Percent predators	<6.5	6.5–13	>13
Percent long-lived individuals	<6	6–12	>12

Rating guidelines	
65–100	Excellent
50–60	Good
30–45	Fair
10–25	Poor
0–5	Very poor

Each metric was scored 0, 5, or 10

(sites 14 and 16), demonstrated the most variance along axis 2 due to extreme differences in soil compaction and silt-clay content of bed sediment. Site 17, a SDG site, plotted with the NG sites. Site 24, a CG site, plotted with the SDG sites.

Benthic macroinvertebrate IBI scores were generally low; the highest score was 41.6 of a possible 100. Twelve variables or metrics were correlated with the first axis and the gradient in IBI scores and riparian management (3 related to riparian management: grazing impact, soil compaction, and PSI; 3 related to riparian vegetation: % tree, % grass, and vegetation height; and 6 to stream bed and channel characteristics: % sand, % cobble, D_{84} , D_{84}/depth , Depth ratio, and slope) (Table 3, Fig. 2). The most stable banks were related to NG with the lowest stability associated with CG. CG sites were associated with a higher proportion of sand in the stream bed, whereas, NG sites had more cobble and a higher D_{84} value. Catchment characteristics were not significantly correlated with the first axis in the ordination.

The ordination for all sites ($n = 26$) explained 88.2% of the variance along axis 1 and 9.1% along axis 2. Final stress was 6.334, indicating a good fit (Clarke 1993) and final instability was 0.00001. The analysis indicated a gradient associated with riparian management treatment and correlations of the variables or metrics were similar to the ordination with IBI scores (Table 4, Fig. 3).

Variable Influence and Channel Stability

Riparian management variables (soil compaction, cattle impact, vegetation type) were the most influential group of metrics measured in this study followed by stream bed metrics (slope, particle sizes, and the D_{84}). Soil compaction and cattle impact showed the strongest differences in both ordinations between treatments; with NG consistently low and CG sites consistently high. Vegetation type was also a strong variable; % tree and % grass were correlated with the variables in the ordinations but had opposite signs along axis 1. Channel slope, D_{84} , D_{84}/depth and % cobble were strongest stream bed variables; mean particle size, % sand and % silt-clay were moderately important variables along axis 2. None of the channel facet ratios (P/RDR, ER, PSR, PLR, CSR, SCW) were correlated with either the IBI or the all site ordinations except Depth ratio.

Catchment metrics which were based on broad land use categories (% cultivation, % forested, and % hay/pasture) explained the least amount of variance in this study. The PSI integrated stream bank and bed variables and served as a link between riparian and channel metrics. Unstable stream banks showed more easily eroded soil with sparse, less dense vegetation and unstable stream beds with smaller bed particle sizes and a lower D_{84} . Further, PSI score was found to have a weaker relationship ($r^2 = 0.014$) with drainage areas less than 32 km² compared to larger drainage areas ($r^2 = 0.120$). This relationship suggests the importance of a possible scale threshold for the region related to changes in Lane's (1955) equilibrium model; flow and the resistance to flow were less tightly correlated in steeper gradient smaller scale study sites regardless of treatment.

Measurements of channel morphology and stability provided data to classify the sites according to Schumm's CEM and Rosgen's stream classification system. Our analysis indicated that most channels in southeastern Minnesota were enlarged by downcutting and widening. Most channels were classified as Rosgen C4 and E4 (Table 5), which are generally more stable than Rosgen D, G, or F type channels. However, based on field evidence, streams in the NG, and SDG management types appeared to be evolving to more unstable morphologies. In general, CG sites evolved past the most erosive CEM stages (2 and 3) and were potentially at less risk of additional stream bank erosion compared to either the NG or SDG sites.

Discussion

We demonstrated a response gradient in riparian and channel characteristics related to CG, SDG, and NG sites. Some variables (riparian management) were stronger

indicators than other variables (channel facet ratios or catchment variables) measured in this study. Nevertheless, our goal was to determine if differences in riparian management would be reflected in both the riparian zone and the stream channel; our analysis suggests there were differences between all three management types. The riparian metrics, which were most closely associated with management type, indicated the strongest response for the macroinvertebrate IBI and across all sites. Stream channel variables related to stream power (streambed slope, D_{84} , % of a given particle size class) were the next strongest group of metrics. Sites with sufficient stream power were able to move clay, silt, and sand, and limit embeddedness, which in-turn, would allow for a more robust biotic response. The macroinvertebrate communities measured at study sites appeared to be more responsive to fine particles in the streambed that contribute to embeddedness than measures of channel pool ratios or entrenchment. Channel shape factors measured over a stream reach can reflect both local riparian management and/or systemic changes in catchment processes (Magner and Brooks 2007). Differences between NG, SDG, and CG channel facets and geometry were integrated by the CEM and Rosgen classifications. Based on land use changes in southeastern Minnesota (Randall and others 2003), and the stream classifications presented in Table 2, systemic changes in catchment hydrology occurred over the past five decades. Nevertheless, our data also suggest that cattle grazing, regardless of stocking rate, produced measurably higher PSI scores.

Short-duration grazing and CG management within study riparian corridors disturbed the riparian and channel quality more than NG land use. Cattle will compact riparian soil even if present for a short period of time; soil compaction from animals is unavoidable. Soil compaction was particularly prominent at site 16 (Fig. 3). Though cattle access was limited at site 16, the soil depth (0.2–0.4 m) was shallow over bedrock. Nevertheless, not all soil compaction is equal. Though soil compaction reduces macropores, limits infiltration, and results in more surface runoff, some compaction of highly erodible stream bank soils may reduce erosion. Riparian soils in southeastern Minnesota are dominated by silt-sized colluvium and loess (Runkel 2002); thus targeting hoof shear on vertical weakened channel stream banks will change the bank shape and increase τ_c and limit potential soil detachment and subsequent transport into the channel bed.

The quality of riparian vegetation and the relative roughness associated with the plant height and type along SDG stream banks provided more resistance to stream bank erosion from both overland and hydraulic forces compared to CG stream banks. Historically, CG has been associated with eroded stream banks (Clark 1998) that lead to more evolved stream channel types (Riedel and others 2001).

Twenty of 26 sites were determined to be at CEM stage 2, indicating that channel enlargement processes were region-wide and beyond the influence of specific riparian management, likely due to row-crop agriculture that exceeded 50% of the area (*sensu* Wang and others 1997) in the basins above our study sites. When stream banks lack sufficient τ_c to transfer the hydraulic energy downstream, stream banks will erode to absorb the energy excess from τ_b . Vibrant stream bank vegetation provides sufficient shear resistance to reduce erosion. However, some NG and SDG stream banks contained woody weed species such as boxelder (*Acer negundo*), whereas CG sites had over-grazed short grasses that lacked sufficient τ_c to withstand excessive τ_b to prevent stream bank erosion. Nerbonne and Vondracek (2001) observed that a majority of wooded riparian areas adjacent to row-crop agriculture in southeastern Minnesota were dominated by boxelder, a fast-growing invasive tree species. Un-managed dense boxelder stands will typically shade the understory and limit adequate forb and grass production along stream banks leading to hydraulically driven toe-slope soil erosion.

Hydraulic force was an important factor present at 25 of 26 study sites; only site 21 had evolved back to a stable channel form. Twenty sites were in a downcutting stage, and the remaining five sites were still adjusting their channel width. Four of nine CG sites evolved further than NG and SDG sites combined, suggesting more stream bank erosion occurred in the past along CG corridors. Because four CG sites evolved to more advanced CEM stages, these site stream banks could be at less potential risk of new hydraulic driven toe-slope erosion unless new downcutting processes were to occur. Changes in catchment land use and associated with increased runoff could increase the channel slope, driving new downcutting processes. Hydraulic forces changed with increasing drainage area; scales over 45 km² typically had channel slopes of 0.001–0.004, whereas scales less the 32 km² contained steeper channel slopes with stronger concordant unit stream power. The flatter channel slopes associated with larger drainage areas tended to be prone to sediment deposition versus downcutting. Some channel metrics (% cobble and D_{84}) were strongly coupled with unit stream power.

Vegetative height in grazed riparian zones was influenced by stocking rate, grazing duration, and type of vegetation. Cattle impact (animal density/km stream/ year) rates between treatments were significantly different. Beside the limited grazing duration, SDG sites contained more vegetative height than CG sites; partially resulting in better PSI scores compared to CG sites. However, PSI scores were also likely influenced by the channel bed particle size distribution. At site 17, the particle size distribution was driven by bedrock geology (Figs. 2 and 3). Another example of bedrock influence is site 24, a CG site

found within the SDG site clusters of Figs. 2 and 3. Both sites 24 and 17 contained high percentages of cobble, which influenced D_{84} , mean particle size and D_{84} /depth. In contrast to sites 24 and 17, sites 12, 13, and 14 were located in glacial Mississippi River backwater lacustrine deposits. Corn cultivation, cattle grazing, carbonate and sandstone bedrock are found in both ecoregions (Fig. 1). Yet, the specific locations of carbonate rock outcrops influenced the % cobble in the stream more than any other ecoregion factor. Catchment land use metrics (% hay/pasture, % cultivated, % forested) were not significantly correlated with the NMS ordination axes, whereas localized differences in geology (rock outcrops that produced stream bed cobble) appear to have exerted a strong influence upon the location of sites in Figs. 2 and 3.

Most sites contained cohesive-silty stream banks with sand and gravel beds. Nevertheless, CG sites indicated evidence of trapping more fine-grained particles (% silt-clay, % sand, PLR) in their pools compared to NG sites and to a lesser extent SDG sites. This observation is similar to that reported by Lyons and others (2000) and Simon and others (2000). Erosion that increases channel bed fines (silt and fine sand) adversely affects benthic habitat (Allan 1995; Waters 1995; Maul and others 2004; Smiley and Dibble 2005). Fine-grained channel aggradation likely embedded important macroinvertebrate substrate in most of the study sites. The highest IBI scores in this study were found at sites #2 and #17, which contained some of the highest values for % cobble, D_{84} , and D_{84} /depth. Habitat degraded by fine particles likely explains some of the poor IBI scores found in this study. However, there are likely other factors not addressed in this study such as upland erosion of loess that could also adversely affect benthic organisms (Wang and others 1997; *sensu* Weigel and others 2000).

Policy Implications

Recent studies suggest that agricultural practices in upper Midwestern catchments contribute to local (Wang and others 1997, 2002, 2006; Stewart and others 2001; Ganske 2004), regional (Payne 1994), and national (Rabalais and others 1998) water quality degradation. Row-crop agriculture is the primary contributor to nonpoint source pollution in the upper Midwest (Goolsby and others 1999). Row-crops in most basins in our study areas exceeded the 50% threshold identified by Wang and others (1997) as detrimental to macroinvertebrate habitat. In particular, farm policy in the U.S. has encouraged land operators to plant more of their land to corn and soybeans (Boody and others 2005). The dominance of the corn-soybean rotation in the upper Midwest has led to the loss of perennial vegetation, particularly in southeastern Minnesota (Randall

and others 2003). Perenniality is under consideration as a BMP (Laughlin 2002); defined as a landscape with vegetation present throughout much of the year, such that evapotranspiration can occur during other periods than the active growth periods for row crops (June, July, and August). Perennial vegetation may not be necessary as long as other vegetation is present prior to and after row crop growth. Historically, in southeastern Minnesota, agricultural perennials have been legumes, grasses, and alfalfa. These perennials are intrinsically linked with animal agriculture in which grazing is a key management component.

The hydrogeology of an incipient karst region will create streams that are groundwater driven and influence cold and warm water fisheries. Yet, the management of the landscape also has profound influences upon the in-stream biological communities (Wang and others 1997; Vondracek and others 2005). Humans cannot change the underlying geology of southeastern Minnesota, but anthropogenic management of soil, vegetation, and animals practiced at varying degrees of intensity can influence stream channel stability and the aquatic life. Is it possible for humans to manage this landscape in an economically viable manner that improves environmental quality? Boody and others (2005) have suggested that less row-crop agriculture and more perennial vegetation, including SDG, throughout the landscape could produce desirable ecological and economical effects. Our study demonstrated some differences in stream habitat for SDG sites compared to CG sites, but because we were unable to constrain the influences of upland row-crop agriculture, we could not demonstrate stronger differences between SDG and CG. Lyons and others (2000) and Weigel and others (2000) suggest that SDG could be used to improve stream channel habitat. Nevertheless, we need to develop future catchment scale studies that more closely exam hydrologic pathways and CEM processes at varying scales before we can confidently say SDG becomes a uniformly accepted BMP.

Conclusion

We demonstrated a response gradient in riparian and channel characteristics related to CG, SDG, and NG sites. Riparian management particularly, soil compaction, cattle impact, and % tree were significantly correlated with gradient in index of biotic integrity (IBI) scores. Benthic IBI scores were relatively poor and distributed along a gradient with riparian management and channel stability. Most stream channels indicated evidence of channel enlargement based on the principles of channel evolution. Understanding the channel evolutionary stage may be important when deciding how to manage a given stream bank for erosion potential, in-channel habitat, and benthic macroinvertebrates. Vegetative vigor,

channel stability, and benthic habitat are dependant upon the type and quality of riparian management. SDG may be a better riparian management practice than CG by limiting riparian erosion that can degrade in-stream habitat. Though current grazing practices in southeastern Minnesota present pollution problems, short duration rotational grazing could reduce sediment pollution if managed in an environmentally sustainable fashion.

Acknowledgments This work was made possible by an USEPA Section 319 grant to the MPCA. Heartfelt thanks are offered to Howard Moechnig for SDG site selection, Neal Mundahl and Winona State University students for their assistance in field data collection (especially benthic macroinvertebrates), and Jason Ewert for field data collection, data entry, and GIS assistance. This article was improved by Sandy Verry, Ashley Moerke, and six anonymous reviewers. Several trade name or commercial products were cited; however, their mention does not imply endorsement by the U.S. Government.

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