INFLUENCE OF WATERSHED GRAZING MANAGEMENT ON STREAM GEOMORPHOLOGY IN GRASSLAND HEADWATER STREAMS

by

BARTOSZ PIOTR GRUDZINSKI

B.S., Eastern Illinois University, 2008
M.S., Northern Illinois University, 2010

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Geography
College of Arts and Sciences

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2014

Abstract

This dissertation increases our understanding of the drivers that shape and maintain grassland streams and their watersheds by examining the influence of grazing management practices on suspended sediment concentrations, bare ground production, and changes to channel geomorphology. Chapter 2 demonstrates that cattle grazing produces significantly higher baseflow suspended sediment concentrations relative to bison grazing. Suspended sediment concentrations within bison-grazed streams are similar to ungrazed streams, indicating that the substitution of cattle for bison has resulted in degradation of baseflow water quality in grassland streams. Burning frequency, discharge, and seasonality are also significant drivers of suspended sediment concentrations, but are generally less influential than grazing treatments. Chapter 3 indicates that high density cattle grazing treatments produce more bare ground within the riparian zones of grassland stream networks, particularly underneath tree canopy cover. The increased bare ground coverage within riparian areas is correlated with increased suspended sediment concentrations during baseflow conditions, while watershed-scale bare ground production is correlated with increased suspended sediment concentrations during storm flow events. Chapter 4 demonstrates channel geometry and sedimentology are significantly influenced by grazing treatments. This dissertation is the first study to comparatively evaluate the relative influence between cattle and bison grazing on stream geomorphology within any environment. Insight gained from this project can be used by public and private land use managers to improve the environmental integrity of native grassland ecosystems.

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Preface

This dissertation has been completed under the guidance of Dr. Melinda D. Daniels, Dr. Philip Barnes, Dr. Walter Dodds, Dr. Richard Marston, Dr. Charles Martin, and Dr. Charles Oviatt. This research presents new findings on the influence of grazing treatments and environmental variables on grassland stream geomorphology. Chapter 2 has been submitted with Melinda D. Daniels, Philip Barnes, and Michael Rawitch as co-authors to *Geophysical Research Letters-Earth Surface.* Chapter 3 is formatted for publication in the *Journal of the American Water Resources Association* with Kyle Anibas, Melinda D. Daniels, and David Spencer as co-authors. Chapter 4 is being formatted for publication in *Earth Surface Processes and Landforms* with Melinda D. Daniels as a co-author. Results from this project may be used to aid in the preservation and restoration of grassland ecosystems.

Chapter 1 - Introduction

Globally, grasslands and wooded grasslands account for approximately 27.9% of terrestrial runoff and 28.4% of terrestrial area (Dodds, 1997). In North America, grasslands make up the largest vegetative biome (Samson and Knopf, 1994), yet most pristine grasslands in the United States have been converted to other land uses, primarily row crop agriculture (Knox, 2006), thus are one of the most altered biomes in the United States (Samson and Knopf, 1994). Historically, grasslands have been shaped by climate, fire, and native herds of large grazers (primarily bison in North America) (Fuhlendorf and Engle, 2001), yet anthropogenic forces have altered climate (IPCC, 2007), suppressed fire (Briggs *et al*., 2005), and replaced native grazers with non-native cattle (Kohl *et al*., 2013). Effective conservation and restoration of grassland stream ecosystems depends on understanding the biophysical drivers that shape and maintain their structure and function (Samson *et al*., 2004), yet due to the drastic loss of pristine grasslands, research on natural grassland streams relative to systems in other ecoregions such as forests has been limited (Matthews, 1988).

Prior to European colonization of the United States, bison (*Bos bison* & *Bison bison*) were the most abundant and influential large grazers within North American grasslands (Kohl *et al*., 2013). By the 1800's, bison populations had collapsed to several thousand due to overhunting (Flores, 1991). Bison populations have since increased to approximately 500,000, yet this represents a very small fraction of the modern grazer community dominated by millions of cattle within North America (Kohl *et al*., 2013). Historically, bison had unlimited access to streams throughout the Great Plains, and their grazing patterns would typically follow fire due to increased nutrient richness in post-fire regrowth (Knapp *et al*., 1999), thereby allowing unburned tracts of the landscape to recover from grazing. The natural burning interval within Great Plains grasslands was between 1-8 years (Malainey and Sherriff, 1996). Currently most cattle grazing operations allow cattle unrestricted access to natural water sources within smaller parcels of land enclosed with fencing. Although patch burn grazing is becoming more common, most cattle grazed parcels of land are entirely burned and grazed annually, a practice that does not allow the landscape significant time to recover.

Prairie headwater streams are important components of grassland ecosystems (Dodds *et al*., 2004), and adjacent land use has been shown to disproportionally influence water quality relative to larger rivers (Dodds and Oakes, 2008). Headwater streams also account for most of the discharge and stream length within a watershed (Dodds and Oakes, 2008). Although sediment pollution is considered one of the most detrimental land use impacts on fluvial systems (i.e. Vidon *et al*., 2008) and grazing management has been identified as one of the most damaging land use practices (Zaimes *et al*., 2008), we know very little about how various grazing management practices (ungulate species and ungulate density) influence grassland streams.

Increased sediment loads in Great Plains streams have led to numerous detrimental effects including, but not limited to, increased stream turbidity and nutrient loading (Wood and Armitage, 1997; Vidon *et al*., 2008), reservoir sedimentation (Juracek, 2011), decreased high quality habitat for fish spawning (Acornely and Sear, 1999), and altered community structure of native biota (Eberle *et al*., 2002). Despite the negative influences of sediment loads highlighted in previous studies, a direct comparison of stream sediment concentrations between bison and cattle-grazed treatments has not been completed. Studies examining impacts of bison on sediment production have also been limited (Larson *et al*., 2013). Furthermore, to the best of our knowledge, the relative influence of discharge, seasonality, grassland burning, and grazing have yet to be evaluated. By examining the sediment concentrations within various grassland grazing treatments we can: 1) begin to understand the relative impacts between bison and cattle on fluvial sediment dynamics, and 2) increase our understanding of sediment regimes within grassland streams.

While numerous studies have shown that cattle grazing increases fluvial suspended sediment concentrations (Olley and Wasson, 2003; Vidon *et al*., 2008), few have related stream sediment concentrations to their adjacent riparian and hillslope source areas (Bartley *et al*., 2010). Dense riparian vegetation greatly decreases soil and stream bank erosion by decreasing runoff and increasing soil stability (Beeson and Doyle, 1995). Ungulate grazing has been shown to significantly alter vegetation cover by decreasing biomass and increasing the proportion of bare ground within riparian areas (i.e. Zhao *et al.*, 2005). Due to the decreased riparian demands of bison, the amount of exposed ground within bison-grazed riparian areas may be less than that of cattle-grazed treatments. Exploring the influence of bare ground production from various grazing treatments and linking it to suspended sediment concentrations can increase our understanding of: 1) relative riparian grazing impacts between cattle and bison, and 2) dynamics between hillslope sediment sources and fluvial suspended sediment concentrations.

The primary goal of this dissertation is to increase our understanding of the relationship among grazing management and grassland stream geomorphology. I focus on the influence of grazing treatments and quantify and compare the relative geomorphic impacts of cattle and bison. I use a replicated paired watershed approach to increase statistical robustness of the analysis (Loftis *et al*., 2001; Veum *et al*., 2009). In chapter 2, I quantify the impact of grazing treatments, burning frequency, discharge, and seasonality on suspended sediment concentrations.

Grazing impacts on total suspended solids, total inorganic solids, total volatile solids, and percent organic matter are measured. In chapter 3, I quantify the impact of grazing treatments on bare ground distributions at the watershed and riparian scales through a combination of field surveys and remote sensing techniques. I then explore the relationship between bare ground production and stream sediment concentrations. In chapter 4, I quantify the long term and short term impacts of grazing management on grassland stream geomorphology. Repeated cross sectional surveys provide data for analysis of annual changes in channel geometry. In chapter 5, I synthesize the overall findings of this dissertation.

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Chapter 2 - Influence of watershed grazing management on baseflow suspended sediment concentrations in grassland headwater streams

Abstract

In the Great Plains region of North America, the sediment regimes of grassland watersheds can be heavily influenced by livestock grazing, particularly cattle. Despite the decline in stream water quality and ecosystem function concomitant with increasing grazing pressures, no studies have quantitatively assessed the relationship between various grazing treatments including cattle and bison on sediment production in natural grassland ecosystems. The purpose of this study is to determine the impact of common grazing practices on suspended sediment concentrations within grassland headwater streams of the Tallgrass Prairie biome. Water samples were measured for total suspended solids (TSS, mg/L), total inorganic solids (TIS, mg/L), total volatile solids (TVS, mg/L), and percent organic matter (POM, %). Both moderate and high density cattle grazing significantly increase TIS concentrations while bison grazing does not. The behavioral differences between cattle and bison are likely leading to more bare ground production in the riparian zones of cattle-grazed treatments, resulting in increased sediment loading, especially within high density cattle treatments. Furthermore, cattle may also be re-suspending sediment by direct trampling of the stream bed, especially during summer months, due to increased need for thermal relief. Burning frequency, discharge and seasonality are generally less influential relative to grazing treatments. For the first time that we are aware of the relative grazing influences between cattle and bison have been separated and based on these unique recommendations can be made for management of the two large ungulates. Since bison

grazing does not substantially increase stream sediment concentration, bison may be considered a cattle replacement to improve water quality within grassland ecosystems.

Introduction

Sediment is considered one of the most widespread and detrimental pollutants impacting streams in the United States, has led to loss of reservoir storage capacity throughout North America and the world [*Renwick*, 1996; *Palmieri et al*., 2001; *Simon and Darby*, 2002; *Graf et al*., 2010], and is implicated as a major source of eutrophication in coastal systems [e.g. *Rabalais et al*., 2002]. In the Great Plains region of North America, the sediment regimes of grassland watersheds are heavily influenced by livestock grazing, particularly cattle [*Matthews,* 1988; *Dodds et al*., 2004; *Freese et al*., 2007]. Increased runoff and hillslope erosion rates have led to decreased water quality [*Matthews*, 1988; *Dodds and Oakes*, 2008], stream eutrophication [*Dodds and Oakes*, 2008; *Zaimes et al*., 2008; *Weber and Deutsch*., 2010], degraded fish spawning habitat [*Acornley and Sear*, 1999], increased turbidity and decreased primary production [*Wood and Armitage*, 1997], increased phosphorous loads [*Vidon et al*., 2008], and increased reservoir sedimentation [*Juracek*, 2011]. Native biodiversity has declined [*Matthews*, 1988; *Klimas et al*., 2009], and many native prairie fishes have been extirpated from much of their historic range [*Eberle et al.*, 2002]. While inorganic sediment is commonly viewed as a pollutant, the organic fraction provides streams with energy and nutrients, forming the base of the stream food web [*Whiles and Dodds*, 2002].

Headwater streams are tightly coupled to hillslope processes, and hence sensitive to changes in water and sediment delivery from the hillslope [*Bartley et al*., 2010a]. Headwater networks also strongly influence downstream biotic integrity by serving as conduits for sediment, nutrients and other contaminants delivered from the hillslope [*Dodds and Oakes*, 2008]. Streams within undisturbed landscapes also naturally receive sediment from sources including channel banks, the stream bed, and from wildlife (i.e. deer and crayfish, among many others due to stream bed disturbance). These sources may provide significant additions of sediment to headwater streams especially during flow events with high erosive power.

Grasslands account for over 25% of terrestrial area and global runoff [*Dodds*, 1997]. Despite the decline in stream water quality and ecosystem function concomitant with increasing gazing pressures within these systems, no studies have quantitatively assessed the relationship between various grazing treatments and sediment production in natural grasslands. Previous studies have shown that ungulates create bare ground within riparian zones by decreasing vegetated biomass due to trampling and grazing [*Kutt and Woinarski,* 2007; *Teague et al*., 2010] leading to large increases in total suspended sediment (TSS) concentrations [*Wohl and Carline*, 1996; *Line et al*., 2000; *Olley and Wasson*, 2003; *Vidon et al*., 2008]. In the most extreme cases, grazers can increase suspended sediment concentrations by several orders of magnitude within aquatic systems [e.g. *Bartley et al*., 2010a]. Consequently, grazers are clearly recognized as important geomorphic agents in the fluvial landscape [e.g. *Trimble and Mendel*, 1995] and are a primary driver of soil erosion within the Great Plains [*Zaimes et al*., 2004] and around the world [*Yiesehak et al*., 2013].

Prior to European settlement, the extent of the tallgrass prairie was approximately 68 million ha and has declined to the current level of about 3.4 million ha [*Knapp et al*., 1999]. Concomitant with the decline in prairie area, bison populations have decreased dramatically in the last two centuries, from an estimated population of over 30 million animals down to several thousand animals in the 1800s, with numbers climbing only very recently with an increase in demand for bison meat and conservation efforts. Historically the American Bison (*Bos bison)* was the dominant native grazer of temperate prairies extending from Canada to Mexico and from the foothills of the Rocky Mountains to Indiana [*Samson and Knopf*, 1994; *Freese et al*., 2007]. American bison are recognized to have been an ecosystem engineer of these terrestrial grasslands [*Collins and Benning*, 1996; *Knapp et al*., 1999; *Soule et al*., 2003]. Significant alterations to tallgrass prairies and drastic decreases in bison populations have led to limited understanding between bison and grassland interactions within aquatic systems.

In the grasslands that do remain, bison herds have largely been replaced by a variety of cattle ranching operations, ranging from year-round calf-cow operations to seasonal intensive stocking. Some debate remains as to whether cattle represent an ecologically equivalent replacement for bison as a grazer in grassland ecosystems. While some argue that the degree of ecological equivalency between cattle and bison is dependent on stocking management, rather than any inherent behavioral or physiological differences [*Hartnett et al*., 1997; *Knapp et al*., 1999], others argue that fundamental differences in physiologies produce meaningful behavioral differences that prevent ecological equivalency regardless of stocking management [*Freese et al*., 2007].

Different grazing treatments, such as cattle versus bison grazing, may produce significantly different hillslope-channel responses due to species-specific physiological and behavioral differences. Cattle are known to be less heat tolerant than bison and to more readily seek thermal relief in the shade of riparian zones and stream channels at lower temperatures (24° C vs 36° C) [*Allred et al.,* 2013], have lower water use efficiency [*Steuter and Hidinger,* 1999], and consume more riparian vegetation (such as forbes) [*Trimble and Mendel,* 1995]. Larson *et al.* [2013] found that bison spend only 6% of their time within a 10 m buffer of the riparian zone and seem to selectively avoid riparian areas. Increased likelihood of cattle grazing within riparian zones would increase sediment production by generating a higher proportion of riparian bare ground area, trampling stream banks and resuspending substrates from the stream bed by trampling. The increased grazing pressure in riparian zones of cattle treatments may be producing clear distinctions between bison and cattle with respect to fluvial sediment concentrations. We are aware of no quantitative studies that have evaluated the relative impacts on stream sediments produced by these different grazing treatments in the same location.

Attempts to understand how stream systems have responded to the shift from bison to cattle grazing have been limited by a lack of comparable and consistent grazing treatments [*Knapp et al*., 1999]. Previous investigations of bison-prairie ecosystem interactions have focused on terrestrial ecosystem dynamics and identified substantial landscape scale interactions influencing vegetation composition, foraging, soil properties, nutrient dynamics, and animal community structure [*Hartnett et al*., 1996; *Knapp et al*., 1998; *Knapp et al*., 1999]. The two studies that we are aware of which examine sediment impacts from bison grazing, have either been done at a local scale [*Fritz and Dodds*, 1999] or were limited in replication and did not compare impacts to other grazers [*Larson et al*., 2013]. Furthermore, rigorous understanding of specific grazing impacts is lacking because of constrained sampling designs in past experiments, including very short grazing treatment periods [*Smith et al*., 1993; *Allen-Diaz et al*., 1998; *Lucas et al*., 2009], upstream confounding influences (such as different grazing treatments, dams, road crossings, etc.), and lack of experimental replication [*Trimble*, 1994; *Zaimes et al*., 2008].

The purpose of this study is to advance our understanding of relative impacts between introduced cattle grazing and native bison grazing in tallgrass prairie headwater streams and to address gaps in knowledge regarding baseflow sediment dynamics of grassland streams in the Great Plains. We hypothesize that suspended sediment concentrations during baseflow conditions are highest in cattle-grazed watersheds (particularly high density cattle treatments), moderate in bison-grazed watersheds, and lowest in ungrazed watersheds due to relative riparian disturbances (i.e. cattle spend more time in riparian zones than bison and a higher grazing density increases riparian disturbance). We define baseflow as subsurface flow or groundwater discharge. Baseflow is the primary source of discharge between precipitation events and during times of drought [*Zhang and Schilling*, 2005]. We chose to analyze sediment dynamics during baseflow as storm events are infrequent and unpredictable and baseflow dominates these seasonally intermittent systems. Furthermore, storms in these streams result in extremely flashy discharge making sample collection from multiple streams simultaneously extremely challenging.

Study Area

The study watersheds are located within the Great Plains tallgrass prairie biome, specifically the Flint Hills sub-province, which contains the largest continuous span of native tallgrass prairie in the United States [*McGregor and Barkley*, 1986]. Since the 1820's extensive agricultural development, particularly cropland, has resulted in increased sediment loading of fluvial systems within grassland ecosystems [*Knox*, 2006]. Pristine grasslands generally produce lower sediment loads than forested streams [*Whiles and Dodds,* 2002] while disturbed grassland streams produce greater sediment loads than forested streams [*Dodds and Whiles*, 2004]. Relative to desert and forested streams, grassland streams are characterized by intermediate bank stability, carbon content, and sediment concentration.

All study watersheds are entirely contained within two land parcels managed by Kansas State University, the Konza Prairie Biological Station (KPBS) and Rannell's Pasture. The KPBS is jointly owned by Kansas State University and the Nature Conservancy as a 3487 ha tallgrass prairie preserve and is the foundation of the NSF Konza Long Term Ecological Research (KNZ-LTER) site. Within KPBS, watershed sub-basins are experimentally treated with a variety of whole-basin grazing and burning regimes. Watershed sub-basins are similar in size, relief and geology, creating an ideal paired watershed experimental design. In order to discern grazing treatment effects on stream water quality, a paired whole-watershed study approach is undertaken, and includes unmodified control sites and replicates [*Bartley et al*., 2010b] to increase the robustness of statistical differences detected between treatments [e.g. *Pizzuto et al*., 2000; *Loftis et al*., 2001; *Udawatta et al*., 2002; *Bishop et al*., 2005; *Veum et al*., 2009]. In this study, we evaluate sediment regimes in ten watersheds, including two seasonally stocked, moderate density cattle-grazed watersheds, two seasonally stocked, high density cattle-grazed watersheds, three permanently stocked, bison-grazed watersheds and three ungrazed watersheds (Figure 2-1). Watersheds R1A and R1B are located within Rannell's Pasture and all other watersheds are located at KPBS. Cattle grazing treatments on KPBS are set at 4 ha per animal, while bison grazing treatments are set at 4.5 ha per animal. Both grazing densities are designed to remove 25% of net primary productivity annually [*Towne*, 1999; *Blair*, 2008]. Rannell's Pasture is a 1175 ha cattle ranch located directly adjacent to Konza Prairie. Designated for rangeland research purposes, Rannell's Pasture is managed with the same intensive seasonal cattle stocking practices as are common on private ranchlands in the Flint Hills. This intensive seasonal stocking treatment consists of stocking at 0.81 ha per animal from May 1st to July 1st, after which half the cattle are removed, resulting in a grazing density of 1.6 ha per animal from July 1st to October 1st, when all remaining cattle are removed [*Owensby et al*., 2008]. During the cattle grazing season the average grazing density (animal units/ha) at Rannell's Pasture is 3.3

times higher than that of Konza Prairie. Both cattle and bison have unrestricted access to stream channels in their watersheds.

The surficial geology within the study area consists of alternating layers of resistant limestones and erosive shales primarily of early Permian age, creating a bench and slope topography [*Jewett*, 1941].Currently the landscape is in a long term erosive stage thus sediment storage sites are typically thin, local and temporary [*Oviatt*, 1998]. Clay loams transition into silty clay loams from higher to lower elevations [*Jantz et al*., 1975]. The primary perennial warm season grasses include big bluestem (*Andopogon gerardii*), little bluestem (*A. Scoparius*), Indian grass (*Sorgastrum nutans*), and switch grass (*Panicum virgatum*) [*Freeman and Hulber*, 1985; *Briggs and Knapp*, 1995]. Established tree canopy coverage is prominent within 3rd and 4th order streams, while grasses are more common adjacent to 1st and 2nd order streams.

Precipitation averages 835 mm, 75% of which falls from May to October, with a peak in June. Snowfall averages 521 mm (52 liquid mm) per year. Mean monthly temperatures range from -2° C in January to 27° C in July. Average summer temperature (June-September) is approximately 24° C with the average high reaching over 33° C in July. A recent modeling study estimated that annual precipitation is partitioned as: 14% runoff, 11% groundwater recharge, and 75% evapotranspiration [*Steward et al*., 2011]. The flow regime is characterized by frequent but irregular flooding and droughts. Headwater streams are intermittent and typically flow from early spring through mid-summer months [*Matthews*, 1988]. Discharge in the study system is highly variable from year to year with an annual average of 200 days of flow [*Gray*, 1997]. During the sampling period for this study, extreme drought resulted in fewer than 140 total days of flow over 2 years (Figure 2-2). The average flood with a two year recurrence interval at Kings

Creek yields a discharge of 10.5 m^3s^{-1}. The highest discharge during sample collection was under 0.3 m^3s^{-1}.

Methods

Watershed attributes

In order to demonstrate similarity across sites, stream networks were automatically extracted from a two meter digital elevation model (DEM) based on the flow accumulation method [*Wieczorek*, 2012]. Field surveying verified the channel delineation to be accurate. Watershed attributes including watershed area, stream slope, stream sinuosity, elevation, and drainage density were calculated using ArcGIS 10.1 (Table 2-1). Stream slope was calculated as the difference between the high and low point of each stream divided by its length, sinuosity was calculated as the flow length of the stream divided by the straight line length from the sampling point to the end of the channel, drainage density was calculated as the total stream length divided by the watershed area, and elevation for each watershed represents the elevation at the sampling location. Watershed burning frequency from 1990 to 2010 was calculated from the KPBS website. Mean daily discharge data is reported from the USGS Kings Creek gaging station #0687650, located on KPBS. The Kings Creek gaging station is located downstream of the bison-grazed and ungrazed tributaries and is the closest USGS stream gage to all the study watersheds (see Figure 2-1), thus we found the gage most appropriate to use as a reference gage for discharge.

Sample collection, processing, and analysis

Due to the shallow nature of the streams caused by the drought, flow samples were collected from each stream by filling a one liter bottle from just below the surface of the thalweg with care not to disturb benthic sediment. As a result of drought conditions, all samples were collected under mean discharge conditions for their respective time periods. Collection of samples occurred every 14 days during rain free periods and 24 hours following precipitation events (on the receding limb of the hydrograph). The 24 hour period allowed for overland flow to cease (only the largest precipitation event resulted in significant overland flow). Samples were collected only when at least half of the study streams were flowing, and at least one stream within each treatment had connected flow. Sample collection started in May of 2011 and ceased in May of 2012 (Figure 2-2) and consisted of 10 sampling dates. Samples were processed following the guidelines of the American Public Health Association, method 2540 [*Eaton et al*., 2005]. Sediment concentration within each water sample was measured by filtering bottle contents, oven drying filtered content for 6 hours at 74° C, weighing to determine the mass of total suspended solids (TSS), and dividing TSS weight by the volume of water filtered. Next, the samples were ashed for an additional 6 hours at 246° C to burn off all organic matter, and then reweighed to measure total inorganic solids TIS (mg/L). By subtracting the ashed weight from the dried weight, total volatile solids TVS (mg/L) were determined. Percent organic matter (POM) was calculated as TVS/TIS * 100. Samples were measured for TSS (mg/L), TIS (mg/L), TVS (mg/L) and POM (%). TIS (n=70) was measured from May 26thth, 2011 thru May 2nd, 2012, while TSS (n=54), TVS (n=54) and POM (n=54) were measured from June 14th, 2011 thru May 2nd, 2012.

ANCOVA analysis tested for correlation with grazing treatment (ungrazed, bison, moderate density cattle, and high density cattle), season (Julian day of year), watershed burn frequency (times burned from 1990-2010), and discharge (m^3s^{-1}). Grazing treatments were treated as categorical factors, while season, burn frequency, and discharge consisted of continuous data. TSS, TIS and TVS values were log transformed in order increase normality among residuals. Akaike information criterion (AIC) was used to determine which variables were included in the statistical models. In order to measure the relative importance of the variables the "relimpo" package in R was used to calculate the R^2 values for each variable. The R^2 values represent the amount of the variance explained by each model [*Groemping*, 2006]. Grazing effects between treatments were compared with a series of ANOVA's followed by post hoc Tukey's HSD analysis. TSS data had to be log transformed to meet statistical assumptions. All statistics were calculated in R (version 3.0; R Development Core Team, Vienna, Austria).

Results

Model results

The strongest models (lowest AIC) included all four variables for TSS and TIS while burn frequency and season were excluded for TVS and discharge was excluded for POM. The models were highly significant for TSS ($P<0.01$; d.f.=6), TIS ($P<0.001$; d.f.=6), TVS ($P<0.01$; d.f.=4) and POM ($P<0.001$; d.f.=5) (Table 2-2). The model explained 44.3%, 56.6%, 22.1% and 40.1% of the variance in TSS, TIS, TVS, and POM respectively. TSS predictors ranked from highest to lowest were grazing treatment, burn frequency, season and discharge. TIS predictors ranked from highest to lowest were grazing treatment, season, burn frequency and discharge. Grazing treatment was the most important predictor followed by discharge in the TVS model while burn frequency was calculated to be the most important predictor followed by grazing treatment and season in the POM model. Results are summarized in Tables 2-2 and 2-3 and Figure 2-3.

Impact of grazing treatment on suspended sediment concentrations

Mean and median sediment concentrations grouped by grazing treatment are shown in Table 2-4. Concentrations of TSS ($P<0.05$; d.f.=3), TIS ($P<0.01$; d.f.=3), and TVS ($P<0.10$;

d.f.=3) significantly varied among grazing treatments, while POM was not found to be significantly different among grazing treatments ($P>0.10$; d.f.=3) (Figure 2-4, Table 2-5). Mean TSS concentrations were lowest in ungrazed treatments (.74 mg/L), followed by bison (2.00 mg/L), moderate density cattle (2.89 mg/L), and high density cattle treatments (7.09 mg/L). TSS concentration was 7.46 times higher in high density cattle treatments relative to ungrazed treatments ($P<0.05$) and 4.16 times higher in high density cattle treatments relative to bison treatments ($P<0.10$). TIS concentrations were lowest in ungrazed treatments (1.01 mg/L) followed by bison (1.43 mg/L), moderate density cattle (5.29 mg/L), and high density cattle treatments (7.43 mg/L). Moderate density cattle treatments had TIS concentrations 3.7 and 5.24 times higher than bison ($P<.10$) and ungrazed treatments ($P<0.05$) respectively. TIS was 7.36 and 5.20 times higher in high density cattle treatments relative to ungrazed ($P<0.01$) and bison treatments ($P<0.01$) respectively. TVS concentration was highest in high density cattle treatments (1.38 mg/L), followed by moderate density cattle (1.00 mg/L), bison, and ungrazed treatments (.47 mg/L). High density cattle treatments had TVS concentrations 2.94 times higher relative to ungrazed treatments ($P<0.10$). No other significant differences were found in TVS and grazing treatments (all $P>0.10$). POM was lowest in high density cattle treatments (27%) followed by bison (56%), ungrazed (56%), and moderate density cattle treatments (57%). With an average POM of 27% high density cattle was the only treatment where POM was less than 50%. The mean POM difference between bison, moderate density cattle and ungrazed treatments was less than 1.5%. There were no significant differences in POM among grazing treatments ($P>0.10$), however high density cattle treatments had significantly lower POM than all other grazing treatments combined (high density cattle vs ungrazed, bison, moderate density cattle)

(P<0.05). Significant differences among grazing treatments are summarized in Table 2-5 and Figure 2-4.

Impact of hydrology, seasonality and burning frequency on sediment concentrations

Trends between sediment variables (TSS, TIS, TVS and POM) and drivers (discharge, seasonality, and burn frequency) are shown in Figure 2-5 and a statistical summary of the data is provided in Table 2-2. Significant trends in the positive direction were found between TSS (P<0.01), TIS (P<0.001), TVS (P<0.05) and discharge. The model did not find discharge to be an informative variable for POM (Table 2-2, Figure 2-5). Ungrazed, bison and moderate density cattle treatments all showed positive relationships between TIS and discharge while the high density cattle treatment showed a negative trend (Figure 2-6).

The Julian day of the year was significantly related to TSS (P<0.01) and TIS (P<0.001) in the positive direction. The model did not find seasonality to be an informative variable in determining TVS. POM was significantly related to the day of the year in the negative direction (P<0.01) (Table 2-2, Figure 2-5). The largest difference in sediment concentrations between ungrazed-bison-grazed treatments and cattle-grazed treatments occurred in the later portions of the year (Figure 2-7a). POM was consistently lowest within the high density cattle-grazed treatments even during times when the cattle were not on the land (Figure 2-7b).

Increased burn frequency significantly increased TSS (P<0.10) and TIS (P<0.05) and was not an informative variable for TVS. Increasing burn frequency significantly decreased POM (P<0.01). Results are summarized in Table 2-2 and Figure 2-5.

Discussion

Our results indicate that grazing treatment is the most influential variable controlling TSS, TIS and TVS (Table 2-3). As expected, cattle-grazed watersheds produced the largest sediment concentrations at baseflow (Figure 2-4, Table 2-4). However, the magnitude of difference between cattle grazing and other treatments, particularly bison grazing, was surprising as were the drastically lower POM values in high density cattle-grazed watersheds (Figure 2-4, Table 2-4). Extensive bare ground underneath riparian trees within cattle-grazed watersheds decreases near stream vegetative biomass while within bison-grazed watersheds bare ground is prevalent in higher elevations particularly adjacent to roads and ridges (Figure 2-8), thereby increasing the potential for sediment loading from cattle-grazed riparian zones [*Butler et al*., 2008]. Inorganic sediment concentrations increased with discharge, burning frequency and seasonally. These results were anticipated as an increase in discharge is able to carry more sediment [*Asselman.,* 1999], burning frequency decreases biomass [*Moody and Martin*, 2001] and grazing ungulates increase their need for thermal relief and water consumption during hotter times of the year [*Allred et al*., 2013].

Increasing temperatures in the summer increase demand for thermal relief and drinking water leading to increased grazing disturbance within the riparian zone and stream channel [*Allred et al*., 2013] thereby increasing sediment loads. Figure 2-7a shows an increased divergence of sediment concentrations between cattle-grazed and ungrazed-bison-grazed treatments during the summer months. Based on this we conclude that the cattle-grazed streams are most significantly impacted during summer. The consistently low POM within high density cattle treatments (Figure 2-7b) indicates a more persistent legacy of high density cattle grazing impacts. This is further supported by the low POM within high density cattle treatments during months when cattle are not on the land. The increased sediment loads may have significant implications for aquatic biota (i.e. fish communities). For example, the already endangered Topeka Shiner (*Notropis topeka*), is not well adapted to the high sediment concentrations within these grassland streams [*Cross and Moss*, 1987]. Increased sediment loads may also result in economic losses as reservoirs experience accelerated sedimentation rates [*Graf et al.*, 2010].

The high density cattle grazing treatments produced a surprising relationship between sediment concentrations and discharge. Our expectation was that TSS, TIS and TVS would all increase with discharge, as increasing stream power enables transport of larger fractions of suspended sediment [*Asselman,* 1999], and this did occur in most of our treatment watersheds. Yet, in the high density cattle treatments, sediment concentrations decreased with increasing discharge. When temperatures are hottest, discharge is likely to be lowest given high evapotranspirative losses [*Gribovszki et al*., 2010] and cattle are most likely to seek thermal relief in and near the stream channel, leading to hoof disturbance to the substrate and re-suspension of fine sediments during low flow periods. Times of increased discharge are accompanied by reduced temperatures and increased rainfall, lowering the thermal stresses on cattle and enabling them to spend more time on hillslopes as opposed to in and near the channel. Despite the negative sediment-discharge trend within the high density cattle-grazed treatments (Figure 2-6), overall an increase in sediment concentration with discharge was found (Figure 2-5) due to the stronger positive sediment-discharge relationship within the remaining grazing treatments.

The different grazing duration between bison (permanent) and cattle (seasonal) may influence sediment concentrations (i.e. bison may directly resuspend sediment during times when cattle are not present on the land). Based on our data (Figure 2-7a) bison do not appear to be impacting the streams during these cooler times. Allred *et al.* [2013] found that bison seek thermal relief at temperatures above 36° C, a temperature that is extremely unlikely prior to the summer. Sediment concentrations were consistently higher within high density cattle-grazed watersheds throughout the year including pre-grazing periods (Figure 2-7a). Within our study the streams dried out prior to cattle being removed from the land, thus both cattle and bison relied on ephemeral pools within the stream network. To test if bison created spikes in sediment concentrations during the hotter summer months if the streams maintained connected flow once cattle were off the land would reveal further sediment dynamics within these systems.

As expected, increased burning frequency results in increased TSS and TIS and decreased POM. Burning grasslands directly removes the majority of organic matter standing stock from the watershed [*Kauffman et al*., 1994], although fire does not necessarily penetrate riparian zones completely (Grudzinski, personal observation). Recent burning attracts cattle and bison due to increased nutrient content in fresh re-growth of recently burned grasses [*Archibald et al*., 2005], leading to increased trampling and soil disturbance while decreasing availability of organic matter. Increased above ground vegetation within less frequently burned watersheds may act as an efficient filter to hillslope sediment runoff. POM likely decreases as the year progresses into summer as the organic matter that was deposited from canopy coverage during the previous autumn is decomposed by aquatic biota and washed out with time. The seasonal decline in POM is consistent with other studies demonstrating regulation of organic matter by detritivores during periods of prolonged baseflow [e.g. *Ferreira et al*., 2013].

Native bison and introduced cattle have many behavioral similarities (both prefer recently burned areas and avoid steep slopes) while maintaining unique differences (cattle prefer woody vegetation and are heavily influenced by location of water, while bison avoid wooded areas and grazing is not limited by water availability) [*Allred et al*., 2011]. The behavioral differences are likely creating new pathways that increase sediment loading within streams as observed in the field by extensive bare ground patches underneath riparian canopy within cattle-grazed treatments, especially high density cattle treatments (Figure 2-8). Although bison wallowing creates bare ground, these features are often located at the higher elevations of watersheds and those in the riparian areas are often separated by a vegetated buffer. Larson *et al.* [2013] found that the production of wallows did not significantly increase sediment concentrations relative to an ungrazed stream. Future studies quantifying driving mechanisms such as bare ground concentration in riparian areas would be extremely beneficial to connecting the alteration of hillslope processes by the large ungulates to fluvial water quality.

Due to extreme drought conditions, we were only able to sample during the spring and summer months. Lower than average precipitation along with higher than average temperatures decrease discharge while also increasing grazing pressure on riparian areas, likely resulting in higher than average sediment concentrations. During years that are cooler and wetter, the streams discharge may be more effective at diluting sediment concentrations (e.g during times of in-stream trampling). If the streams were to flow year round additional sediment dynamics may be revealed. For example, during the winter months when the stream banks are typically experiencing frequent, sometimes daily, freeze thaw cycles (Grudzinski, personal observation), sediment input may be increased into the stream. During autumn months significant leaf inputs are deposited onto the stream bed from riparian canopy prior to stream flow beginning. If the leaf litter is exported earlier in the season we may expect lower TVS and POM during summer months. Thus we may expect that during flow periods outside of our study period sediment dynamics may be variable, especially from year to year. Additional sampling during non-drought conditions may reveal the extent to which these and additional drivers alter suspended sediment dynamics within grassland headwater stream systems.

The global demand for meat continues to increase during a time of debate on the ecological equivalencies between cattle and bison. Increasing grazing pressure on the few remaining grasslands of the Great Plains increases the need to understand the landscape scale impact of various grazing ungulates. With better knowledge of how the grazers interact with the landscape, conservation efforts on remaining grasslands can be better understood and may become more effective. Currently published comparisons between cattle and bison are sparse although their influence on aquatic landscape structure and function is immense and unequivocal.

Conclusions

This study has for the first time elucidated the relative influences of cattle and bison grazing treatments on baseflow suspended sediment concentrations. While both moderate and high density cattle grazing treatments significantly increase stream sediment concentrations, bison grazing treatments do not. The increased bare ground located within the riparian zones and direct trampling of the stream bed are likely leading to the increase in sediment concentrations in cattle-grazed watersheds. By increasing bare ground and directly trampling stream banks into the channel, cattle grazing accelerates the natural rate of hillslope erosion and landscape denudation rates, meanwhile altering natural sediment budgets particularly during summer months. Due to the significant influence of cattle grazing on sediment dynamics, grazing management should be considered as a significant contributor to exogenic processes on the Earth's surface.

These results indicate that modern practices of high density cattle grazing are responsible for significant degradation of baseflow water quality in the Great Plains of North America. The most significant damage is occurring during summer months likely due to increased demand for thermal relief and water consumption. Efforts to address this non-point source of sediment pollution might involve cattle exclusion fencing, shade and water provision outside of the riparian zone, reduction in stocking densities, or replacement of cattle with bison. Burning frequency, discharge and seasonality significantly influence stream suspended sediment dynamics at baseflow, but are generally less influential relative to grazing treatments.

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Figures

Figure 2-1 Paired whole-watershed study design. N watersheds are bison-grazed, K are ungrazed, C are moderate density cattle-grazed (grazing density is equivalent to bison-grazed treatments), R watersheds are high density cattle-grazed (grazing density is 3.3 times higher than in C and N watersheds). All watersheds are located within Konza Prairie other than R1A and R1B which are both within Rannell's Pasture. The Kings Creek gaging station has a drainage basin area of 10.59 sq. km.

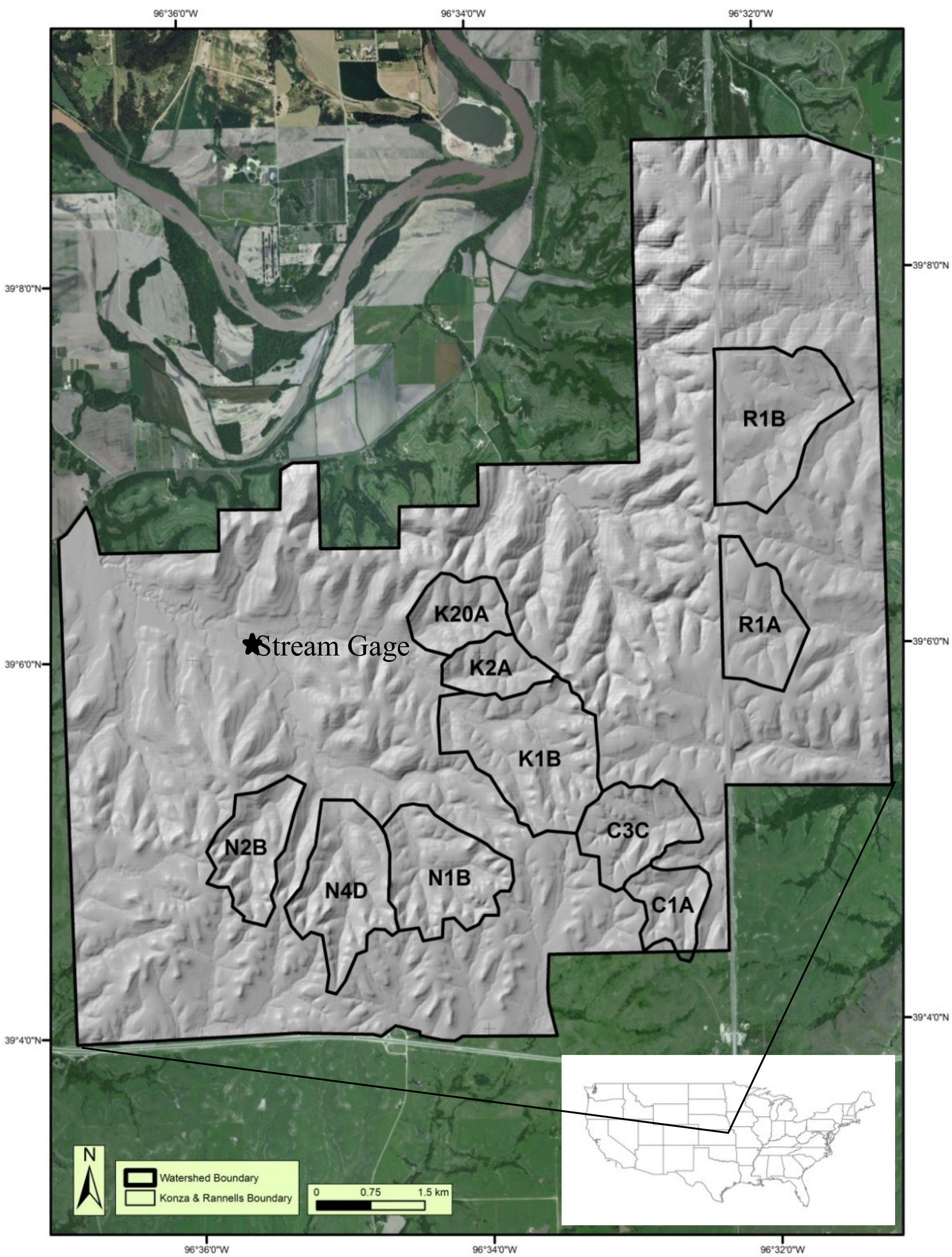

Figure 2-2 Hydrograph during the sampling seasons (USGS gaging station #0687650). Triangles indicate days when samples were collected. Extreme drought was experienced during the sampling season. The two year flood yields a discharge of 10.5 m^3s^{-1}. The highest discharge during sample collection was under 0.3 m^3s^{-1}.

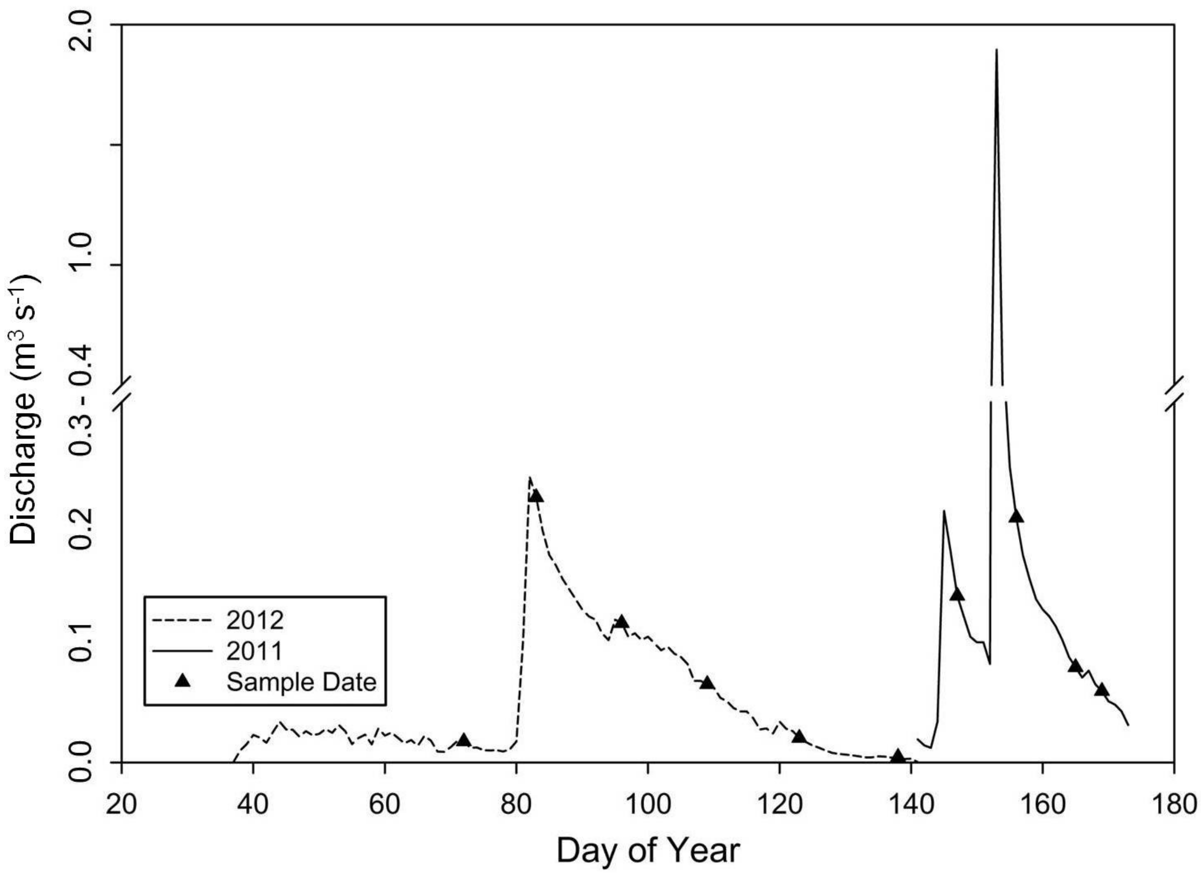

Figure 2-3 Multiple R^2 values for total suspended solids (TSS), total inorganic solids (TIS), total volatile solids (TVS), and percent organic matter (POM) were calculated using the "Relimpo" package in R studio 3.0.0. The R^2 values represent the amount of variance explained by the model. AIC excluded burn frequency and season from TVS analysis and discharge from POM analysis.

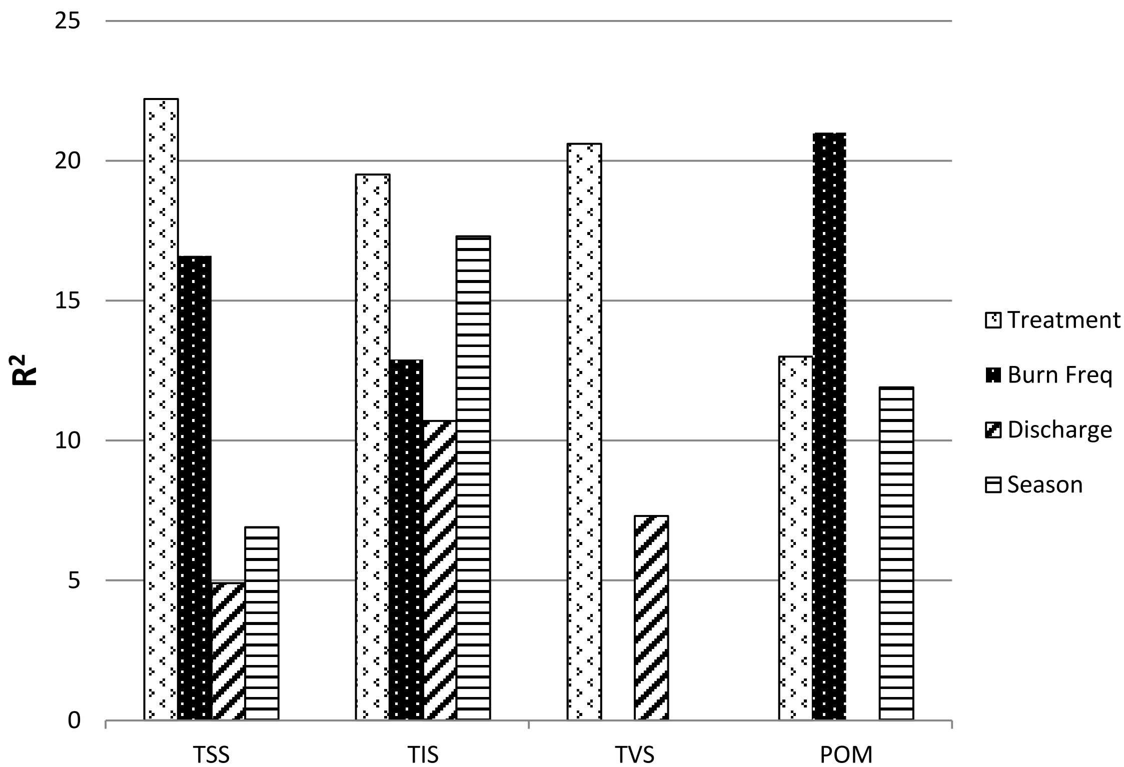

Figure 2-4 Variability in total suspended solids (TSS), total inorganic solids (TIS), total volatile solids (TVS), and percent organic matter (POM) between ungrazed (U), bison (B), moderate density cattle (MC), and high density cattle (HC) treatments. "A", "B" and "AB" represent similarities and differences among grazing treatments. If treatments do not share a letter, then a significant difference between the grazing treatments has been detected. Numbers under treatment labels represent the total number of samples collected (and the total number of watersheds within each treatment).

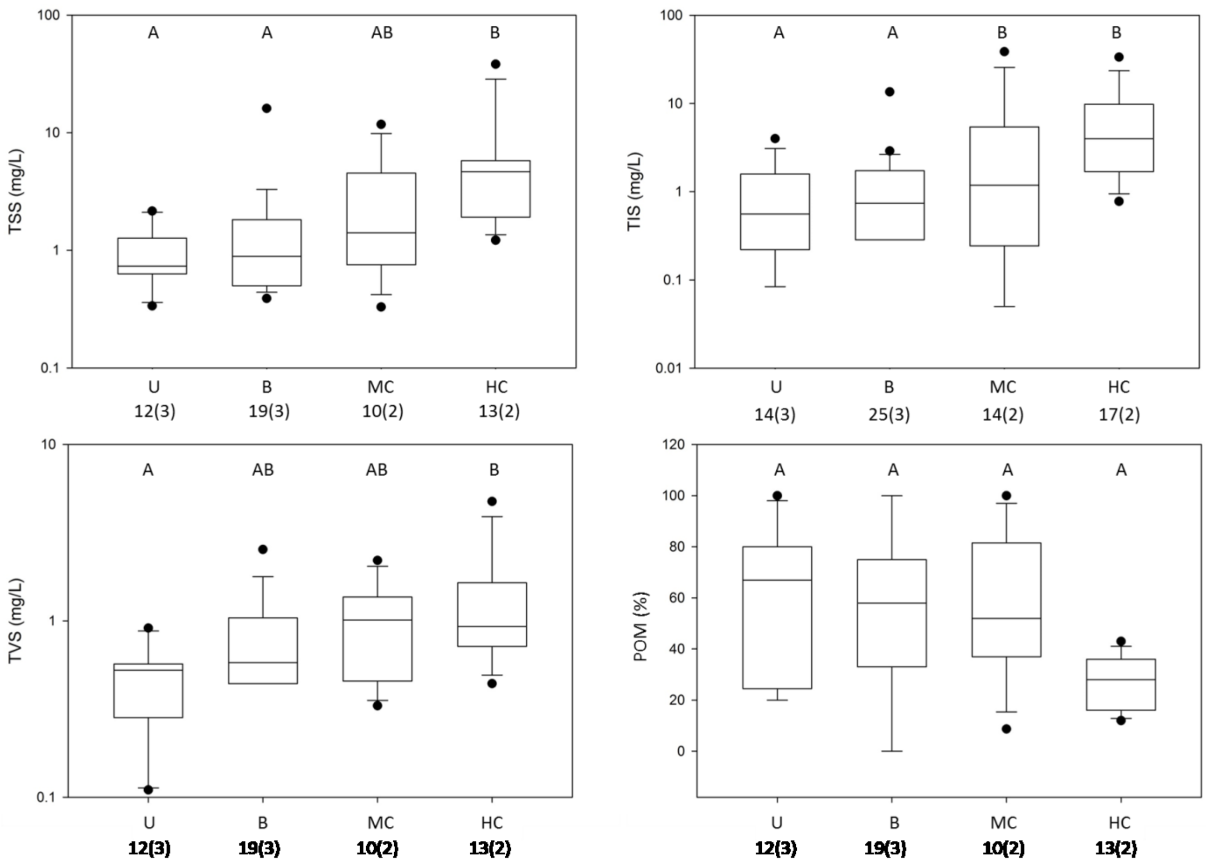

Figure 2-5 Trends among sediment dynamics and predictor variables. Significance values are shown in Table 2-2. All sediment concentrations increased with discharge, burn frequency and varied seasonally. Percent organic matter (POM) increased with discharge while decreasing with burn frequency and as the year progressed.

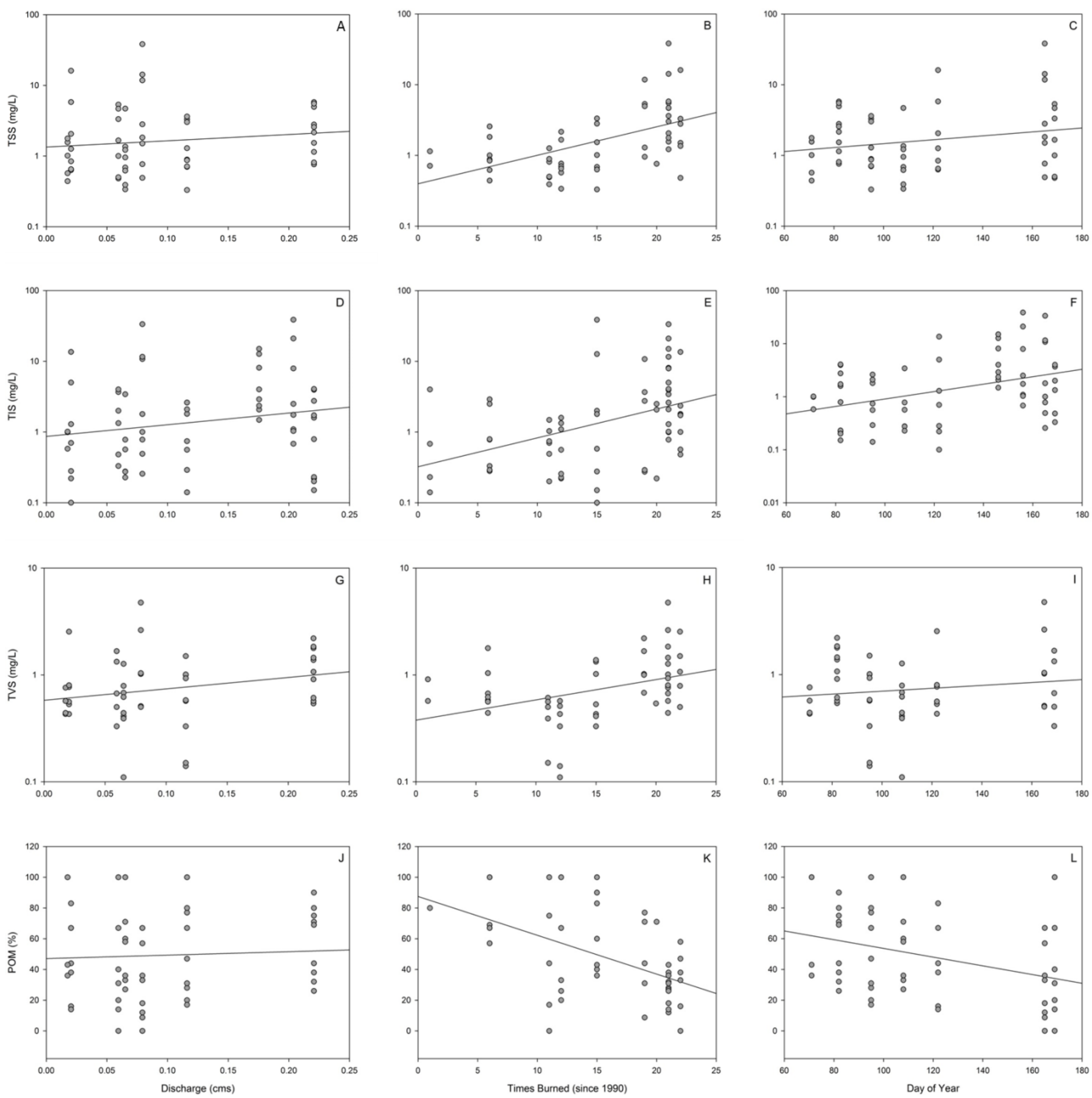

Figure 2-6 Relationship between discharge and total inorganic solids (TIS). Note the scale on the Y-axis is much higher for MC and HC treatments. U, B and MC treatments all showed positive relationships between discharge and TIS while the HC treatment showed a negative trend. Significant trends (p<.05) were observed within bison and moderate density cattle grazed treatments.

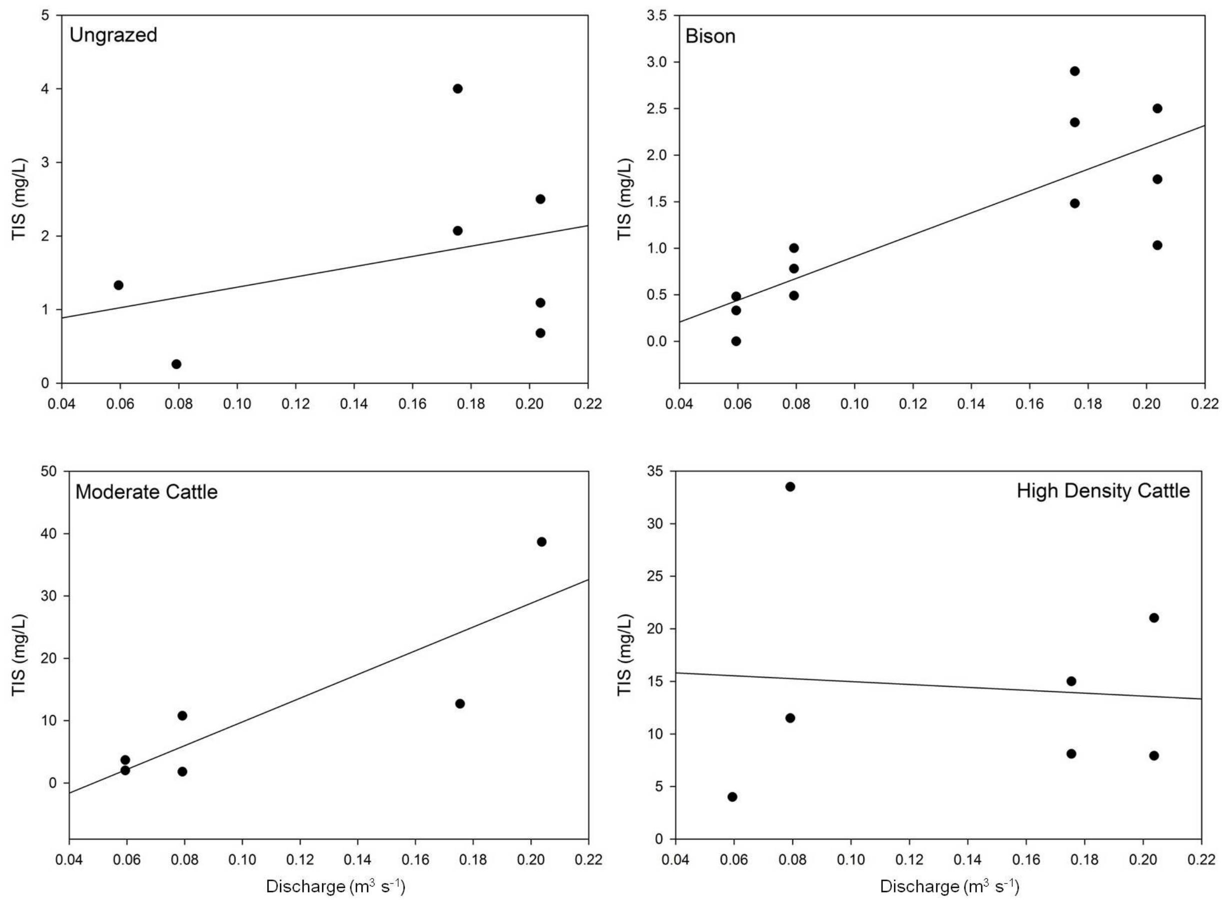

Figure 2-7 Relationship between total suspended solids (TSS) and percent organic matter (POM) with the day of year separated by grazing treatment. Sediment concentrations within cattle-grazed treatments, especially high density cattle increase the most during summer months while POM remains low within high density cattle-grazed treatments throughout the year including times when cattle are not on the land.

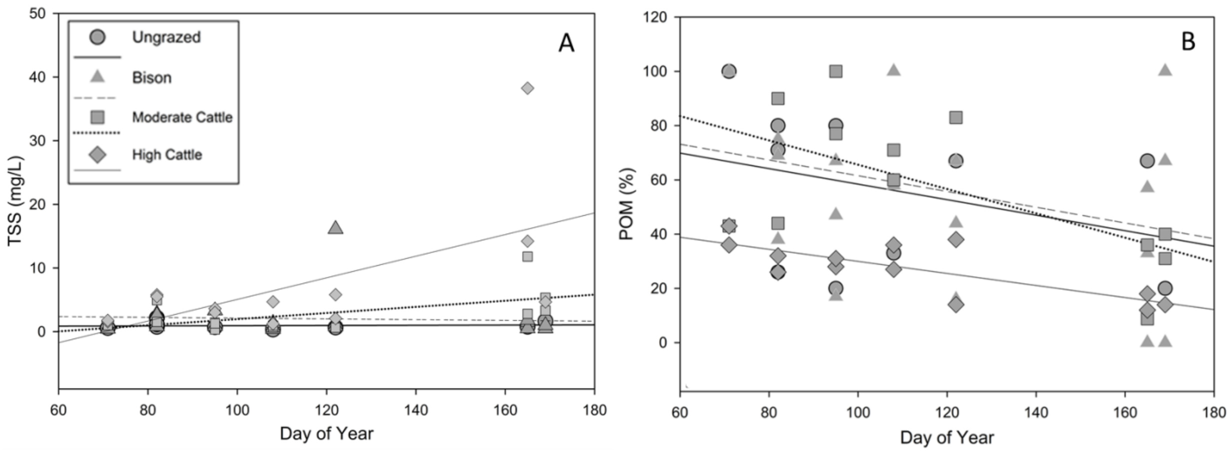

Figure 2-8 Cattle seeking thermal shelter underneath canopy cover (A). Heavily trampled and unvegetated stream banks (B & C). Wallows located away from riparian areas in bison grazed watersheds (D).

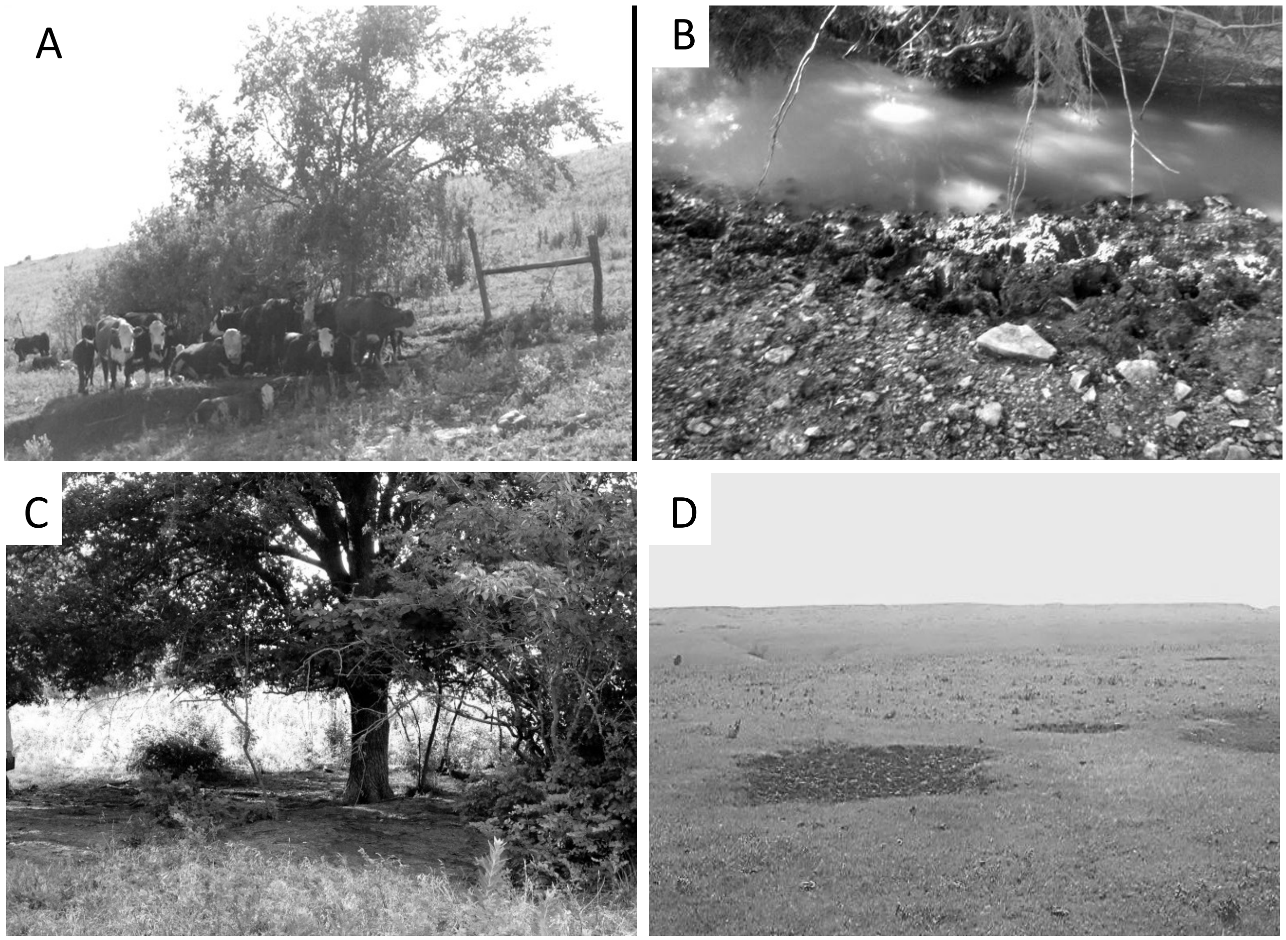

Table 2-1 Watershed attributes.

Watershed[a]	Grazing Density (ha/AU)	Grazing Season (months)	Area (ha)	Burn Frequency (1990-2010)	Drainage Density (m/m^2)	Elevation (m)	Slope (%)	Sinuosity (m/m)
K1B	NA	None	412	20	0.0062	374	2.7	1.31
K2A	NA	None	119	12	0.0061	371	3.75	1.11
K20A	NA	None	146	1	0.0059	363	3.74	1.28
N1B	4.5	Year Round	287	22	0.006	376	3.53	1.21
N2B	4.5	Year Round	197	11	0.0056	361	3.57	1.2
N4D	4.5	Year Round	301	6	0.0055	365	2.9	1.15
C1A	4.0	May-Oct	126	15	0.005	404	3.37	1.19
C3C	4.0	May-Oct	186	19	0.0067	401	2.66	1.18
R1A	1.2	May-Oct	225	21	0.0051	386	2.54	1.22
R1B	1.2	May-Oct	390	21	0.0054	378	1.89	1.37

[a] K watersheds are ungrazed, N are bison-grazed, C are moderate density cattle-grazed and R are high density cattle-grazed.

Table 2-2 ANCOVA results.

Sediment (n)	Model *p* value (d.f)	Model Adj. R^2	Treatment *p* value	Discharge *p* value[a]	Burn Freq. *p* value[a]	Season *p* value[a]
TSS (54)	<0.01 (6)	44.3	<0.01	<0.01	<0.10	<0.01
TIS (70)	<0.001 (6)	56.6	<0.001	<0.001	<0.05	<0.001
TVS (54)	<0.01(4)	22.1	<0.01	<0.05	NA	NA
POM (54)	<0.001 (5)	40.1	>0.10	NA	<0.01	<0.01

[a] NA's indicate variables that were excluded by the AIC analysis.

Table 2-3 Relative importance of variables.

	TSS[a]	TIS[a]	TVS[a]	POM[a]
Treatment	22.2	19.5	20.6	13.0
Discharge	4.9	10.7	7.3	N/A
Burn Freq.	16.6	12.9	N/A	21.0
Season	6.9	17.3	N/A	11.9
Total	50.6	60.4	27.9	45.9

[a]Multiple R^2 for each variable found with the "Relimpo" package in R studio 3.0.0. The R^2 represents the percent of the variance explained by the model.

Table 2-4 Mean and median sediment values.

Treatment	TSS (mg/L) median	TSS (mg/L) mean	TIS (mg/L) median	TIS (mg/L) mean	TVS (mg/L) median	TVS (mg/L) mean	POM (%) median	POM (%) mean
Ungrazed	0.74	0.95	0.56	1.01	0.53	0.47	67	56
Bison	0.89	2.00	0.74	1.43	0.58	0.75	58	56
Moderate Cattle	1.41	2.89	1.18	5.29	1.01	1.00	52	57
High Cattle	4.67	7.09	4.00	7.43	0.93	1.38	31	27

Table 2-5 Significant differences among grazing treatments. Model d.f.=3 for each sediment variable.

Treatments[a]	TSS *p* value	TIS *p* value	TVS *p* value	POM *p* value
Model	<0.05	<0.01	<0.10	>0.10[b]
MC-B	0.82	0.057	0.70	0.99
HC-B	0.08	0.004	0.21	0.37
U-B	0.30	0.99	0.84	0.81
HC-MC	0.29	0.20	0.72	0.40
U-MC	0.13	0.042	0.35	0.88
U-HC	0.01	0.004	0.09	0.15

[a]Post hoc Tukey's HSD P values. U, B, MC and HC represent ungrazed, bison, moderate density cattle and high density cattle-grazed treatments.

[b]A secondary test was run for POM in which U, B, and MC treatments were grouped and tested against HC treatments. The HC treatments were found to have significantly lower POM values ($p<0.05$).

Chapter 3 - Watershed grazing management, bare ground coverage, and links to suspended sediment concentrations in grassland headwater streams

Abstract

This study quantifies the impact of various cattle and bison grazing management practices on bare ground coverage at the watershed, riparian, and forested riparian scales. We test for correlations between bare ground coverage and fluvial suspended sediment concentrations during baseflow and storm flow events. We use remotely sensed imagery combined with field surveys to classify ground cover and quantify the presence of bare ground. Baseflow water samples were collected bi-monthly during rain-free periods and 24 hours following precipitation events. Storm flow water samples were collected on the rising limb of the hydrograph using singe stage automatic samplers. Ungrazed treatments contain the lowest coverage of bare ground, fewest bare ground patches, and smallest mean bare ground patch size at the watershed, riparian, and forested riparian scales. Bison treatments contain the highest coverage of bare ground at the watershed scale, while high density cattle treatments contain the highest coverage of bare ground at the riparian and forested riparian scales. In bison and cattle grazed treatments a majority of bare ground is located near fence lines, watershed boundaries, and 3rd and 4th order stream segments. Inorganic sediment concentrations at baseflow are best predicted by riparian zone bare ground coverage, while storm flow concentrations are best predicted by watershed scale bare ground coverage. Bare ground coverage underneath forested riparian areas can be accurately predicted based on land use and remotely sensed land cover data.

Introduction

Sediment is currently recognized as the most detrimental non-point source pollutant of stream ecosystems within the United States (Simon and Darby, 2002). Livestock production occupies 25% of terrestrial land area (Asner *et al*., 2004) and is recognized as a primary contributor to soil degradation, sediment erosion and desertification (Mainguet, 1994; Milton and Dean, 1995; Li *et al*., 2000; Asner *et al*., 2004; Zaimes *et al*., 2004; Yiesehak *et al.,* 2013). Vegetation cover is the most influential variable in determining aquatic sediment and nutrient loading from adjacent hillslopes (Haan *et al*., 2006). Vegetation decreases wind and runoff erosion by limiting the area of exposed soils (Ludwig *et al*., 1997; Li *et al*., 2007; Bastin *et al*., 2012), entrapping mobilized sediment particles, increasing soil stability, infiltration rates, and litter cover, while decreasing rain splash impact (Naeth *et al*., 1991; Pearce *et al*., 1998; Bear *et al*., 2012). Many studies indicate that cattle grazing decreases grass biomass, resulting in bare ground (Popolizio *et al.,* 1994; Kutt and Woinarski, 2007; Teague *et al*., 2010), leading to accelerated soil erosion and increased fluvial suspended sediment concentrations (Olley and Wasson, 2003; Vidon *et al*., 2008; Bartley *et al*., 2010a).

Watershed areas with less than 10% vegetation cover are associated with the greatest contributions of hillslope sediment to stream systems (Bartley *et al*., 2010a), and relatively small areas of degradation can lead to severe increases in suspended sediment loading; in one hillslope erosion study, 97% of hillslope derived sediment came from only 3% of the grazed basin surface area (Bartley *et al*., 2010b). Stream bank erosion can be up to 30 times higher in unvegetated reaches relative to those with vegetated riparian zones (Beeson and Doyle, 1995). A decrease in riparian vegetation from unrestricted cattle access to streams can result in a twofold increase in soil erosion rates relative to areas with forested buffers (Zaimes *et al*., 2004).

Increased fine sediment loads lead to many adverse impacts on aquatic ecosystems, including, but not limited to, decreased photosynthesis, plant and fish abrasion, decreased populations and diversity of macroinvertebrates, and increased potential for non-native species invasion (Wood and Armitage, 1997). Within North America, increased sediment loads have decreased the quality of habitat for native flora and fauna within both freshwater (Richeter *et al*., 1997) and saltwater (Short and Wyllie-Echeverria, 1996) habitats, severely decreased reservoir storage (Graf *et al*., 2010), and contributed to eutrophication of estuaries (Rabalais *et al*., 2002). Due to soil binding properties, suspended sediment may also be associated with increases in nutrient, bacteria, and heavy metal concentrations (Leivuori, 1998; Lei *et al.,* 2005).

Despite widespread recognition that livestock grazing increases sediment pollution, very little is known about how different grazing management practices (i.e. stocking densities, different species) influence sediment controlling variables such as vegetation cover and bare ground exposure within a watershed. Furthermore, research demonstrating the connection between spatial arrangement of bare ground within a landscape and in-stream suspended sediment concentrations has been limited.

Previous studies examining the impact of grazing influence on riparian structure and function have varied in their design, making broad comparisons among grazing treatments a challenge. For example, some studies apply cattle to a previously ungrazed field for less than an hour (Russell *et al*., 2001), while others have been grazed for decades and perhaps centuries (Yisehak *et al*., 2013). Furthermore, previous studies exploring grazing-riparian relationships have yielded mixed results. In a three year study Bear *et al*. (2012) did not find significant differences in bare ground coverage nor bank erosion between high and low intensity grazing in riparian zones. Meanwhile, other studies have shown significant increases in bare ground coverage with increasing grazing pressures (Russell *et al*., 2001; Zhao *et al*., 2005), and in some instances cattle have been shown to increase bare ground quite rapidly (over 10% within two years) (Hillhouse *et al*., 2010).

Historically the prairies within the United States were grazed by over 30 million American Bison. However, populations fell to several thousand in the 1800's, primarily due to hunting (Flores, 1991; Shaw and Lee, 1997). Recently, bison populations have increased due to demand for bison meat as well as conservation efforts. Although numerous studies have conclusively documented increased bare ground resulting from cattle grazing (e.g. Wahren *et al*., 1994; Bartley *et al*., 2010a), we are not aware of any studies comparatively evaluating bare ground production by native bison. The effects of bison may vary from those of cattle, particularly in riparian areas, due to lower demands for thermal relief and water consumption, along with decreased browsing preference for riparian vegetation by bison (Allred *et al*., 2013). Recent studies have determined that bison select to graze outside of riparian zones (Larson *et al*., 2013) and spend less time in riparian zones relative to cattle (Allred *et al*., 2013). However, bison may increase bare ground outside of riparian areas due to unique behaviors such as wallowing (McMilian *et al*., 2000). The only study that we are aware of comparing bison to cattle grazing impacts on aquatic systems showed that suspended sediment concentrations were significantly higher within cattle-grazed watersheds, while bison and ungrazed treatments were similar to one another (see Chapter 2). Furthermore, high density cattle grazing was associated with the highest suspended sediment concentrations (see Chapter 2). The difference in bare ground coverage between bison and cattle grazing treatments remains unknown.

The goal of this study is to: 1) quantify the impact of various grazing management practices (moderate *vs*. high density cattle and bison *vs.* cattle) on bare ground coverage within watershed, riparian, and forested riparian areas and, 2) to test for links between bare ground coverage and fluvial suspended sediment concentrations. We hypothesize that: 1) grazed watersheds will contain significantly more bare ground area than ungrazed watersheds due to large grazer foraging and trampling. Relative to bison, cattle-grazed watersheds are predicted to have more bare ground area, a larger number of bare patches, and larger average patch size near streams because of higher physiological requirements for shade and water, 2) more bare ground area will be located within the riparian zones of larger streams due to increased riparian canopy cover for shade and increased water availability, and 3) instream sediment loads will be correlated with bare ground coverage, especially within the riparian zones, due to increased runoff and hillslope erosion potential.

Study Area

This study was conducted within the Flint Hills ecoregion, which contains the largest segment of unplowed tallgrass prairie in the United States. Precipitation averages 835 mm a year, 75% of which falls from May to October, with a peak in June. Mean monthly temperatures range from -2° C in January to 27° C in July. Average summer temperature (June-September) is approximately 24° C with the average high reaching over 33° C in July. The climate regime results in intermittent stream flow which becomes disconnected before completely drying out, typically in summer months. Soils within the study area primarily originate from weathered Permian limestone and shale parent material (Ransom *et al*., 1998) and are representative of the Flint Hills ecoregion (Briggs and Knapp, 1995). Soils at higher elevations primarily have a clay loam texture and transition into a silty clay loam texture in the lowlands (Jantz *et al*., 1975). The dominant vegetation within the study area consists of native, perennial warm season grasses. The primary species include big bluestem (*Andopogon gerardii*), little bluestem (*A. Scoparius*), Indian grass (*Sorgastrum nutans*), and switch grass (*Panicum virgatum*) (Freeman and Hulbert, 1985; Briggs and Knapp, 1995). Riparian areas have established tree canopy coverage along 3rd and 4th order streams, while increased grassland cover is along 1st and 2nd order streams.

The study watersheds are located within the Konza Prairie Biological Station (KPBS), a Long Term Ecological Research (LTER) site, and Rannell's Pasture, which is located directly adjacent to KPBS. In this study, we evaluated bare ground patch distributions in nine watersheds, consisting of two seasonally stocked (May-October), moderate density cattle-grazed watersheds (C1A, C1C), two seasonally stocked (May-October), high density cattle-grazed watersheds (R1A, R1B), two permanently stocked (Year-round), bison-grazed watersheds (N1B, N4D), and three ungrazed watersheds (K1B, K2A, K20A) (Table 3-1, Fig. 3-1). Watersheds R1A and R1B are located within Rannell's Pasture and all other watersheds are located within the Konza Prairie. The research sites are managed by Kansas State University's Division of Biology and Department of Agronomy and are intended for grassland and rangeland research. Grazing treatments on Konza Prairie are set to remove 25% of the net primary productivity, so cattle are stocked at 4 ha per animal and bison are stocked at 4.5 ha per animal (Towne, 1999; Blair, 2008). Rannell's Pasture is managed similarly to private rangelands in the Flint Hills with intensive seasonal cattle stocking. From May 1st to July 1st stocking is set at 0.81 ha per animal, after which half the cattle are removed, resulting in a grazing density of 1.6 ha per animal from July 1st to October 1st, when all remaining cattle are removed (Owensby *et al*., 2008). The average grazing density at Rannell's Pasture is 3.3 times higher than that of Konza Prairie. Within all study watersheds, bison and cattle have unrestricted access to riparian areas although cattle-grazed watersheds have fencing separating the cattle into smaller sub-watershed patches of equal grazing density. In Rannell's Pasture, salt licks and watering troughs are located near ridges of the watersheds. Watersheds R1A and R1B have 4 and 6 stream ponds, respectively, constructed throughout the pasture. No other treatments have stream ponds. Cattle-grazed treatments in Rannell's pasture and Konza Prairie are burned annually during the spring, a common grazing management practice in the Great Plains. The bison and ungrazed watersheds are burned at various time intervals (1, 2, 4, and 20 years) and are designed to represent natural landscape fire dynamics prior to intensive anthropogenic management. All study watersheds correspond to those of Grudzinski-Chapter 2, thus making the link between bare ground and suspended sediment concentrations testable.

Methods

Bare Ground Mapping and Suspended Sediment Collection

We defined bare ground areas as exposed patches of sediment with less than 20% vegetation cover and an area >1 m^2. Bare ground patches consisted of areas that have been extensively forged and trampled, pawed at (potentially for minerals within the soil), or created by wallowing (only bison watersheds contain wallows) (Larson *et al*., 2013). Bare ground patches may also develop naturally on the hillslopes within the landscape due to local variability in soils, nutrient availability, precipitation, sunlight availability, interactions with wildlife, drought conditions, and other erosive forces (i.e. runoff on steep hillslopes).

We used remotely sensed imagery combined with field surveys to classify ground cover and quantify the presence of bare ground. Remote sensing and accompanying spatial analysis have been shown to be efficient and effective at monitoring landscape effects of grazing (Pickup and Chewings, 1994; Washington-Allen *et al*., 2006; Bradley and O'Sullivan, 2011). Remote sensing imagery was downloaded from the State of Kansas Data Access and Support Center (Kansasgis.org). National Agriculture Imagery Program (NAIP) imagery collected by the Farm

Service Agency was selected as it provided the finest spatial and highest spectral resolution imagery for the study area. The most current imagery available was from 2012 and provided 3 visible bands with 1 m^2 spatial resolution. An infrared band from 2006 NAIP images was downloaded and combined with the 2012 imagery to increase the accuracy of the classification. A supervised classification technique using the maximum likelihood algorithm was used, and all land cover was classified based on the Anderson (1976) level one classification scheme with one exception. To accomplish project goals, the barren class was subdivided in order to differentiate between exposed rock and bare ground (Table 3-2). Bare ground overlaying roads was removed prior to analysis as it was not created by grazing. Bare ground patches (>1 m^2 in area) underneath canopy cover and within 10 meters of the streams were mapped in the field with a handheld Trimble GeoXT GPS unit, and area was measured with a rolling field tape. Stream networks were delineated automatically based on hillslope contributing area from a digital elevation model (DEM) using ArcGIS 10.1 software and accuracy was verified in the field. The riparian areas from each stream were surveyed from the base of the watershed to the point where the stream channel became vegetated and terminated into hillslope (Larson *et al*., 2013) in the summer of 2013 from July 3rd to July 17th. A riparian buffer (10 m) and a fence and watershed boundary buffer (50 m) were created in order to capture the high concentrations of bare ground near these features. Riparian analysis included all bare ground within the 10 meter stream buffer and embodied bare ground underneath canopy cover as well as bare ground outside of canopy cover. Riparian area buffers and the fence-watershed buffers were collectively grouped as “attractants”. Bare ground patches were also grouped as either along 1st and 2nd order streams or 3rd and 4th order streams and scaled by stream length following the methods of (Larson *et al.,* 2013). Analysis was completed at the watershed scale (remotely sensed bare ground inside and outside of the riparian zone along with field surveyed bare ground underneath riparian canopy coverage), riparian scale (remotely sensed bare ground within riparian zone and field surveyed bare ground underneath riparian canopy coverage), and a forested riparian scale (only field surveyed bare ground underneath riparian canopy coverage) (n=9) (Fig 3.2).

Bi-monthly water sampling started in May of 2011 and stopped in May of 2012 once stream flow became disconnected due to drought conditions. Baseflow water samples (n=70) were collected when at least one stream within each treatment and at least half of the study streams had connected flow. Although extreme drought was experienced during the sampling period, we were able to collect multiple storm flow samples (n=35) from each treatment using single stage automatic samplers (Vanoni, 2006). The single stage samplers are especially beneficial in flashy streams where an operator cannot be present during a storm to sample sediment (Interagency Committee, 1961). Samples were processed total inorganic solids (TIS, mg/L) and percent organic matter (POM, %) following the guidelines of the American Public Health Association, method 2540 (Eaton *et al*., 2005).

Statistical Analysis

Statistical analysis was completed in R studio (version 3.0.0) and SigmaPlot (version 12.0). Initially an ANCOVA tested for correlation among grazing treatment and burning frequency on bare ground coverage (bare ground area (m^2)/landscape area (m^2)), density of bare ground patches (number of patches/landscape area (m^2)), and mean patch size (m^2). The model determined burn frequency was not a relevant variable (the best fitting model with the lowest AIC did not include burn frequency) thus we moved forward by testing grazing treatment effects on bare ground with an ANOVA (d.f=3). A post hoc Tukey's HSD analysis tested for significant differences among grazing treatments. Data that did not meet statistical assumptions was log transformed. Transformed data that did not meet statistical assumptions was tested with a non-parametric pairwise Kruskal-Wallis test. We used a paired t-test to compare bare ground coverage near attractants to overall watershed scale bare ground coverage (n=9). Paired t-tests were also used to analyze differences in bare ground dynamics between 1st and 2nd order streams to 3rd and 4th order streams (n=9). If data did not meet normality a Wilcoxon signed rank test was applied. An ANCOVA was used to test for relationships between remotely sensed riparian bare ground coverage and grazing treatment to bare ground coverage underneath forested riparian areas. Lastly, linear regression was used to test for relationships between bare ground coverage and baseflow TIS, storm flow TIS, and POM. Data that did not meet normality was log transformed prior to analysis.

Results

The overall accuracy of the land cover classification was 89.6%. Proportions of land cover type within each watershed and riparian buffer are reported in Table 3-3. The majority of land cover within each watershed was classified as grassland, although K20A had more forest cover relative to grassland within the riparian zone, due to the 20 year burn interval that has allowed trees to establish. In all study watersheds, forest cover was significantly higher ($p < .01$; n=9) within riparian areas relative to their overall encompassing watersheds (Fig. 3-3).

Bare Ground Coverage

At the watershed scale, percentage bare ground area (bare ground area (m^2)/watershed area (m^2)*100) was 6.09 times higher ($p < .05$; d.f=1) within grazed treatments relative to ungrazed treatments. Percent bare ground at the watershed scale was highest within bison treatments (2.58%) followed by high density cattle (2.16%), moderate density cattle (1.58%), and ungrazed (.35%) treatments (Table 3-4, Fig. 3-4a). No significant differences in percentage of bare ground among grazing treatments were detected at the watershed scale (p >.10; d.f=3) (Table 3-5).

At the riparian scale, percent bare ground (bare ground area (m^2)/riparian area (m^2)*100) was significantly different (p <.05; d.f=3) among grazing treatments. Percent bare ground within the riparian zone was highest in high density cattle treatments (7.71%), followed by moderate density cattle (2.47%), bison (1.95%), and ungrazed (.84%) treatments (Table 3-4, Fig. 3-4a). Bare ground coverage was 9.18 and 3.95 times higher in high density cattle treatments relative to ungrazed treatments (p <.05) and bison grazed treatments (p <.10) respectively (Table 3-5).

Next we analyzed bare ground coverage that was located explicitly underneath forested riparian areas. Percent bare ground underneath riparian canopy (bare ground area (m^2)/forested riparian area (m^2)*100) was significantly different among grazing treatments (p <.05; d.f=3) and was highest in high density cattle treatments (7.87%), followed by moderate density cattle (1.60%), bison (.23%), and ungrazed (.073%) treatments (Table 3-4, Fig. 3-4a). Moderate density cattle treatments had 7.1 times more bare ground coverage relative to bison treatments however the results were not significant (p >.10). Bare ground coverage was 108 times higher in high density cattle treatments relative to ungrazed treatments (p <.05) (Table 3-5).

Bare Ground Patch Density

The bare ground patch density at the watershed scale (number of patches/watershed area (m^2)*100) was 3.20 times higher (p <.10; d.f=1) within grazed treatments relative to ungrazed treatments. The density of patches was highest within bison (.051) treatments, followed by high density cattle (.034), moderate density cattle (.032), and ungrazed treatments (.012).

The density of bare ground patches within the riparian area (number of patches/riparian area (m^2)*100) was significantly different among grazing treatments (p <.05; d.f=3). The highest density of patches was within high density cattle treatments (1.41) followed by bison (1.06), moderate density cattle (.99), and ungrazed (.42) treatments. The density of patches was 2.52 times higher (p <.10) within bison treatments and 3.36 times higher (p <.05) within high density cattle treatments relative to ungrazed treatments.

The density of bare ground patches underneath riparian canopy (number of patches/ riparian forest area (m^2)*100) had highly significant differences (p <.001; d.f.=3) among grazing treatments. Bare ground patches were densest within high density cattle grazed treatments (1.53) followed by moderate density cattle (.72), bison (.24), and ungrazed (.10) treatments. High density cattle grazed treatments had a patch density that was 2.13, 6.38, and 15.3 times higher relative to moderate density cattle, bison, and ungrazed treatments respectively (p <.01). Moderate density cattle treatments had a patch density that was 7.2 times higher than ungrazed treatments (p <.01) and 3.0 times higher than bison-grazed treatments (p <.05) (Table 3-4 & 3-5, Fig. 3-4b).

Average Patch Size

Average patch size (m^2) at the watershed scale was 1.9 times higher (p <.05; d.f.=1) within grazed treatments relative to ungrazed treatments. Average patch size was highest within high density cattle treatments (63.1 m^2) followed by bison (45.8 m^2), moderate density cattle (44.7 m^2), and ungrazed (26.9 m^2) treatments. Average patch size was 2.4 times larger within high density cattle treatments relative to ungrazed treatments (p <.10).

Average patch size (m^2) within riparian areas was marginally different (p <.10; d.f.=3) among grazing treatments. Patches were largest in high density cattle treatments (55.1 m^2), followed by moderate density cattle (24.0 m^2), bison (19.6 m^2), and ungrazed (19.2 m^2)

treatments. Patch size was 2.3 and 2.9 times larger within high density cattle and moderate density cattle treatments relative to ungrazed treatments (p<.10).

Average patch size (m^2) under riparian canopy was marginally different (p <.10; d.f.3) among grazing treatments and was highest in high density cattle treatments (50.9 m^2), followed by moderate density cattle (21.9 m^2), bison (9.4 m^2), and ungrazed (5.14 m^2) treatments. Patch size was 9.9 and 2.3 times larger within high density cattle treatments relative to ungrazed and moderate density cattle-grazed treatments (p <.10) (Table 3-4 & 3-5, Fig. 3-4c).

Bare Ground Distribution

Bare ground coverage was 9.2 times higher (p <.01; d.f.=1) along attractants (ridges, fence lines, and streams) within grazed watersheds relative to ungrazed watersheds. Grazed areas near attractants also had 2.14 times more bare ground coverage relative to their overall bare ground coverage at the watershed scale (p <.01; n=6). Relative to 1st and 2nd order streams riparian areas adjacent to 3rd and 4th order streams had 4.0 times more bare ground (p <.05; n=9), a density of bare ground patches 3.4 times higher (p <.01; n=9), and patches that were 1.4 times larger (p <.01; n=9) (Table 3-6, Fig. 3-5).

Predicting Bare Ground Coverage Under Riparian Canopy

Grazing treatment and remotely sensed riparian bare ground coverage was significantly related to bare ground coverage underneath riparian canopy (p <.01, d.f.=4) (Fig. 3-6). Grazing treatment was a slightly stronger predictor than remotely sensed bare ground (R^2 = 49.52 and 47.79 respectively).

Bare Ground and Suspended Sediment Dynamics

Baseflow TIS (mg/L) was positively related to riparian scale bare ground coverage (p <.05) and forested riparian bare ground coverage (p <.05). Baseflow TIS was not significantly related to watershed scale bare ground coverage ($p > .10$). Storm flow TIS (mg/L) significantly increased with watershed scale bare ground coverage ($p < .01$), and marginally increased with riparian scale bare ground coverage ($p < .10$). Storm flow was not significantly related to forested riparian bare ground coverage ($p > .10$). POM was significantly related to riparian scale bare ground coverage ($p < .05$), forested riparian bare ground coverage ($p < .05$), and marginally related to watershed scale bare ground coverage ($p < .10$) all in the negative direction (Fig. 3-7).

Discussion

As expected, ungrazed treatments had the least bare ground coverage, fewest bare ground patches, and smallest mean bare ground patch size at the watershed, riparian, and forested riparian scales. High density cattle treatments had the most degraded riparian areas, especially underneath canopy cover. In forested riparian areas, moderate density cattle treatments had over 7 times more bare ground area relative to bison treatments although significant differences were not detected. Average bare ground coverage within high density cattle treatments was 3.11 (riparian areas) and 4.43 (forested riparian areas) times higher than in moderate density cattle-grazed treatments, however, significant differences were also not detected. The differences between the aforementioned tests were likely not significant due to the small number of replicates within each treatment (2 or 3) and relatively high within treatment variance. A more robust sampling design may reveal if the trends observed are significantly different, however access to similar grazing treatments and watershed characteristics make this prohibitively difficult.

The differences in the coverage and position of bare ground patches between bison and cattle-grazed treatments are likely due to physiological and behavioral differences between grazer species. Specifically, bison-grazed treatments contained minimal bare ground underneath riparian canopy cover but had a large percentage of bare ground at the watershed scale due to wallowing (Grudzinski, personal observation), a behavior not exhibited by cattle. Bison may be avoiding canopy coverage as indicated by Larson *et al*. (2013) potentially due to lower availability of grasses and decreased demand for thermal relief (Allred *et al*., 2013). Both cattle and bison increased impacts near attractants including fence lines (Fig. 3-8) and ridges located at the tops of watersheds. Higher bare ground coverage, increased density of bare ground patches, and larger bare ground patch size indicate that cattle and bison are creating more detrimental impacts along 3rd and 4th order stream corridors relative to those adjacent to 1st and 2nd order streams. The favorable habitat in the lower portions of the watersheds may be due to larger water sources and wider floodplains with lower slopes. Cattle are also likely taking advantage of increased canopy coverage for thermal relief.

In our study we observed high concentrations of bare ground and rock exposure near cattle ponds (Fig. 3-8). Cattle spend time in and around stream ponds for drinking water (Campbell *et al*., 2009) and thermal relief, especially in areas of low discharge with minimal canopy cover. By standing in the ponds, cattle increase sediment loads through resuspension from trampling and nutrient and E.coli loads from depositing waste into the water. Cattle that drink the polluted water increase their chances for disease spread and illness, have less weight gain due to physiological stresses, and increase their probability of death (Willms *et al*., 2002). During times of intermittent flow, freshwater springs and permanent pools may also be experiencing increased cattle presence.

Our results reveal the connection and complex dynamics between bare ground coverage at various scales (watershed, riparian, and forested riparian) and fluvial suspended sediment concentrations at various flow regimes (baseflow and storm flow). Bare ground coverage significantly increases TIS concentrations at both baseflow and storm flow conditions while decreasing POM. TIS at baseflow was best predicted by riparian scale bare ground coverage, while TIS at storm flow was best predicted by watershed scale bare ground coverage. Riparian scale bare ground coverage may be a better predictor for TIS at baseflow since it may be representative of the intensification of pressure on water sources during baseflow conditions. Ungulate dependence on riparian zones is highest during the hottest and driest times of the year which are also coincident with baseflow periods. Treatments that have the highest percentages of bare ground in their riparian zones are most likely to have ungulates within the stream during baseflow sampling thereby increasing the sediment concentration during collection. TIS at storm flow is likely more closely related to watershed scale bare ground coverage due to runoff delivering sediment from outside of the riparian zone. This is most evident by the large spike in TIS within bison-grazed watersheds which have the highest bare ground coverage at the watershed scale while retaining low TIS concentrations at baseflow which correspond with low riparian and forested riparian bare ground coverage.

Riparian trees are often viewed as a source of streambank stabilization and beneficial to water quality (Wynn and Mostaghimi, 2006; Laub *et al*., 2013). Within the grasslands of the Great Plains (Briggs *et al*., 2002) and those around the world (Heisler *et al*., 2004) stream riparian areas have experienced shrub and tree encroachment due to fire suppression (Briggs *et al*., 2005) thereby increasing shade adjacent to streams (Veach *et al.,* 2014). Our study suggests that canopy cover within riparian areas of cattle-grazed watersheds may be driving increased bare ground coverage and availability of easily erodible sediment sources near the stream thereby increasing sediment inputs from the hillslope. Previous studies have indicated that alternative shade and water sources can decrease the amount of time grazed within riparian zones

(Godwin and Miner, 1996; Agouridis *et al*., 2005; Tomkins and O'Reagain, 2007). Providing shade shelters and watering tanks away from stream channels may be an effective means of decreasing riparian and in-stream cattle impacts, particularly during summer months.

Bare ground coverage is likely to increase in grazed watersheds given that climate models predict that the Great Plains will experience increases in temperature over the next several decades (Brunsell *et al*., 2010; Patricola and Cook, 2013). With higher temperatures cattle and bison will likely increasingly seek shade and water within riparian zones and streams over the next several decades, on both daily (earlier in the day) and annual (earlier in the year) time scales, thereby increasing suspended sediment concentrations and magnifying already existing water problems in grassland regions.

Finally, the strong correlation with grazing treatment and remotely sensed riparian bare ground coverage with forested riparian bare ground coverage shows that we can remotely calculate bare ground coverage underneath forested riparian areas with a high degree of accuracy. Thus, remote sensing methods and land use data can reduce the need for extensive field work which often proves to be impractical, time consuming, and expensive.

Conclusions

Grazing significantly increased bare ground coverage, density of bare ground patches, and bare ground patch size. Bison-grazed treatments have the highest percentage of watershed scale bare ground although the values are not significantly different from other grazing treatments. High intensity cattle grazing contained the most severe levels of riparian degradation by significantly increasing bare ground coverage, especially underneath forested riparian areas. In grazed treatments, a majority of bare ground was located near fence lines, watershed boundaries, and 3rd and 4th order stream segments. TIS concentrations at baseflow are best predicted by riparian scale bare ground coverage, while TIS concentrations at storm flow are best predicted by watershed scale bare ground coverage. Riparian fencing, alternative water sources, or shading structures may be essential to allow vegetation to reestablish adjacent to cattle-grazed streams.

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Figures

Figure 3-1 Paired watershed study design and remotely sensed land cover classification. N watersheds are bison-grazed, K are ungrazed, C are moderate density cattle-grazed (grazing density is equivalent to bison-grazed treatments). R watersheds are high density cattle-grazed (grazing density is 3.3 times higher than in C watersheds). Burn intervals are identified by the number following the first letter within each watershed. All watersheds are located within Konza Prairie other than R1A and R1B which are both within Rannell's Pasture.

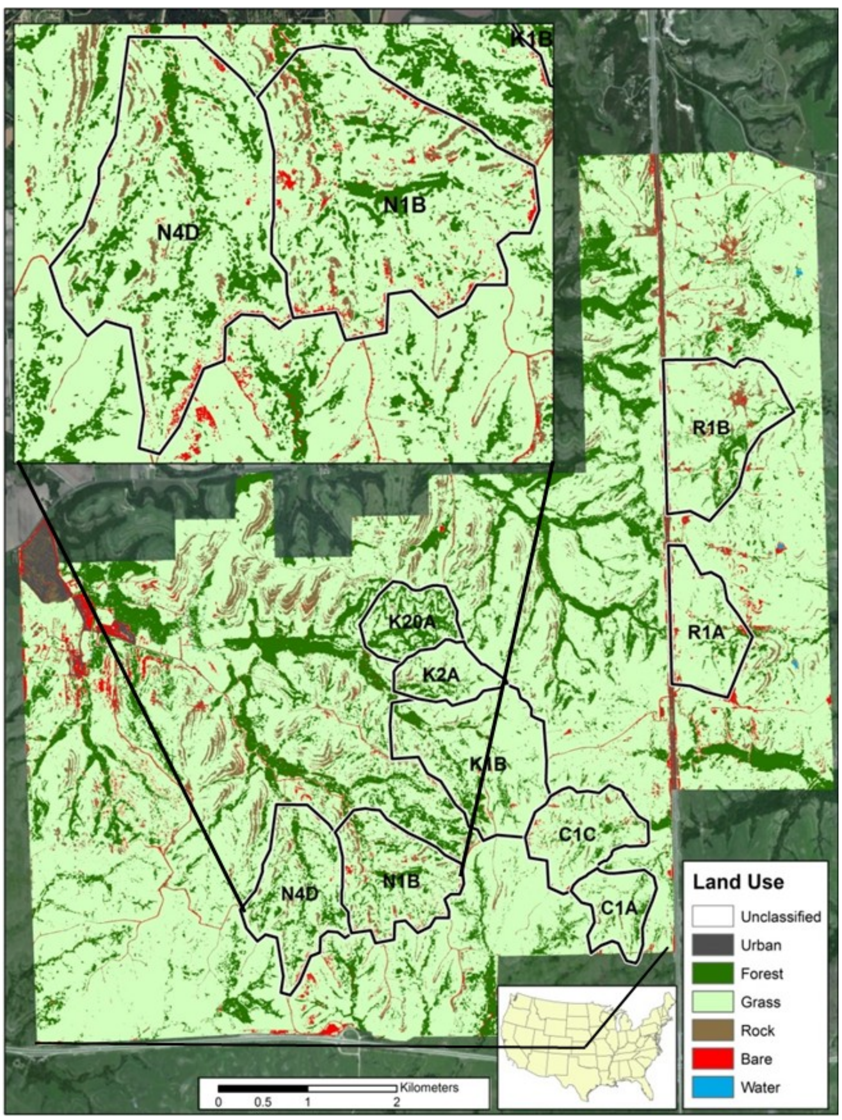

Figure 3-2 Bare ground underneath canopy cover within the riparian zone (A), bare ground within the riparian zone and outside of canopy cover (B), and bare ground in the form of a bison wallow outside of the riparian zone (C).

Figure 3-3 Percent forest cover within each watershed and riparian buffer.

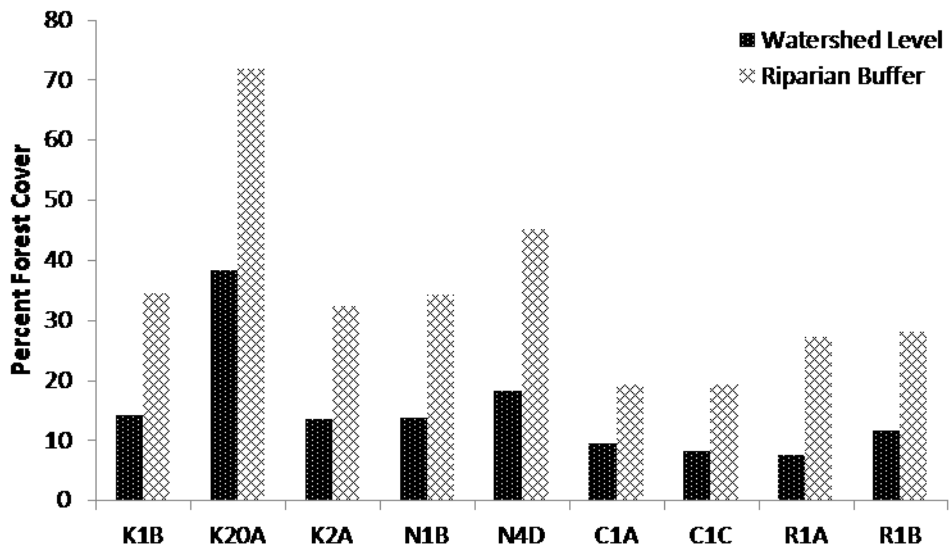

Figure 3-4 Bare ground patch dynamics grouped by grazing treatments.

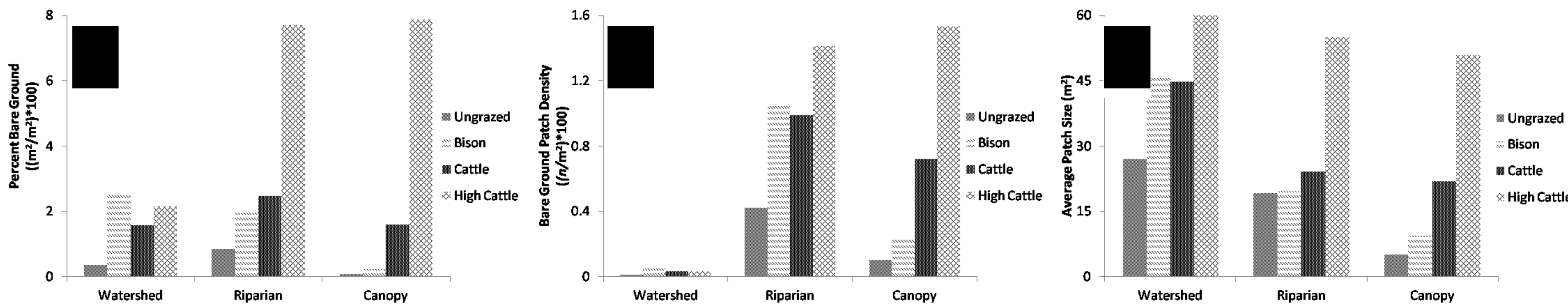

Figure 3-5 Comparison of 1st and 2nd order streams to 3rd and 4th order streams (n=9).

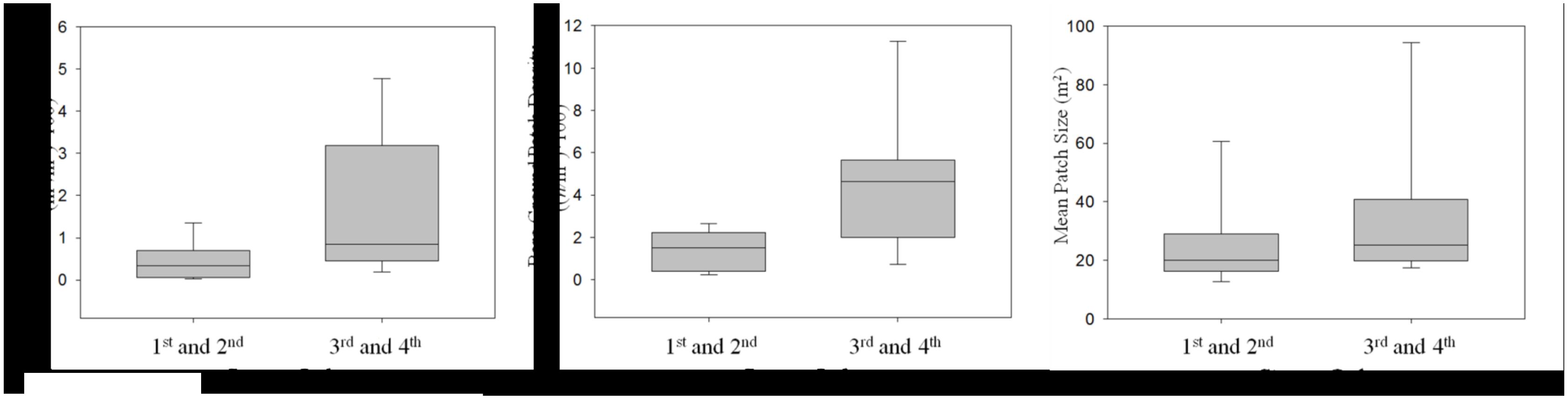

Figure 3-6 Relationship between remotely sensed riparian bare ground coverage with forested riparian bare ground coverage.

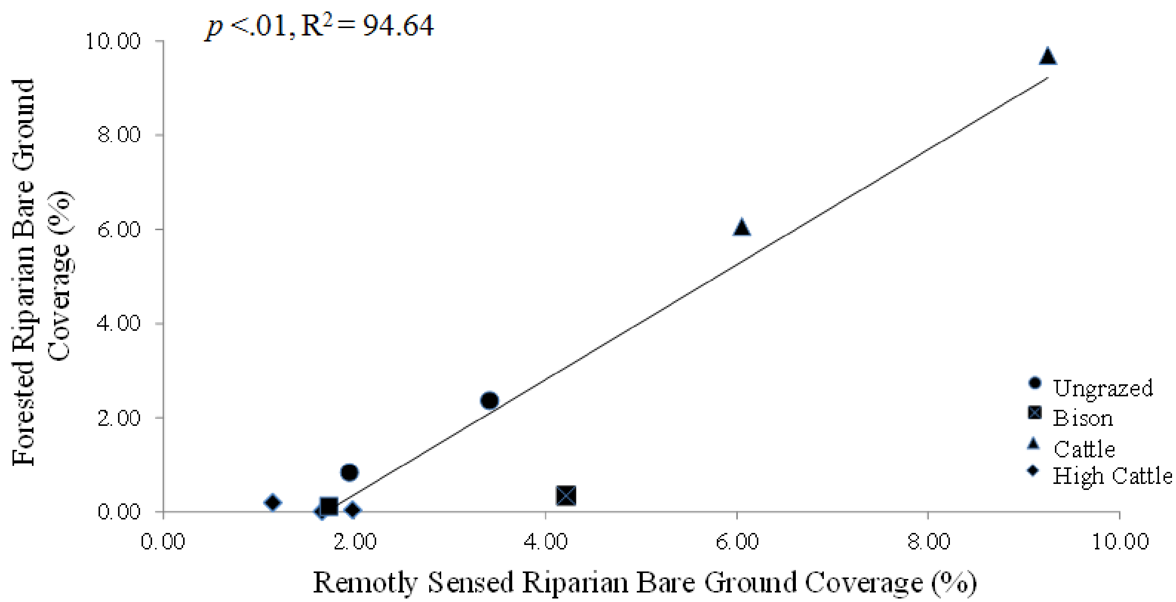

Figure 3-7 Relationship between bare ground coverage and stream suspended sediment dynamics.

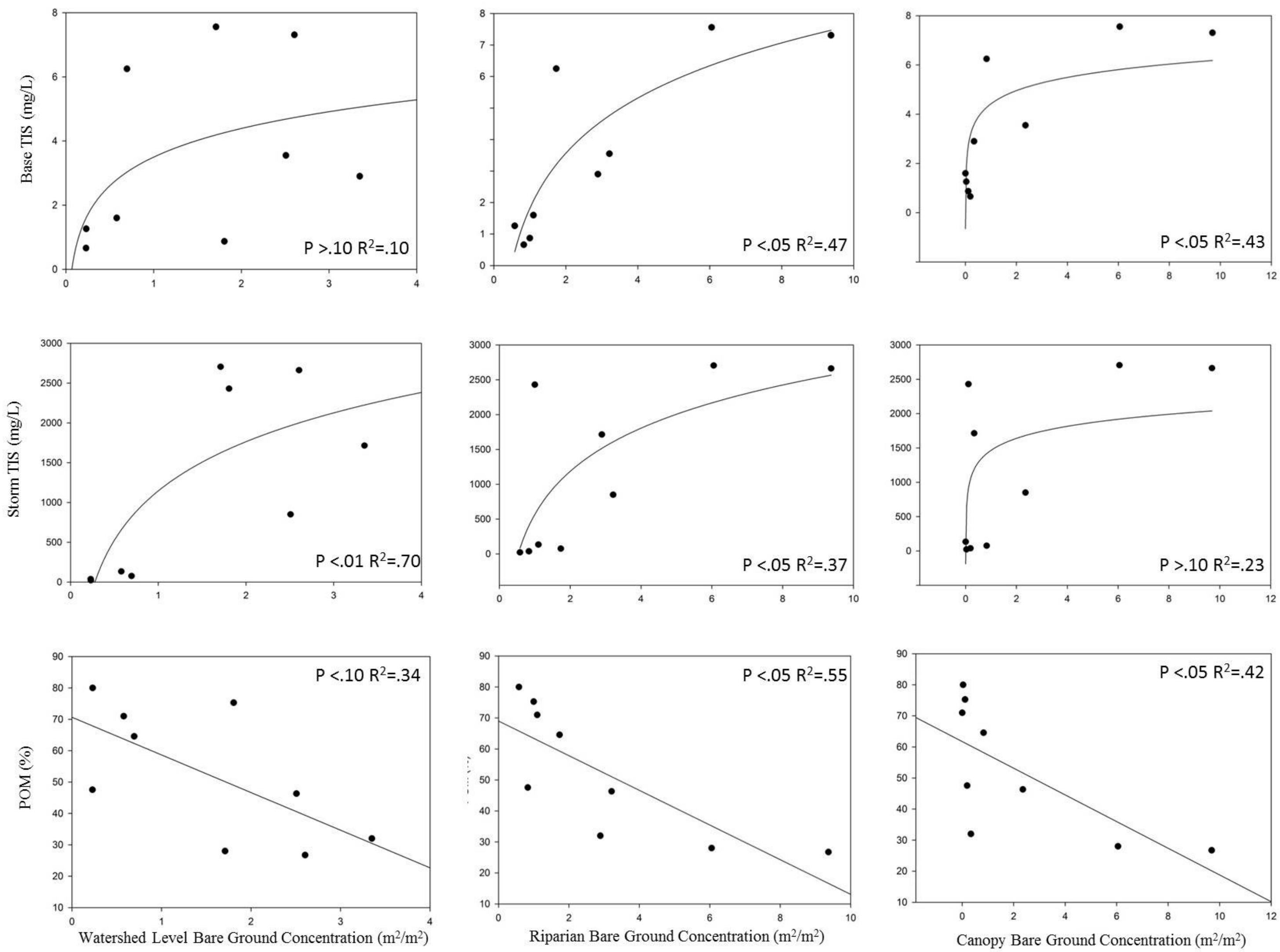

Figure 3-8 Bare ground and rock exposure near water sources and fence lines.

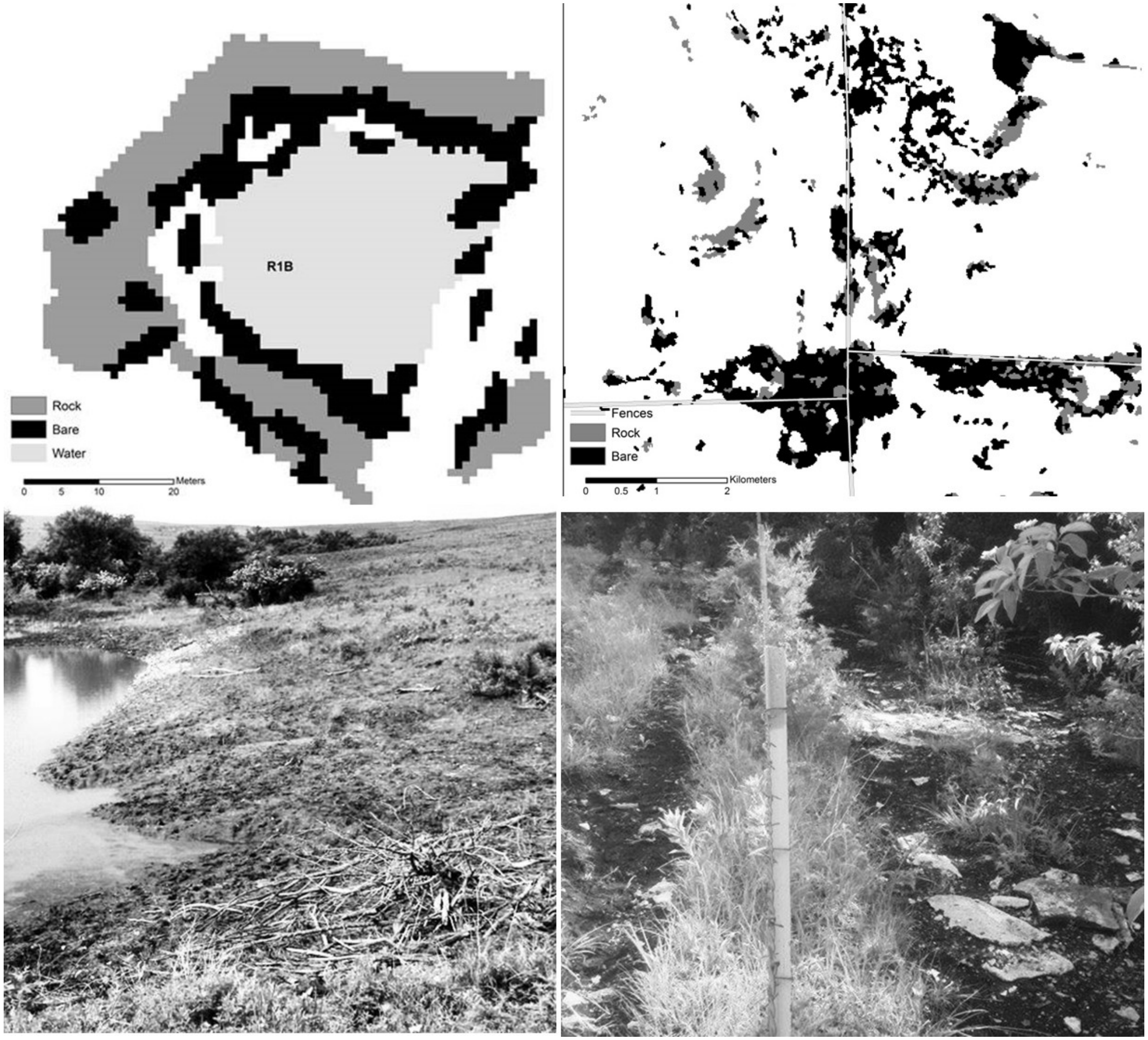

Table 3-1 Watershed characteristics. Burn frequency represents the number of times each watershed was burned from 1990 to 2010 and includes both prescribed and wild fires.

Watershed	Treatment	Grazing Density (ha/AU)	Grazing Season (months)	Area (ha)	Burn Frequency (1990-2010)	Drainage Density (m/m^2)	Elevation (m)	Slope (%)	Sinuosity (m/m)
K1B	Ungrazed	NA	None	412	20	0.0062	374	2.7	1.31
K2A	Ungrazed	NA	None	119	12	0.0061	371	3.75	1.11
K20A	Ungrazed	NA	None	146	1	0.0059	363	3.74	1.28
N1B	Bison	4.5	Year Round	287	22	0.006	376	3.53	1.21
N4D	Bison	4.5	Year Round	301	6	0.0055	365	2.9	1.15
C1A	Cattle	4.0	May-Oct	126	15	0.005	404	3.37	1.19
C3C	Cattle	4.0	May-Oct	186	19	0.0067	401	2.66	1.18
R1A	Cattle	1.2	May-Oct	225	21	0.0051	386	2.54	1.22
R1B	Cattle	1.2	May-Oct	390	21	0.0054	378	1.89	1.37

Table 3-2 Remote sensing classification scheme, modified from Anderson (1976).

Class	Description	Definition
1 Urban	Urban/Built Up	Comprised of areas of intensive use with much of the land covered by structures and roads.
2 Forest	Forested Land	Forest Lands have a tree-crown areal density of 10 percent or more and exert an influence on the climate or water regime.
3 Grassland	Rangeland	Land where the potential natural vegetation is predominantly grasses, grass like plants, forbs, or shrubs and where natural herbivory was an important influence in its pre-civilization state.
4 Rock	Barren Land	Barren Land is land of limited ability to support life and in which less than one-third of the area has vegetation or other cover.
5 Bare Ground		
6 Water	Water	All areas within the land mass that persistently are water covered.

Table 3-3 Percentage of land cover type within each watershed (top) and riparian buffer (bottom).

	Watershed Level Land cover (%)					
Watershed	Urban	Forest	Grass	Rock	Bare	Water
K1B	<0.1	14.1	81.9	2.9	1.1	0.0
K20A	0.0	38.2	59.1	2.4	0.4	0.0
K2A	0.0	13.5	82.7	3.6	0.3	0.0
N1B	0.0	13.7	74.4	7.1	4.8	<0.1
N4D	0.0	18.1	74.4	4.9	2.6	0.0
C1A	<0.1	9.3	87.1	2.8	0.8	0.0
C1C	<0.1	8.1	84.1	4.7	3.1	0.0
R1A	0.0	7.5	87.7	1.9	3.0	0.0
R1B	0.0	11.6	81.3	5.5	1.6	<0.1

	Riparian Land Cover (%)					
Watershed	Urban	Forest	Grass	Rock	Bare	Water
K1B	0.0	34.3	63.7	0.9	1.1	0.0
K20A	0.0	71.8	27.5	0.1	0.6	0.0
K2A	0.0	32.1	65.9	1.2	0.8	0.0
N1B	0.0	34.1	59.0	4.2	2.8	0.0
N4D	0.0	45.1	52.7	1.3	1.0	0.0
C1A	0.0	19.2	77.5	1.8	1.6	0.0
C1C	0.0	19.1	75.7	2.4	2.8	0.0
R1A	0.0	28.1	66.9	1.1	3.9	0.0
R1B	0.0	27.8	62.1	5.2	4.4	0.5

Table 3-4 Summary of bare ground patch dynamics grouped by watershed, riparian, and forested riparian (canopy) areas.

		Bare Ground Area (%)			Patch Density ((n/m^2)*100)			Patch Size (m^2)		
Site	Treatment	Watershed	Riparian	Canopy	Watershed	Riparian	Canopy	Watershed	Riparian	Canopy
K1B	Ungrazed	0.58	1.10	<0.01	0.015	0.50	0.01	39.50	21.55	1.00
K20A	Ungrazed	0.23	0.58	0.03	0.012	0.30	0.06	18.01	18.57	5.67
K2A	Ungrazed	0.23	0.83	0.19	0.010	0.46	0.22	23.31	17.51	8.75
N1B	Bison	3.35	2.89	0.34	0.074	1.30	0.36	45.02	21.78	9.35
N4D	Bison	1.81	1.00	0.11	0.028	0.82	0.12	46.60	17.49	9.43
C1A	Moderate Cattle	0.66	1.73	0.83	0.020	0.74	0.71	33.83	22.77	11.71
C1C	Moderate Cattle	2.51	3.21	2.36	0.045	1.24	0.73	55.61	25.32	32.13
R1A	High Cattle	2.61	9.37	9.69	0.035	1.33	1.62	74.76	70.23	59.69
R1B	High Cattle	1.71	6.05	6.05	0.033	1.49	1.44	51.44	40.03	42.04

Table 3-5 Statistical summary (d.f.=3) and post hoc treatment comparisons of bare ground patch dynamics. U, B, MC, and HC respectively represent ungrazed, bison, moderate density cattle, and high density cattle treatments.

	Percent Bare Ground Area			Patch Number			Patch Size		
	Watershed	Riparian	Canopy	Watershed	Riparian	Canopy	Watershed	Riparian	Canopy
Summary	>.10	**<.05**	**<.05**	>.10	**<.05**	**<.001**	**<.05**	**<.10**	**<.10**
U-B	NA	>.10	>.10	NA	**<.10**	>.10	>.10	>.10	>.10
U-MC	NA	>.10	>.10	NA	>.10	**<.01**	>.10	**<.10**	**<.10**
U-HC	NA	**<.05**	**<.05**	NA	**<.05**	**<.001**	**<.10**	**<.10**	**<.10**
B-MC	NA	>.10	>.10	NA	>.10	**<.05**	>.10	>.10	>.10
B-HC	NA	**<.10**	>.10	NA	>.10	**<.001**	>.10	>.10	>.10
MC-HC	NA	>.10	>.10	NA	>.10	**<.01**	>.10	>.10	>.10

Table 3-6 Comparison of patch distributions between 1st and 2nd order streams to 3rd and 4th order streams (n=9).

	Percent Bare Ground ((m/m)*100)	Patch Density ((*n*/m)*100))	Mean Patch Size (m^2)
Model *p* Value	**0.0148**	**0.0078**	**0.0080**
1st and 2nd order	0.422	1.36	25.09
3rd and 4th order	1.694	4.56	34.28

Chapter 4 - Impact of watershed grazing management on grassland headwater stream geomorphology

Abstract

Despite extensive research on the environmental influences of livestock grazing within fluvial systems, a comprehensive evaluation of the relative geomorphic impacts produced by various grazing treatments, including non-native cattle and native bison, on grassland streams has yet to be completed. The purpose of this study is to determine the long and short term effects of large ungulate grazing on grassland stream geomorphology. Impacts were evaluated over a three year period using a replicated, watershed-level study design. Channel geometry and bed particle size were measured at the reach scale within each watershed by surveying permanently installed cross sections and completing Wolman pebble counts. Channel geometry and pebble sizes were first measured in the summer of 2010 and channel geometry was resurveyed in 2011 and 2012 for annual comparisons. Widths, depths, and width to depth ratios were not statistically different between grazing treatments. Smaller streams appear to be more severely impacted by grazing relative to larger streams. D_{16} particle sizes are larger within grazed treatments, particularly within smaller streams relative to ungrazed treatments, while D_{50} and D_{84} particle sizes are similar among grazing treatments. Generally, grazed streams widened while ungrazed streams narrowed over the study period. Significantly more widening occurs within newly cattle-grazed streams relative to long term cattle-grazed streams. Low flow conditions produced by drought result in stream bed aggradation throughout most of the study sites. In some instances, significant geomorphic changes in one direction (i.e widening) in one year show significant geomorphic changes in the opposite direction (i.e narrowing) the following year, indicating that

drawing conclusions on geomorphic impacts from short term studies may be misleading and not representative of long term trends.

Introduction

Livestock grazing is a dominant land use practice throughout grassland ecoregions (Yisehak *et al.,* 2013; Di Bella *et al*., 2014) and is very prevalent in remnants of U.S. native Great Plains prairies (Knapp *et al*., 1998; Steuter and Hidinger, 1999). Despite the significant grazing pressure on these grassland ecosystems, little is known about the impacts of cattle and other large ungulates, such as native bison, on grassland stream geomorphlogy (Knapp *et al*., 1998; Steuter and Hidinger, 1999; Larson *et al*., 2013). Studies in other ecoregions have shown cattle grazing to be one of the most detrimental land use practices in riparian zones (Krueper, 1996; Trimble and Mendel, 1996), with impacts including but not limited to, increased sediment and nutrient loading (Tufekcioglu *et al*., 2013), loss of habitat for native flora and fauna (Richter *et al*., 1997), and stream eutrophication (Maasri and Gelhaus, 2011). However, previous research of grazing impacts on stream morphology has produced several contradictory results (from no impacts to severe impacts) and employed a wide range of experimental and observational approaches (e.g. George *et al.,* 2002; Zaimes *et al*., 2008; Lucas *et al.,* 2009; Strauch *et al*., 2009), making generalizations about grazing impacts difficult, particularly when extending into previously unstudied ecoregions. Furthermore, many studies examining grazing impacts on stream geomorphology have consisted of non-replicated or controlled treatments and have been completed within short time frames (from 5 years to as short as 20 days) (e.g. Smith *et al*., 1993; Allen Diaz *et al*., 1998; Lucas *et al*., 2009). Most commercial cattle grazing operations differ from these short term studies in that they apply cattle to the land for the duration of spring and summer and often the same land is grazed every single year for decades and perhaps centuries (Owensby *et al*., 2008).

Significant geomorphic influences resulting from cattle grazing include: decreased hillslope soil porosity (Cluzeau *et al*., 1992), decreased infiltration rates resulting in increased runoff (Gifford and Hawkings, 1978), destabilized stream banks with increased erosion potential (Platts, 1991; Myers and Swanson, 1995), and broken-up sediment clusters and armor layers on stream beds (Trimble and Mendel, 1996). Rapidly eroding stream banks increase channel widening thereby producing increased fluvial sediment loads that lead to high turbidity, increased water temperatures, lower dissolved oxygen levels (Krueper, 1996; Trimble and Mendel, 1996), and generally reduce ecosystem services such as wildlife habitat, water purification, and biodiversity maintenance (Magilligan and McDowell, 1997).

Although some studies have begun to evaluate ecological differences between cattle and other ungulates such as bison (Knapp *et al*., 1999; Steuter and Hidinger, 1999; Allred *et al*., 2013) the impacts related to aquatic systems and fluvial geomorphology remain largely unknown. Behavioral ecology studies have demonstrated that cattle spend more time grazing than bison, especially within riparian zones and near sources of water due to their lower physiological heat tolerance, higher demand for drinking water and shade, and preference for woody vegetation such as forbes, which are common in riparian areas (Allred *et al*., 2013; Kohl *et al*., 2013). Because cattle spend more time within riparian zones and are more likely to move in and out of the stream multiple times a day, they are likely to influence channel and near-channel geomorphology more than bison.

The purpose of this study is to determine the relative long term and short term impacts of cattle and bison grazing on grassland stream geomorphology by comparing a number of carefully controlled and replicated watershed treatments. We test the following hypotheses regarding grazing impacts on grassland channel geomorphology: 1) width to depth ratios (w:d) will be greatest in long-term cattle-grazed watersheds, followed by bison, and ungrazed treatments due to increased channel widening based on relative grazing time in riparian zones, 2) stream substrates will contain the highest proportion of fines in cattle-grazed watersheds, followed by bison and ungrazed watersheds, due to the breakup of sediment clusters and imbrications layers from stream bed trampling, 3) channel geometry will change rapidly upon introduction of cattle grazing to previously ungrazed watersheds, followed by lower rates of change in long-term grazed cattle watersheds, and minimal change will occur in bison and ungrazed watersheds. To our knowledge, this is the first study to quantitatively assess the relative impacts of two large herbivores (cattle and bison) on stream geomorphology in any ecoregion, and the first to assess cattle grazing impacts in a replicated, watershed-scale study.

Study Area

This study was completed in the Flint Hills ecoregion which contains the largest continuous extent of unplowed tallgrass prairie within the United States. The Flint Hills have avoided intensive crop development common in surrounding grasslands, largely due to the prevalence of shallow and rocky soils and high relief, thereby creating an environment that is difficult to plow and thus more favorable towards grazing (Anderson and Fly, 1955). The climatic characteristics along with fire and grazing have prevented extensive forests from developing within the ecoregion (Bachelet *et al.,* 2000). Modern controlled fire regimes suppress tree growth throughout uplands but are less effective in riparian zones and have resulted in the establishment of riparian gallery forests in many areas (Veach *et al*., 2014). Annual precipitation averages 835 mm, but is highly variable from year to year. Approximately 75% of precipitation falls from May to October, and June is usually the wettest month. Average temperatures range from -2° C in January to 27° C in July. The geology within the study area consists of alternating layers of soft shales and harder limestones. Soils within the study area have textures consisting of primarily clay loams and silty clay loams, and the dominant grassland species include big bluestem (*Andopogon gerardii*), little bluestem (*A. Scoparius*), Indian grass (*Sorgastrum nutans*), and switch grass (*Panicum virgatum*) (Freeman and Hulber, 1985; Briggs and Knapp, 1995).

The study watersheds are located within Konza Prairie Biological Station and Rannell's Pasture (Figure 4-1, Table 4-1). The flow regime within these intermittent headwater steams is highly variable from year to year, and commonly includes periods of no flow from late summer to early spring. During our study period, drought occurred resulting in lower than average monthly discharge, and annual cessation of flow occurred by July each year (Figure 4-2). Only June of 2011 exhibited above average mean monthly discharge during the study period.

Konza Prairie and Rannell's Pasture are both designed for grassland research and are managed at the watershed scale by Kansas State Universities Division of Biology and Department of Agronomy, respectively. On Konza Prairie, cattle are seasonally stocked from May to November at a moderate density of 4 ha per animal, and bison are stocked year round at 4.5 ha per animal (Towne, 1999; Blair, 2008). Both grazing densities are designed to remove 25% of net primary productivity. Rannell's Pasture is managed similarly to private rangelands in the Flint Hills and consists of intensive seasonal cattle stocking from May 1st to July 1st at 0.81 ha per animal, after which half the cattle are removed, resulting in a grazing density of 1.6 ha per animal from July 1st to October 1st, when all remaining cattle are removed (Owensby *et al*., 2008). The average grazing density at Rannell's Pasture is 3.3 times higher than that of Konza Prairie. Both study sites are burned in the spring. Watersheds at Konza Prairie are burned at 1, 2, 4, and 20 year intervals in order to mimic interactions between grasslands and fire prior to intensive land management following European settlement, while watersheds within Rannell's Pasture are burned annually and represent common burning practices of rangelands within the surrounding area. Due to replicated watershed-level grazing management at both sites, a unique experimental design is available for comparison of grazing impacts between equivalent densities of bison and cattle.

The sampling design consisted of thirteen watersheds and contained: one seasonally stocked, moderate density cattle-grazed watershed (C1C), two seasonally stocked, high density cattle-grazed watersheds (R1A, R1B), three permanently stocked, bison-grazed watersheds (N1B, N2B, N4D), and seven ungrazed watersheds (K1B, K2A, K20A, C3SA, C3SB, C3SC, C3SM). In 2011 the four ungrazed C3S watersheds became seasonally stocked, moderate density cattle-grazed treatments. Prior to the change in land management in 2011, the C3S watersheds had been ungrazed since at least 1980. All other watersheds had the current grazing management since at least 1980.

Methods

Channel geometry was measured at the reach scale within each watershed by establishing permanent cross sections and topographically surveying each cross section with a surveyor's level and leveling rod. Active channel width was defined as the distance from the top of the lower bank to the equivalent elevation on the opposite bank. Top of bank was identified primarily by a break in bank slope and changes to perennial vegetation (Harrelson *et al*., 1994). Spacing between cross sections was about 10 m. Channels (n=13) were originally surveyed starting in the summer of 2010 (baseline) and were resurveyed in 2011 and 2012 for annual comparisons (Figure 4-3 a,b). Based on the channel surveys, we calculated the average width, depth, and w:d for each stream. In 2010, standard 100 pebble Wolman counts were completed just downstream of each cross section survey in order to determine bed particle size distributions (Wolman, 1954) (Figure 4-3c). $D_{16,}$ $D_{50,}$ and, D_{84} were calculated for each cross section and averaged for each stream.

Statistical Analysis

To enable cross watershed comparisons of grazing impacts, channel width, depth, and w:d were scaled by watershed area. Long term grazing impacts on channel geometry (width, depth, and w:d) and pebble size ($D_{16,}$ $D_{50,}$ and, D_{84}) were analyzed with ANOVA. Influences of watershed area (ha) and burn frequency (times burned from 1990-2010) were tested with regression analysis. Data that did not meet statistical assumptions was log transformed. If data did not meet statistical assumptions following transformation, it was analyzed with a non-parametric Kruskal-Wallis ANOVA (for categorical data) or a non-parametric Spearman Correlation test (for continuous data). Annual changes in width, depth, and w:d were analyzed from 2010 to 2011, 2011 to 2012, and 2010 to 2012 using paired t-tests. Data which did not meet statistical assumptions was tested with a Wilcoxon signed rank test. Differences in annual changes in width, depth, and w:d among grazing treatments were tested with ANOVA. Data that did not meet statistical assumptions was log transformed. If data did not meet statistical assumptions following transformation, it was analyzed with a non-parametric Kruskal-Wallis ANOVA.

Results

Following consistent land use management since at least 1980, stream width, depth, and w:d were not significantly different between grazing treatments (p>.10; d.f.=2) (Figure 4-4). Within ungrazed treatments, stream width (p<.05), depth (p>.10), and w:d (p<.05) increased with watershed area. Within grazed treatments, stream width (*p*>.10), depth (*p*>.10), and w:d (*p*>.10) decreased with watershed area (Figure 4-4). Within ungrazed streams width and w:d increased with burn frequency (*p*<.10) Statistical relationships between burn frequency while within grazed treatments depth increased significantly with burn frequency (Figure 4-5).

D_{16} was about 1.16 times larger (*p*<.10; d.f.=1) within grazed streams relative to ungrazed streams and significantly decreased (*p*<.05) with watershed area within grazed streams. D_{50} and D_{84} values did not significantly vary among grazing treatments (*p*>.10; d.f.=2) and were not significantly related to watershed area (*p*>.10) (Figure 4-6). No significant differences in D_{16}, D_{50}, or D_{84} were detected between cattle and bison grazed treatments (*p*>.10; d.f.=2).

Overall, average stream width marginally decreased (*p*=.10; n=13) from 2010 to 2011, significantly increased (*p*<.01; n=13) from 2011 to 2012, and showed no significant changes (*p*>.10; n=13) from 2010 to 2012 (Figure 4-7). From 2010 to 2012, eleven of the thirteen streams increased in width and two decreased (Table 4-2). Of the eleven streams that increased in width, five increases were significant (*p*<.10) and they were all within grazed treatments (N4D, N1B, C3SA, C3SB, and C3SC), while one stream significantly decreased in width (*p*<.10) and it was ungrazed (K1B) (Table 4-3).

Overall, average stream depth showed no significant changes (*p*>.10; n=13) from 2010 to 2011, marginally decreased (*p*<.10; n=13) from 2011 to 2012, and marginally decreased (*p*<.10; n=13) from 2010 to 2012 (Figure 4-7). From 2010 to 2012, eleven of the thirteen streams decreased in depth (Table 4-2) and four of the decreases (K20A, K2A, C1A, R1) were significant (*p*<.10). No significant increases in depth from 2010 to 2012 were detected (Table 4-3).

Overall, average stream w:d did not significantly change (*p*>.10; n=13) from 2010 to 2011, 2011 to 2012, or 2010 to 2012 (Figure 4-7). From 2010 to 2012, eleven of the thirteen streams increased in w:d (Table 4-2) and three of the increases (K2AM, K20A, R1A) were significant ($p<.10$). No significant decreases in stream w:d from 2010 to 2012 were detected (Table 4-3).

No significant changes ($p>.10$; d.f.=2) in width were found among grazing treatments from 2010 to 2011 or 2011 to 2012. However, from 2010 to 2012, newly cattle-grazed and long term bison-grazed streams showed significantly more ($p<.05$; d.f.=2) widening than ungrazed streams and marginally more ($p<.10$; d.f.=2) widening than long term cattle-grazed streams. No significant differences ($p>.10$; d.f.=2) in changes of depth or w:d among grazing treatments were detected throughout the study period (Figure 4-8).

Discussion

Streams grazed by cattle and bison are generally wider, deeper, and have larger width to depth ratios relative to ungrazed streams, although the differences in our study are not statistically significant. Landscape impacts of ungulate grazing are apparent in the form of heavily trampled stream banks that in some areas completely lack vegetation (Figure 4-9a), trails that run adjacent to and across streams (Figure 4-9b), established cattle ramps (Figure 4-9c), and in-stream grazing, particularly during hot summer days (Grudzinski, personal observation; Figure 4-8d). Prior to the establishment of Konza Prairie Biological Station as a Long Term Ecological Research site, the currently ungrazed watersheds were cattle-grazed, likely as early as the late 1800's. Additional time on the scale of several more decades may be necessary to reveal statistically significant differences between grazed and ungrazed streams as the ungrazed watersheds continue to reestablish riparian vegetation resulting in bank development and a decrease in channel width (Kondolf, 1993).

As expected width, depth, and width to depth ratios increased with watershed area within ungrazed streams (Charlton, 2008). Surprisingly, within grazed treatments the largest widths, depths, and width to depth ratios were within the smallest watersheds indicating that cattle may be more extensively grazing within smaller streams. Previous studies have shown that cattle will avoid entering large streams particularly in areas with tall and steep banks except in locations where they have established heavily trampled cattle ramps as accessibility points (Trimble, 1994).

A distinct cluster of high width to depth ratios within small grazed streams is evident in Figure 4-4. K20A, the only ungrazed watershed within the cluster, has a dense forested riparian area (see Chapter 2) due to its 20 year burn interval (Figure 4-4). Less frequently burned areas increase recruitment of tree species within riparian zones (Briggs *et al*., 2005). Once wood enters headwater streams the mobility is relatively low, particularly for channel spanning pieces. In areas with woody debris jams and vegetated mid channel bars, sediment is retained thus creating shallow cross sections and increased w:d's.

Grazing also resulted in coarser fine sediment fractions (D_{16}), particularly within smaller watersheds (Figure 4-6). These findings suggest that either, 1) less fine material is introduced to the channel from cattle-grazed banks and hillslopes, or 2) that this fine material is more efficiently exported from grazed systems. Since the first possibility contradicts our observations of channel geometry adjustments, the second scenario is more likely. This is supported by previous research demonstrating that in-channel trampling (Figure 4-3d) breaks up imbricated and clustered sediment structures (Trimble and Mendel, 1996) thereby making bed sediment, particularly smaller sediment fractions, more easily transportable (Bunte and Abt, 2001).

As expected, significantly more widening occurred within newly cattle-grazed streams relative to long term cattle-grazed streams. This suggests that long-term cattle-grazed streams may have reached a new pseudo-equilibrium following several decades of consistent grazing or the newly grazed streams have breached a geomorphic threshold. Unexpectedly, bison-grazed streams widened more than long term cattle-grazed and ungrazed streams. Due to the decreased grazing pressures on riparian zones by bison, the streams may have yet to establish a new equilibrium. Additional sampling over longer temporal periods would reveal if the observed trends are persistent through time.

Our results demonstrate the added benefits of long term data collection. Within this study significant geomorphic changes in one direction (i.e widening) in one year showed significant geomorphic changes in the opposite direction (i.e narrowing) the following year, indicating that drawing conclusions on geomorphic influences from short term studies may be misleading and not representative of "surprises" found in long term trends (Dodds *et al*., 2012). Geomorphic changes may be responding slowly to environmental forces and may need several additional years for the impacts to become statistically recognizable. For example, in several streams depth did not show significant annual differences (2010 to 2011 or 2011 to 2012), however, analysis of the two-year period (2010 to 2012) revealed significant aggradation. Along with insufficient time for a landscape to respond to grazing pressures, a short study period also limits the measurement period to climatic phases (Lindenmayer *et al.,* 2010). During our study, our already intermittent network experienced an extreme drought that produced lower than normal mean monthly and peak annual flows, thereby decreasing the potential for geomorphically effective flow events.

While the specific influence of drought on our study of grazing impacts is not clear, drought likely produced some effect, as bankfull flows are considered the geomorphically dominant discharge (Junk *et al*., 1999) and were absent during our study. While little work has investigated grazing and climate interactions, Trimble (1994) found that bank erosion in grazed systems was only significant during the highest flow events which had a minimum of 10-25 year return intervals. Other work also suggests dry periods limit erodeability from ungulate grazing (George *et al*., 2002). Based on these findings, the sustained drought during our study may have limited the magnitude of grazing impacts on stream geomorphology. This possibility is qualitatively supported by changes produced within the newly cattle-grazed watersheds (Figure 4-9d). In these systems, banks have been extensively trampled and loosened and now completely lack vegetation cover in many areas, extensive cattle trails and bare ground patches have developed adjacent to the streams, and in-channel substrates have been heavily trampled. All of these visually documented changes have produced large volumes of eroded loose sediments that represent a great potential for extensive sediment flux, channel erosion and widening with the return of the next high flow event (Figure 4-3b).

The drought conditions are very likely to be the primary driver of the widespread aggradation and channel width dynamics we observed across our watersheds. Typically, during drought conditions streams will aggrade and narrow, as low discharges produce insufficient stream power to transport sediment sourced from higher in the watersheds which then accumulates in the channel, while banks become narrower as vegetation encroaches into the channel (Johnson, 1994; Scott *et al*., 1996; Talling and Sowter, 1998), as we observed in our ungrazed watersheds. Cattle and bison trampling may be responsible for the observed lack of narrowing within grazed watersheds, as grazing pressure effectively eliminates understory vegetation from both the channel and riparian corridor and produces bank erosion. This grazing pressure in the channel and near channel areas is only magnified during drought conditions (Allred *et al*., 2013).

Despite the potential confounding influence of the drought, our study represents a major advance in experimental design for studies of grazing treatment impacts on stream geomorphology. By having replicated treatments in very similar watersheds, we are, for the first time, able to document specific changes that can be attributed to differences in duration of cattle grazing as well as the differences between cattle and bison. Several decades of consistent grazing treatments within our study systems provided a unique opportunity to overcome the short grazing treatment periods common within the existing literature. Another benefit to our study design is that we were able to sample streams without upstream confounding factors (i.e. road crossings, urban development, different grazing treatments, dams, etc.) that are likely to exist at the landscape scale. Despite our attempts to create a robust sampling design with similar watershed characteristics we still had a limited number of watersheds available to us. To provide a more robust statistical analysis a larger number of replicates within each treatment would need to be sampled, but this would be difficult given land use histories and ownership patterns within the Great Plains.

Conclusions

Grazing management significantly influences channel geomorphology within grassland headwater streams. During a drought sampling period, channel narrowing occurred within ungrazed streams but not in grazed streams. Drought conditions appear to have led to aggradation throughout our study sites regardless of grazing treatment. The introduction of cattle grazing into previously ungrazed watersheds resulted in accelerated stream widening relative to streams within watersheds that have undergone prolonged cattle grazing. Short term analyses reveal fewer statistically significant relationships relative to long term analyses. Future research would clearly benefit from longer durations of repeated sampling regimes to accommodate slow rates of adjustment as well as climatic variability to further expand our understanding of the interactions among grazing and climate on the geomorphology of grassland streams.

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Figures

Figure 4-1 Paired watershed study design. N watersheds are bison-grazed, K are ungrazed, C are moderate density cattle-grazed. The C3S watersheds were ungrazed in 2010 and became grazed in the spring of 2011 (cattle grazing density is equivalent to bison-grazed treatments). R watersheds are high density cattle-grazed (grazing density is 3.3 times higher than in C watersheds). Burn intervals are identified by the number following the first letter within each watershed. All watersheds are located within Konza Prairie other than R1A and R1B which are located within Rannell's Pasture.

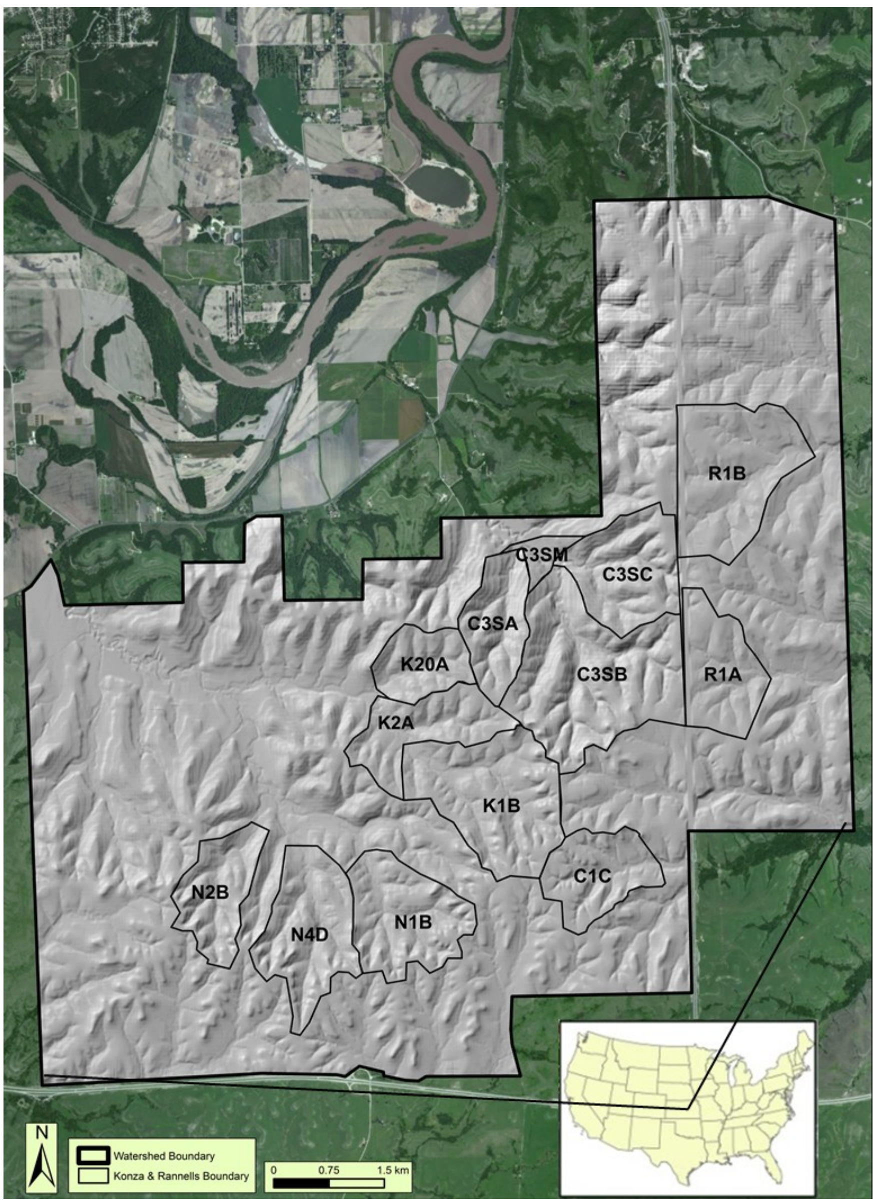

Figure 4-2 Mean monthly discharge at Kings Creek (USGS gaging station #0687650) within Konza Prairie Biological Station (the beginning of the study period is indicated by the start of the 2010 discharge data). Extreme drought was experienced during the study period and resulted in below average mean monthly flow.

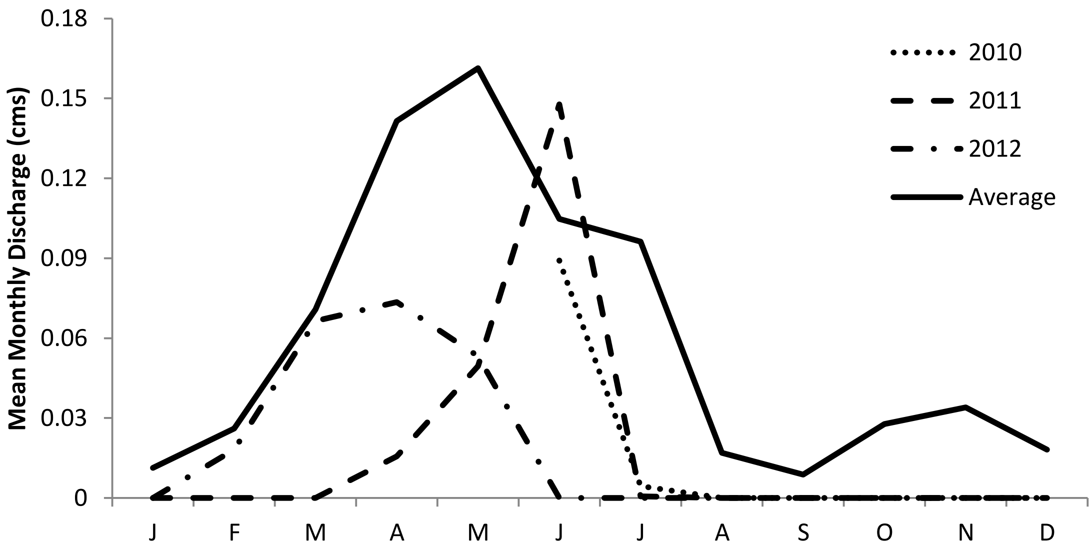

Figure 4-3 Example of annual surveys (A), drought conditions prevented export of loosened bank material (B), representative gravel stream bed substrate (C), instream trampling breaks up sediment structures making them more easily transportable (D).

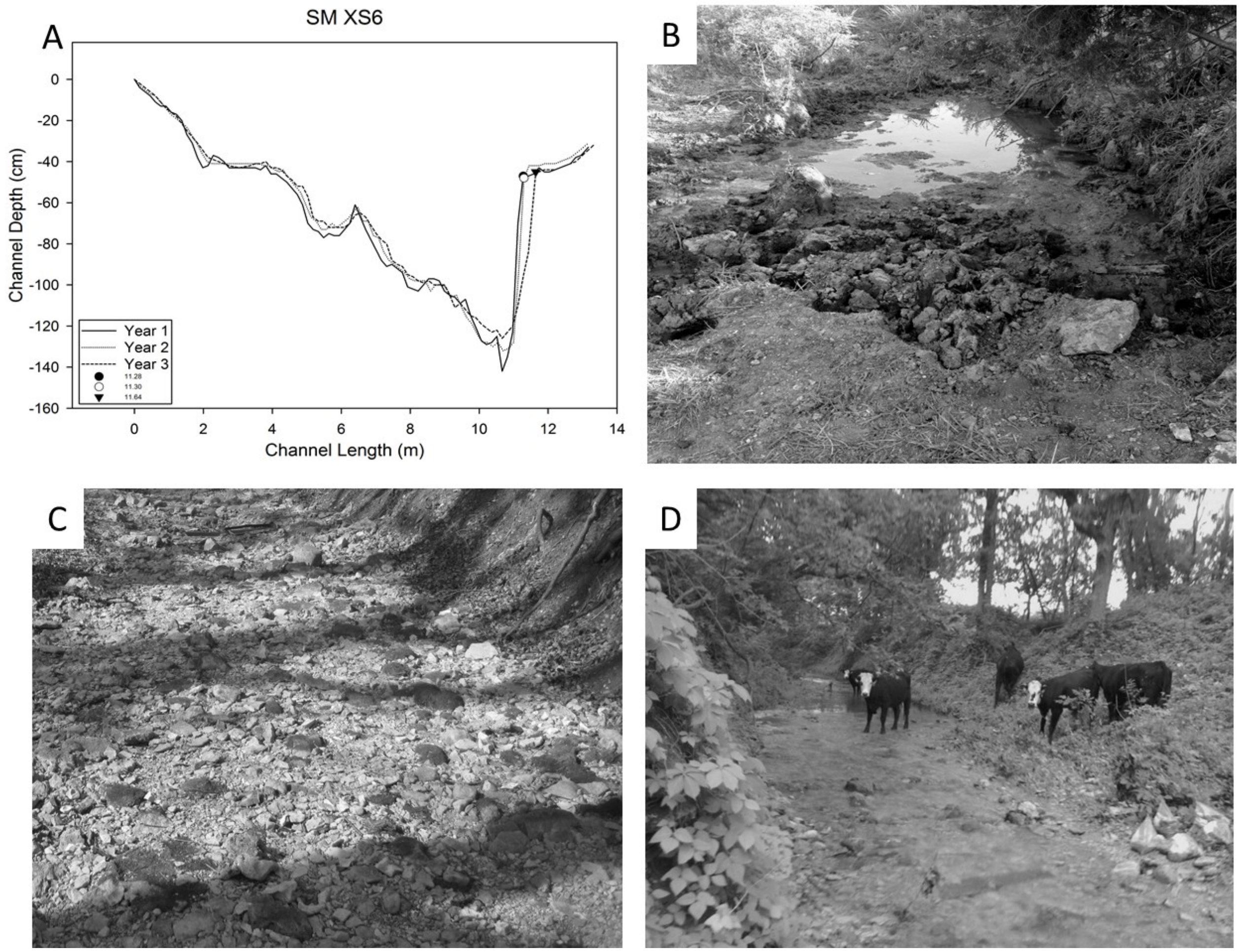

Figure 4-4 Influence of grazing treatment (top) and watershed area (bottom) on channel geometry. In order to allow cross watershed comparisons of grazing impacts, channel width, depth, and w:d were scaled by watershed area (top).

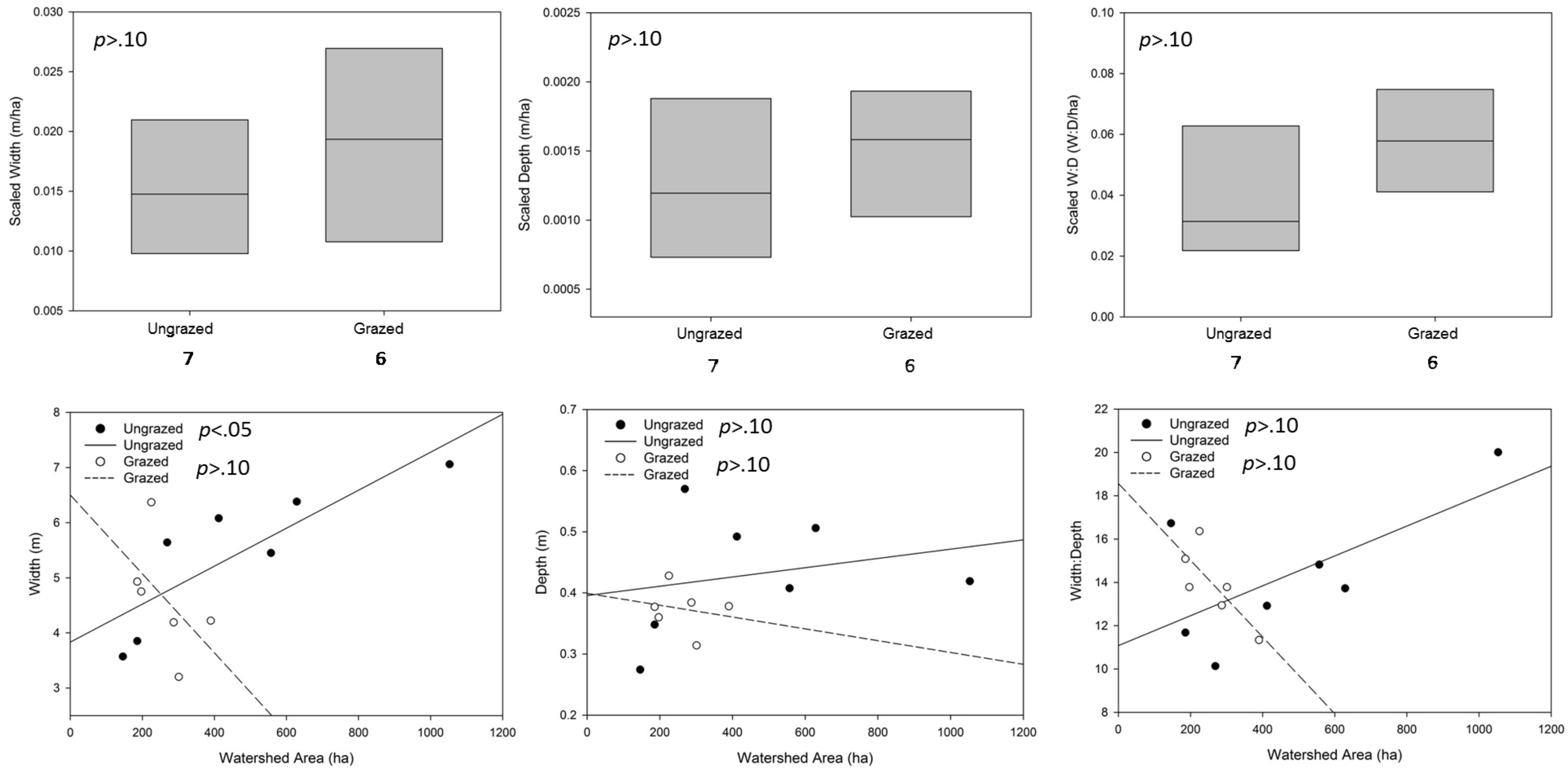

Figure 4-5 Influence of burning frequency (1990-2010) on channel geometry.

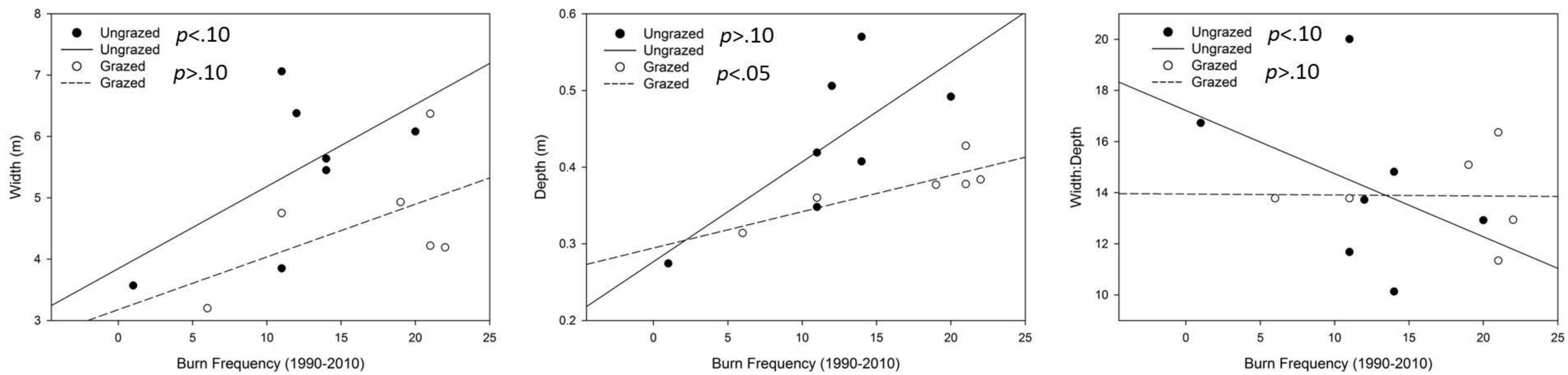

Figure 4-6 Influence of grazing treatment (top) and watershed area (bottom) on stream bed particle size distribution.

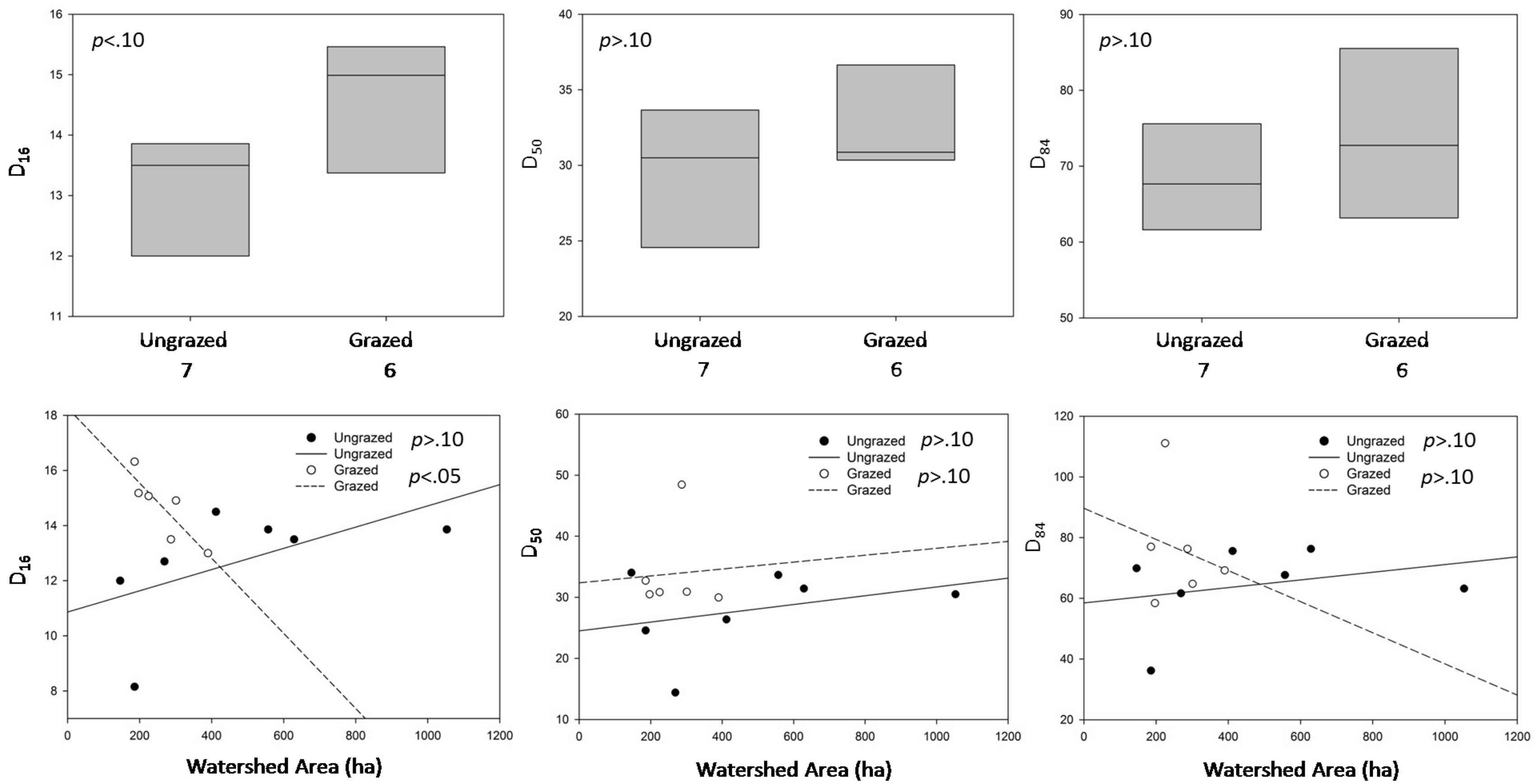

Figure 4-7 Overall changes in width (left), depth (middle) and w:d (right) from 2010 to 2011, 2011 to 2012 and 2010 to 2012 (n=13). Negative numbers represent erosion (widening and deepening) while positive numbers represent bank narrowing and bed aggradation.

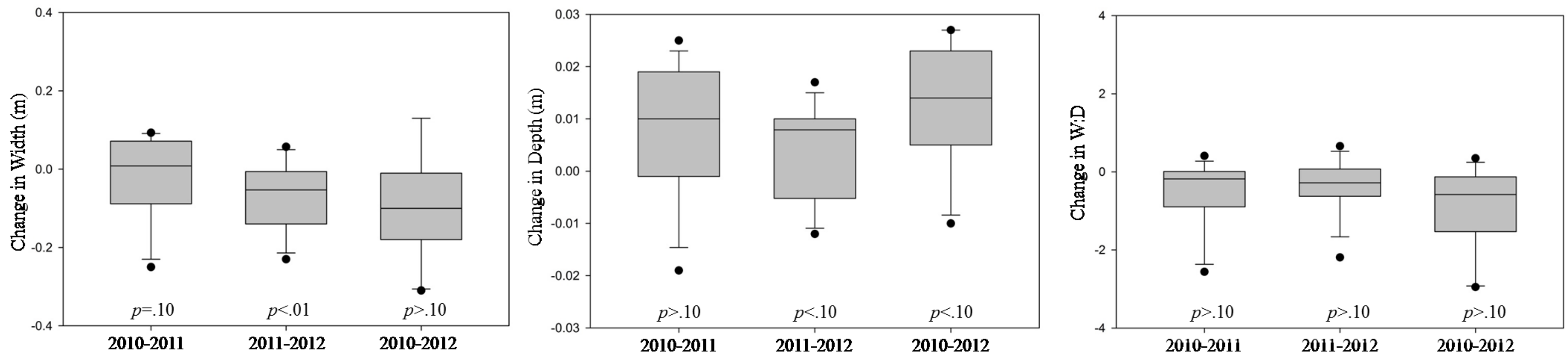

Figure 4-8 Comparison of change in width, depth, and w:d among grazing treatments from 2010 to 2012. Negative numbers represent erosion (widening and deepening) while positive numbers represent bank narrowing and bed aggradation.

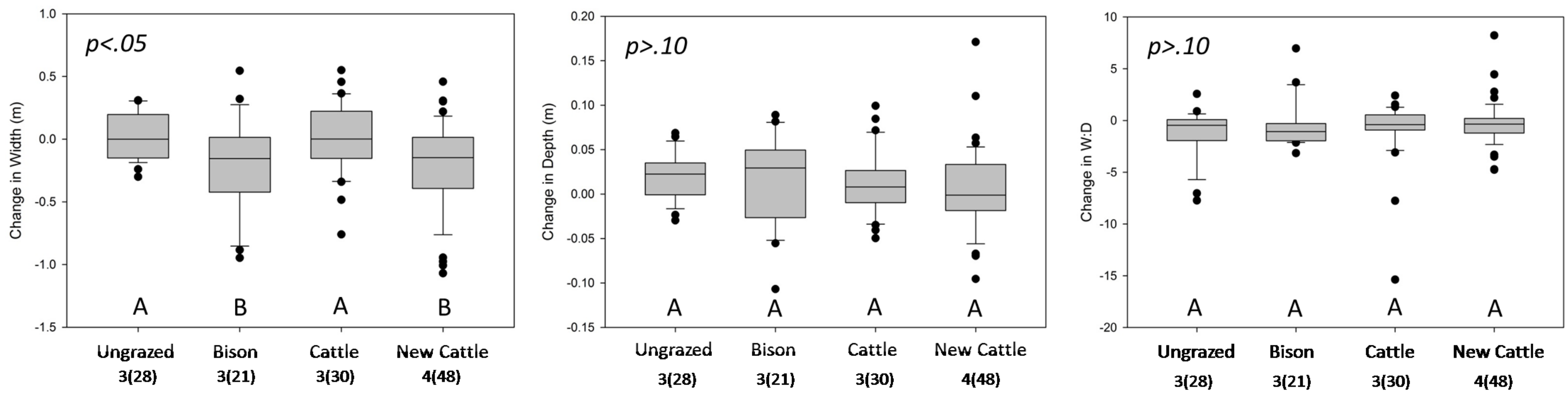

Figure 4-9 Heavily trampled stream banks which lack vegetation (A). Cattle trail and stream crossing (B). Heavily trampled cattle ramp. Note deposition of fine sediment adjacent to cattle ramp (C). Destabilization of stream bank following approximately 3 years of grazing in a previously ungrazed watershed (D).

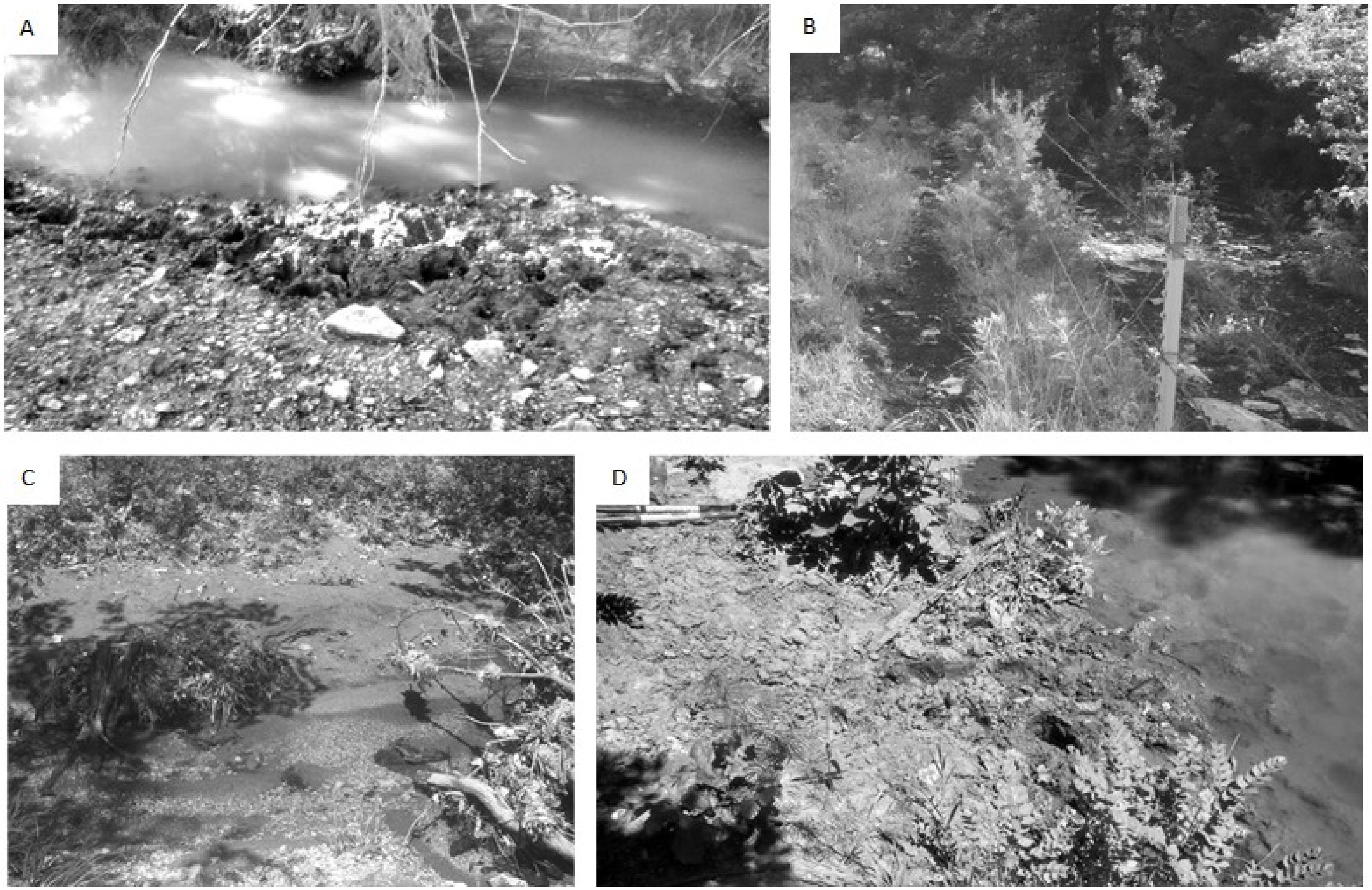

Table 4-1 Watershed grazing treatments and general watershed characteristics.

Watershed	1980- 2010 Treatment	2010-2014 Treatment	Grazing Season Months	Grazing Density ha/AU	Area (ha)	Burn Freq. (1990-2010)	Drainage Density (m/m^2)	Slope (%)	Sinuosity (m/m)
C1A	Moderate Cattle	Moderate Cattle	May-Oct	4.0	126	19	0.0050	3.37	1.19
K1B	Ungrazed	Ungrazed	None	NA	412	20	0.0062	2.7	1.31
K20A	Ungrazed	Ungrazed	None	NA	146	1	0.0059	3.74	1.28
K2A	Ungrazed	Ungrazed	None	NA	629	12	0.0062	2.53	1.26
N1B	Bison	Bison	Year Round	4.5	287	22	0.0060	3.53	1.21
N2B	Bison	Bison	Year Round	4.5	197	11	0.0056	3.57	1.2
N4D	Bison	Bison	Year Round	4.5	301	6	0.0055	2.9	1.15
R1A	High Cattle	High Cattle	May-Oct	1.2	225	21	0.0051	2.54	1.22
R1B	High Cattle	High Cattle	May-Oct	1.2	390	21	0.0054	1.89	1.37
C3SA	Ungrazed	Moderate Cattle	May-Oct	4.0	186	11	0.0054	4.45	1.26
C3SB	Ungrazed	Moderate Cattle	May-Oct	4.0	557	14	0.0053	3.69	1.18
C3SC	Ungrazed	Moderate Cattle	May-Oct	4.0	269	14	0.0054	4.12	1.21
C3SM	Ungrazed	Moderate Cattle	May-Oct	4.0	1053	11	0.0052	3.26	1.26

Table 4-2 Changes in geomorphic variables grouped by watershed from 2010 to 2011, 2011 to 2012 and 2010 to 2012. Negative numbers represent erosion (widening and deepening) while positive numbers represent bank narrowing and bed aggradation.

Watershed	Width (m) 2010-2011	Width (m) 2011-2012	Width (m) 2010-2012	Depth (m) 2010-2011	Depth (m) 2011-2012	Depth (m) 2010-2012	W:D 2010-2011	W:D 2011-2012	W:D 2010-2012
N4D	0.046	-0.23	-0.18	0.025	0.0024	0.027	-0.18	0.0073	-0.17
N2B	-0.079	-0.02	-0.1	-0.0044	0.012	0.0076	0.071	-0.76	-0.59
N1B	-0.2	-0.12	-0.31	0.02	-0.0093	0.01	-1.12	0.66	-0.46
K20A	0.065	-0.08	-0.016	0.019	0.0079	0.027	-2.08	-0.87	-2.95
K1B	0.078	0.057	0.13	0.019	-0.0049	0.014	-0.41	0.33	-0.083
K2A	0.093	-0.098	-0.0047	0.011	0.0095	0.02	-0.091	-0.49	-0.58
C1C	0.088	0.039	0.13	0.015	0.01	0.026	-2.56	-0.28	-2.88
R1B	-0.037	0.0078	-0.03	-0.019	0.0086	-0.01	0.41	-0.061	0.35
R1A	-0.04	-0.034	-0.07	0.0031	0.017	0.02	-0.039	-2.19	-2.23
C3SM	0.013	-0.16	-0.15	0.01	0.0021	0.012	0.025	-0.38	-0.36
C3SA	-0.25	-0.053	-0.3	-0.008	0.01	0.0024	-0.42	-0.41	-0.83
C3SB	0.0083	-0.19	-0.18	0.006	-0.012	-0.006	-0.0033	0.096	0.093
C3SC	-0.098	-0.04	-0.14	0.0024	-0.0055	0.018	-0.67	0.05	-0.61

Table 4-3 Statistical analysis (*p* values) of changes in geomorphic variables grouped by watershed from 2010 to 2011, 2011 to 2012 and 2010 to 2012. Negative numbers represent erosion (widening and deepening) while positive numbers represent bank narrowing and bed aggradation. Bolded values highlight significant changes (*p*<.10).

Watershed	Width (m) 2010-2011	Width (m) 2011-2012	Width (m) 2010-2012	Depth (m) 2010-2011	Depth (m) 2011-2012	Depth (m) 2010-2012	W:D 2010-2011	W:D 2011-2012	W:D 2010-2012
N4D	0.56 +	0.12 -	**0.033 -**	**0.019 +**	0.85 +	0.16 +	0.43 -	0.99 +	0.44 -
N2B	0.69 -	0.84 -	0.65 -	0.86 -	0.47 +	0.79 +	0.89 +	0.29 -	0.46 -
N1B	**0.0068 -**	0.18 -	**0.015 -**	0.26 +	0.57 -	0.49 +	0.29 -	0.4 +	0.20 -
K20A	0.38 +	0.36 -	0.82 -	**0.04 +**	0.29 +	**0.003 +**	**0.03 -**	0.24 -	**0.01 -**
K1B	0.21 +	0.31 +	**0.02 +**	**0.018 +**	0.59 -	0.13 +	0.13 -	0.36 +	0.84 -
K2A	**0.06 +**	**0.053 -**	1 -	0.11 +	0.34 +	**0.094 +**	0.7 -	0.2 -	**0.1 -**
C1C	0.15 +	0.57 +	0.19 +	0.25 +	**0.085 +**	**0.053 +**	0.31 -	0.57 -	0.43 -
R1B	0.43 -	0.89 +	0.48 -	0.11 -	0.20 +	0.34 -	**0.08 +**	0.73 -	0.25 +
R1A	0.63 -	0.77 -	0.53 -	0.68 +	0.12 +	**0.043 +**	0.9 -	**0.004 -**	**0.01 -**
C3SM	0.87 +	**0.07 -**	0.22 -	0.22 +	0.79 +	0.22 +	0.97 +	0.52 -	0.18 -
C3SA	**0.014 -**	0.63 -	**0.05 -**	0.55 -	0.39 +	0.85 +	0.35 -	0.22 -	0.13 -
C3SB	0.8 +	**0.048 -**	**0.064 -**	0.57 +	0.29 -	0.5 -	0.36 -	0.78 +	0.85 +
C3SC	**0.037 -**	0.38 -	**0.048 -**	0.16 +	0.5 -	0.77 +	**0.03 -**	0.84 +	0.14 -

Chapter 5 - Conclusions

Grassland ecosystems throughout the world are strongly influenced by livestock grazing, yet prior to this study we lacked a comprehensive understanding of how various grazing management practices specifically influence the geomorphology of grassland headwater streams. A replicated watershed level study design is used to evaluate the relationship among grazing treatments, burning frequencies, and other environmental variables on suspended sediment concentrations, bare ground production, and changes in channel geometry. The inclusion of ungrazed control watersheds also lends insight into fundamental characteristics of grassland streams in the absence of grazing impacts. Currently, published comparative studies of bison and cattle impacts on stream geomorphology are lacking.

Chapter 2, Influence of Watershed Grazing Management on Baseflow Suspended Sediment Concentrations in Grassland Headwater Streams, directly compares impacts of equivalent bison and cattle grazing treatments on suspended sediment concentrations. Cattle significantly increased TIS concentrations at baseflow conditions, and high density cattle grazing treatments had sediment concentrations furthest from pristine conditions (ungrazed and bison-grazed streams). Bison and ungrazed streams had similar TIS concentrations likely due to decreased riparian and in-stream grazing by bison. Suspended sediment concentrations were also significantly altered by discharge, burning frequency, and seasonality, however, grazing treatment was generally the most influential variable during baseflow conditions.

Chapter 3, Watershed Grazing Management, Bare Ground Coverage, and Links to Suspended Sediment Concentrations in Grassland Headwater Streams, comparatively evaluates bare ground generation and distribution between ungrazed, bison-grazed, and cattle-grazed treatments and links bare ground production to stream sediment concentrations. Bare ground area significantly varied between cattle and bison-grazed treatments. Cattle-grazed treatments had significantly more bare ground within riparian areas, particularly underneath canopy cover. At the watershed scale bison treatments had the most bare ground although no statistically significant differences were detected between grazing treatments. Baseflow suspended sediment concentrations were most closely linked to bare ground production within riparian areas, likely due to increased riparian and in stream grazing during low flow periods. Storm flow suspended sediment concentrations were most closely linked to watershed scale bare ground production, suggesting runoff erosion during intense rain storm events is importing additional sediment from bare ground sources located outside of riparian areas.

Chapter 4, Impact of Watershed Grazing Management on Grassland Headwater Stream Geomorphology, demonstrates that watershed grazing treatments can significantly alter stream geomorphology. Grazers seemed to prevent channel narrowing during drought conditions, and drought conditions generally resulted in aggradation. The introduction of cattle grazing to previously ungrazed watersheds increased stream widths at a significantly faster rate than observed within long term cattle grazed treatments. A lack of stream widening within long term cattle grazing treatments suggests that prolonged cattle grazing results in a new pseudo-equilibrium channel morphology.

This dissertation has addressed significant gaps in the literature regarding the geomorphic influences of native bison and non-native cattle on grassland headwater streams. Grassland headwater streams and their watersheds are significantly altered by grazing management practices, and cattle and bison grazing impacts are not geomorphically equivalent. First, baseflow sediment concentrations are significantly increased by cattle, yet bison do not appear to alter sediment dynamics relative to ungrazed streams. Second, bare ground production is related to grazing treatments and is significantly correlated with suspended sediment concentrations, yet varies in amount and distribution between cattle and bison. Third, grazing and climate both significantly influence grassland headwater stream geomorphology. Along with implications for grassland management our results indicate that grazing management is responsible for altered rates of landscape denudation and impacts natural sediment budgets particularly during summer months.

Several limitations within this study should be pointed out: 1) all of the water samples and channel geometry measurements were collected during drought conditions, thereby making inferences from grazing impacts during higher flows difficult, 2) in some instances treatments were limited to 2 or 3 replicates, thereby limiting our statistical power for detecting significant differences, and 3) we did not have high density bison-grazed treatments to directly compare to our high density cattle-grazed treatments. Despite these limitations, we conclude that cattle grazing at both moderate and high densities is damaging to grassland stream water quality, stream structure and surrounding riparian habitats. Bison grazing appears to mitigate most of the damage caused by cattle in and near grassland streams. Substitution of bison for cattle may be used as a best management practice for conserving grassland ecoregions, although the required time period for recovery is currently unknown.