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Fenceline contrasts: grazing increases wetland surface roughness

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Abstract A warming earth has lost substantial mountain-stored frozen fresh water, thus generating a pressing need for greater liquid–water storage within upper-elevation riparian systems. Liquid–water storage can be enhanced by avoiding microtopographic channels that facilitate land drainage and rapid runoff. A number of authors have attributed certain forms of wetland hummocks and inter-hummock channels to grazing livestock but there is little evidence in the scientific literature for a cause and effect mechanism. We used comparisons at six fencelines on four meadow and wetland complexes to test the null hypothesis that grazing management makes no difference in hummocks and inter-hummock channels measured as surface roughness. Surface roughness was measured both photogrammetrically (photo) and with an erosion bridge (EB), and the measurements expressed as surface roughness indices (SRIs). Wetland surface roughness inside fenced areas was 44 (EB) and 41 (photo). Wetland surface roughness outside fenced areas was more than 50 % higher ($p < 0.0001$), measuring 76 (EB, $n = 6$) and 62 (photo, $n = 4$). The site with the longest period of conservation management (50+ years) had the lowest inside EB SRI at 27. The two independent measurement methods, EB and photo, yielded similar, correlated results ($R = 0.71$, $n = 8$). Historical aerial photography provides supporting evidence for our findings. We reject the null hypothesis and while we suspect macrotopography, hydrology, soil type, and climate are factors in hummock formation, our evidence supports the thesis that hummocks formed surface-down by inter-hummock channels result primarily from grazing by domestic livestock.

Keywords Climate change · Erosion bridge · Hummocks · Land management · Photogrammetry · Riparian

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Introduction

The earth is warming (NASA 2013). That warming is occurring and has resulted in huge losses of fresh water stored as mountain ice and snow is a fact emphasized by the 1991 discovery of a mummy preserved for 5,300 years in ice under a now-absent glacier of the Alps (Seidler et al. 1992). Storage of frozen fresh water has likewise ominously decreased in other mountains. Nayak et al. (2010), working at the Reynolds Creek Experimental Watershed in the Owyhee Mountains near Boise, Idaho, U.S., analyzed 45 water years (1962–2006) of temperature, precipitation, and streamflow data from 12 sites. They found a trend of warming temperatures at all elevations and concluded that changes in snow deposition and melt have altered stream-flow patterns such that land and water management practices are affected—a conclusion evident in a recent report on wetland water-management practices at three U.S. federal wildlife refuges (Downard and Endter-Wada 2013).

Since fresh water is a renewable resource that, increasingly, is in short supply, and since climate change may exacerbate that shortage, land-management practices affecting water retention in riparian systems must be examined and altered to emphasize the need for: (1) maintaining a vegetative cover protecting against soil erosion, (2) maintaining, or significantly increasing, soil organic matter (carbon)—the soil sponge factor—through annual additions from senescing vegetation, and (3) maintaining microtopographic water storage by avoiding channels that facilitate drainage and rapid runoff.

Several publications cite grazing as a prominent cause for wetland hummocking, inter-hummock channels, and related negative consequences. Girard et al. (1997) write, "Soil pedon descriptions done in 1992 also indicate increased erosion, soil compaction, trampling, and trailing result from concentrated livestock and wildlife use of riparian areas. … These trails cause increased drainage, increased soil erosion and compaction … and dry microsites or hummocks." Magnusson et al. (Magnusson et al. 1998; Fig. 1a) state: "Hummocks are usually a very distinct character of Icelandic rangelands where grazing has been intense." Corning (Corning 2002; Fig. 1b) observed that Wyoming wetlands south of the upper Sweetwater are, "becoming hummocked areas rather than true riparian wetlands". He attributed hummock formation to cattle compacting wetland organic matter into trails that dewatered the wetland so that drying and erosion created the hummocks. Jankovsky-Jones (1999) similarly linked cattle grazing to hummocking for a number of Idaho wetlands. Johnson and Carey (Johnson and Carey 2004; Fig. 1c) discussed hummocked wetlands in Colorado, stating that cow trails result in compaction and erosion creating grazing-induced hollows. They differentiate between grazing-induced hummocks and "natural" hummocks formed by accretion of mosses and other perennial vegetation, thus implying that "good" hummocks contain organic matter and are formed surface up; "bad" hummocks are formed surface-down from trampling, channeling, and erosion. Despite the agreement among these land-management publications for a link between domestic livestock grazing and hummock formation, we know of no paper providing data to support a cause and effect relationship. Indeed, Smith et al. (2012) observed that "The management literature in the US often attributes hummock formation to domestic livestock impacts …, but there is little support for this in the scientific literature."

As land management adapts to changing stream-flow patterns and the need for more effective water-storing riparian systems, the question of the formation and effect of hummocks on wetland water storage is increasingly important. We postulated that if grazing resulted in degradative hummocks as claimed in the above cited literature, then hummocking would be detectable in surface microtopography using (a) erosion-bridge measurements expressed as a surface roughness index (SRI) (Jester and Klik 2005 citing Luk 1983) and (b) using photogrammetric methods.

Ullah and Dickinson (1979) used photogrammetry to create digital elevation models (DEMs) from which they measured soil-depression water storage. Smart et al. (2002) demonstrated that low level photogrammetry is a practical tool for creating microtopographic DEMs to measure river bed surface roughness and Taconet and Ciarlati (Taconet and Ciarletti 2007) utilized a similar procedure to measure soil roughness in furrowed agricultural fields. We used microtopographic DEMs of rangeland wetlands and meadows to measure surface roughness and we report the measurements as mean SRIs.

We further postulated that if grazing causes or contributes to interhummock channels, then wetlands with less, or no, grazing would have lower SRIs than wetlands with greater exposure to livestock–the null hypothesis being that grazing management makes no difference in SRI values. We tested the null hypothesis using six fence-line contrasts at four meadow and

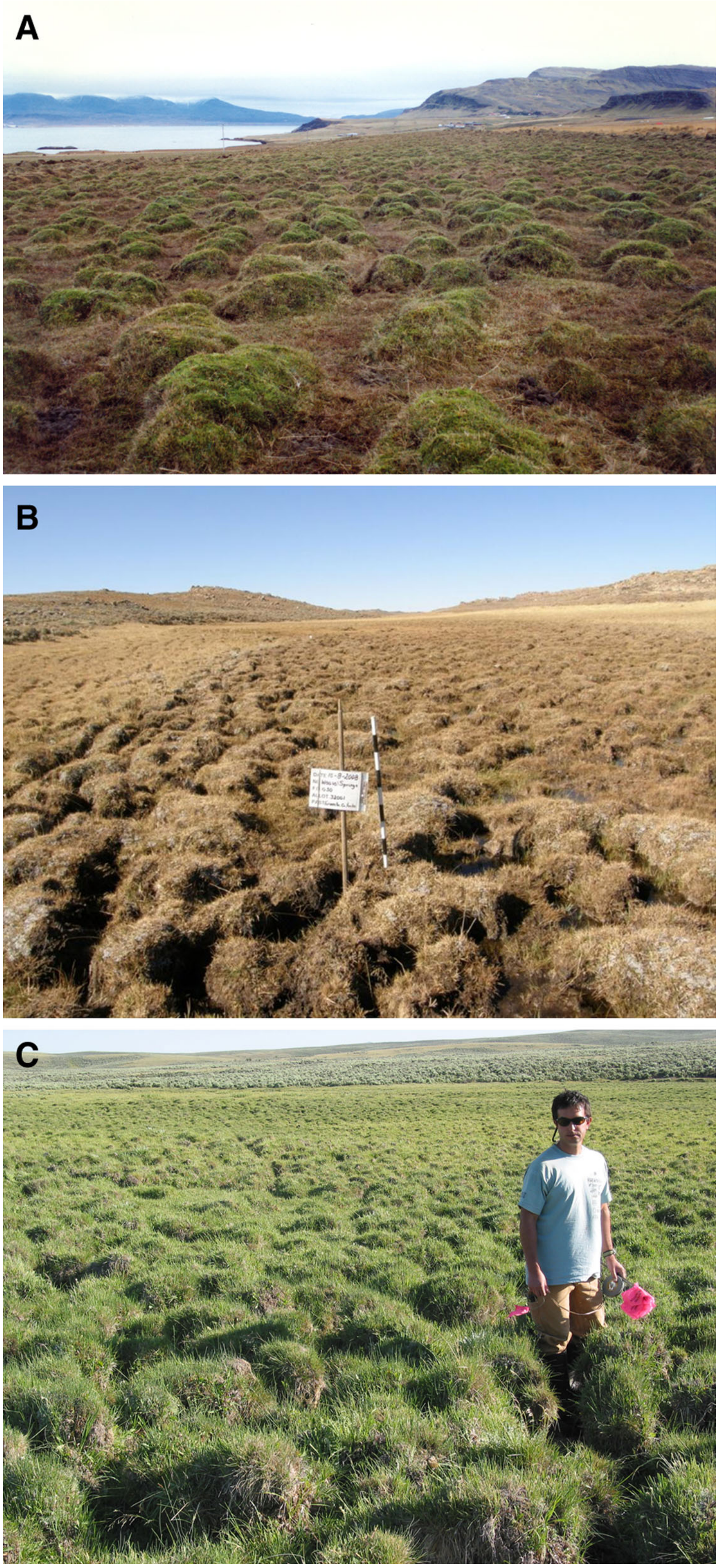
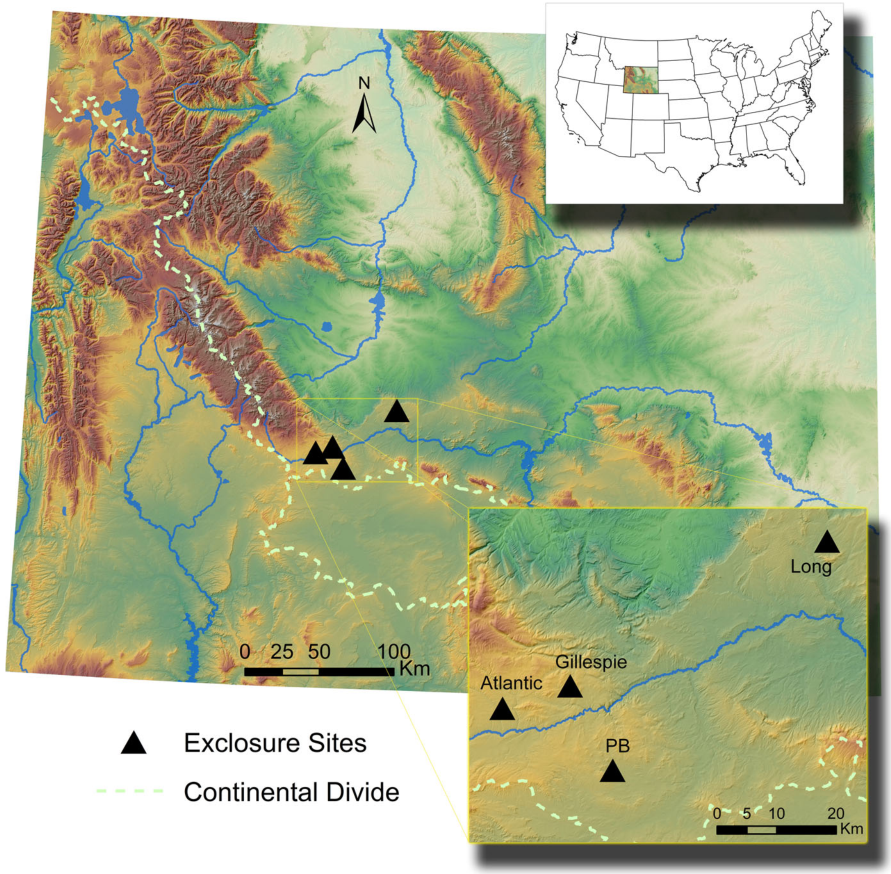


Fig. 1 (Colour figures online) **a** Hummocks on heavily grazed horse pasture in Hvalfjordur, SW-Iceland, October 1996. Photo: Borgthor Magnusson (Magnusson et al. 1998).**b** Hummocks on Wyoming wetlands south of the upper Sweetwater (Corning 2002). Photo: J. C. Likins. **c** Hummocks on Federal wetlands in northern Colorado (Johnson and Carey 2004)

Fig. 2 (Colour figures online) Study site locations



wetland complexes within the upper Sweetwater River watershed of Fremont County, Wyoming, U.S. (Fig. 2).

Methods

Study sites

Three of our study sites, Atlantic City (42.338°–108.652°), Gillespie (42.463°–108.516°), and Long Creek (42.697°–108.001°), are 30-year-old United States Department of the Interior, Bureau of Land Management exclosures intended to exclude livestock. Violations of the exclusion are known; however, the long-term goal of a meaningful reduction in grazing was accomplished. PB Creek (42.338°–108.422°) is a private pasture grazed <20 days annually for >50 years. Public land around these four sites has been predominately grazed season long (180 days) for the approximately four decades since free-roaming cattle replaced most of the herded sheep on the allotments; the regions public wetlands are hummocked and crisscrossed with inter-hummock channels (Fig. 3).

Erosion-bridge (EB) measurements

An EB, also called a pin meter, is a device for measuring microtopography and is commonly used to detect changes in the ground surface due to erosion or deposition (Gilley and Kottwitz 1995; Jester and Klik 2005; Maurin and Berggren 2011; Ypsilantis 2011). Our bridge was 1-m long, had three adjustable legs and a bubble level attached to a frame which supported a horizontal bar of aluminum channel drilled to accept ten equally-spaced pins (Fig. 4). The bridge was leveled at each new position. Data were collected using digital photographs of pin height against a white backdrop. Pin

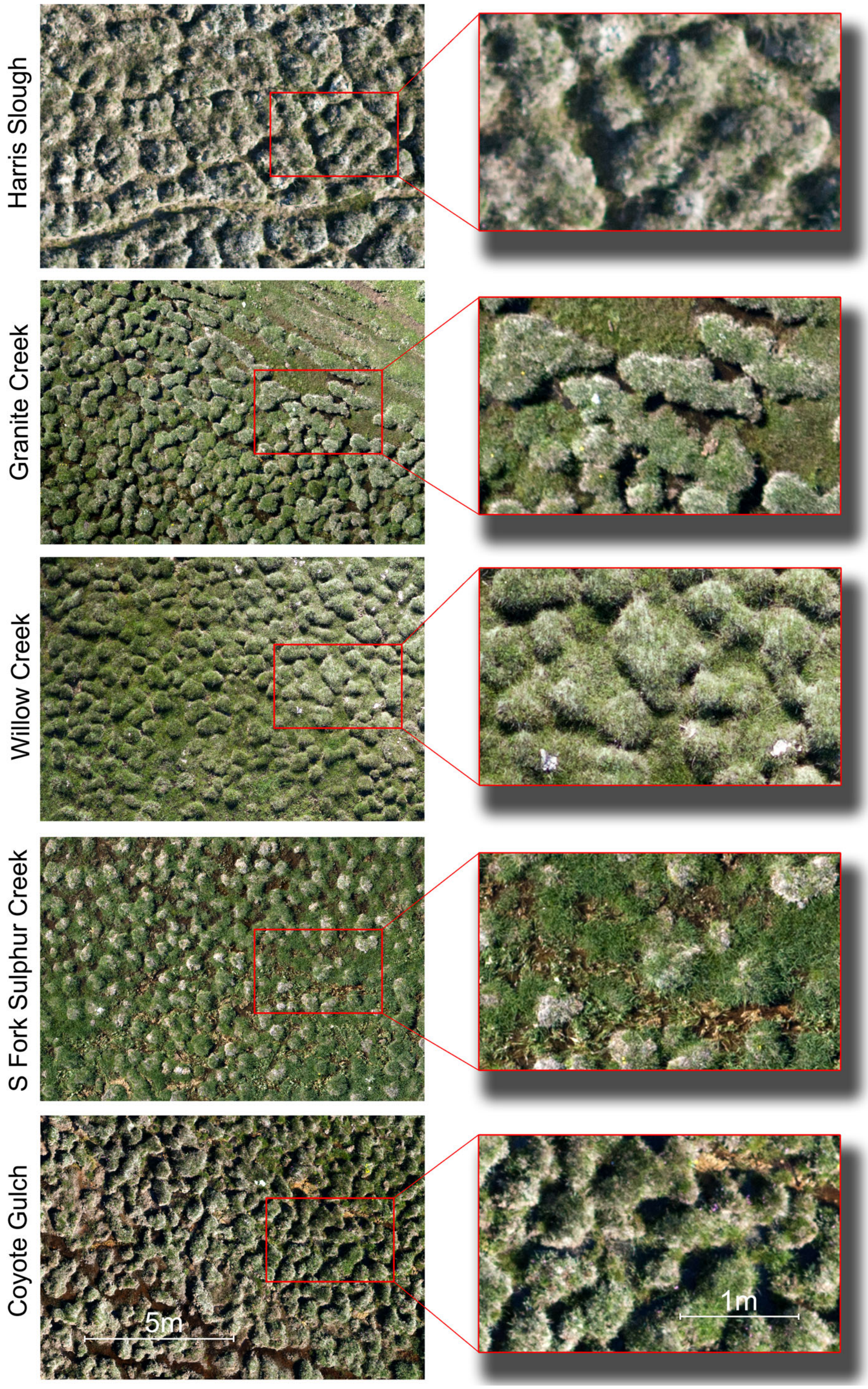


Fig. 3 (Colour figures online) Aerial images (~8 mm GSD) of hummocked wetland in five drainages spanning a 21-km west (Harris Slough)-to-east (Coyote Gulch) region within the same watershed as the study sites listed in Table 1. These scenes are typical of the drainages they represent, illustrating that hummocked wetlands are as ubiquitous across this landscape as domestic-livestock grazing. Panels in the right column show 4× magnification. Scale shown in the lower panels is nominally the same in each column

height above the horizontal bar was later measured from the digital images using Image Measurement software (Booth et al. 2006). The SRI was calculated as the standard deviation of pin elevations for each placement of the bridge (Jester and Klik 2005 citing Luk 1983).

Fig. 4 (Colour figures online) A transect sample made with the erosion bridge. Photo: S. E. Cox

Photogrammetric (photo) measurements

We used a Canon 1Ds MkII camera with a 28 mm lens to acquire nadir, stereo imagery of a 1-m swath of ground adjacent to each transect (see section on sampling). The camera was mounted at 30° on a monopod to achieve a level position 1.3-m above ground level, yielding 0.33-mm ground sample distance (GSD) imagery with a 1.7 × 1.1-m field-of-view. We used aperture priority and a single manual focus to fix camera calibration at each site. A unique combination of aperture, shutter speed and ISO was selected at each site to achieve optimal image quality. Generally, we used *f*/7.1 or *f*/8, shutter speed 1/50–1/250 s and ISO 200–400. A first pass acquired images with image X-axis parallel to the transect at 25-cm intervals, and a second pass with the X-axis perpendicular at 33-cm intervals, resulting in 85 and 70 % overlap, respectively. This overlap provided ten different look angles for each point in the 1-m swath. Because sites varied in size, the number of acquired images ranged between 203 and 635 per transect. For ground control points (GCPs) intended to orient the model into a coordinate space, we anchored a white DVD disc level on the ground near each transect end. We collected location coordinates (XYZ) for the center of each GCP for 30 s with a Juno B3 GPS (Trimble, Sunnyvale, CA). GPS data were post-processed with Pathfinder Office v5.3 (Trimble) resulting in modeled precision of 57 cm, and these GCPs were utilized in model orientation. Three additional GCPs were mathematically created at the edge of each disc using the transect bearing and disc radius (6 cm), resulting in GCPs that were more accurate, relative to the collected disc center point, than our GPS could have produced. Discs were assumed to be level for purposes of assigning Z to each GCP, and an assessment of this assumption was made after processing. For image tie points, we pushed 10-cm, fluorescent-head nails into the ground at 1-m intervals along each transect. We didn't collect coordinates for these points as they were not intended as GCPs.

We used PhotoScan v0.9.1 (Agisoft, St Petersburg, Russia) to process imagery and create 5 mm-pixel digital elevation models (DEMs) using a semi-automated workflow of (1) aligning images based on common features and feature recognition, (2) assigning GCPs to the ground targets, (3) eliminating poor-fit control points to reduce root mean square error (RMSE), (4) creating the model surface using aerotriangulation and (5) exporting the resulting DEM as an ascii grid (Fig. 5). Camera calibration parameters were solved by the software and applied to the model. Automated tie-point creation failed in some models, requiring time-intensive manual tie point creation that did not always result in correct image alignment. The assumption of level disc orientation (equal elevation

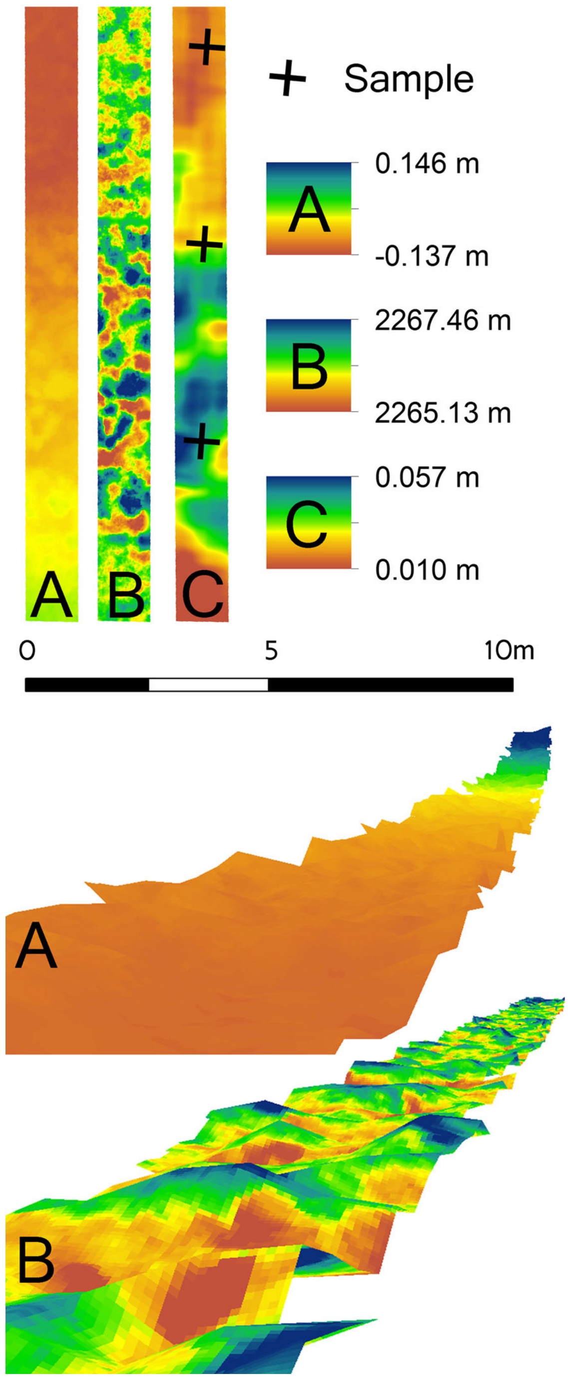


Fig. 5 (Colour figures online) Sections of photogrammetrically-derived surface models for the transect inside the north fenceline of the Gillespie exclosure, showing **a** the digital elevation model, **b** the detrended elevation model and **c** sampled locations on a modeled surface of standard deviations from a 1 × 1 m moving window applied to B. Scale applies only to the three upper surface models

for all GCPs on a single disc) was examined, and in some cases where the resulting model appeared to tilt or twist, one or more GCP Z-values were adjusted by <1 cm to result in a surface model that approximated reality. However, such leveling was not strictly necessary since surface roughness was derived from relative heights, rather than absolute elevations.

To measure surface roughness, we had to remove the confounding factor of slope across each transect. Following the procedure of Smart et al. (2002), we created a modeled-slope surface where each raster pixel represented the mean elevation of a 1 × 1-m moving window using ArcMap 10.0 (ESRI, Redlands, CA). A 1-m window smoothed visible hummocks without removing too much slope, relative to windows of 0.5, 1.5 and 2 meters. Smart et al. (2002) recommended a moving window 2.5 × the 90th percentile diameter of river channel gravel/rock substrate, but since hummocks at these sites are not circular (Fig. 1b), we could not objectively compute a hummock diameter, and relied instead on visual inspection. We subtracted the modeled slope surface from the DEM to produce a slope-detrended DEM which showed microtopography as if on a flat plane (Fig. 5). We created a fourth surface where each new raster value represented the standard deviation of all detrended-surface elevation values within a 1 × 1-m moving window. This fourth surface model was sampled with equally-spaced points placed down the center of the surface model, where each point was essentially the center of a 1 × 1-m plot (Fig. 5). Each point's raster value was the standard deviation of all detrended elevations within that 1-m plot, and was used as the surface roughness indicator (SRI), similar to pin-height standard deviation, as a SRI (Hairsine et al. 1992, McEldowney et al. 2002), but with a stark difference in sample size. Whereas EB SRI measurements relied on ~10 observations per plot, SRI from DEMs drew from 40,000 observations per plot. (See online supplement for surface models.).

Sampling and statistical analysis

Transects were established 20-m inside, and outside, of fencelines (2 transects per fenceline) by stretching a measuring tape perpendicular to the channel and beginning and ending at the visible riparian-upland vegetation boundary (usually *Artemisia* spp.) or as allowed by exclosure size. Transect length ranged

Table 1 Erosion bridge and Photogrammetry soil roughness indicators (SRI) derived from multiple measurements (n) at each site. These values were used in a correlation analysis of EB and photo data. Below, ANOVA tables for the 2-way, unbalanced analysis

Site	Erosion bridge				Photogrammetry			
	inside	n	outside	n	inside	n	outside	n
Atlantic E	52.9	10	65.0	11	46.6	10	65.2	11
Atlantic W	47.6	9	110.8	10	52.4	10	78.0	10
Gillespie N	42.4	10	79.3	10	29.9	10	53.5	10
Gillespie S	41.5	11	61.6	11	34.9	10	49.1	10
Long Creek†	50.0	10	75.6	10	–	–	–	–
PB Creek†	26.6	11	64.3	11	–	–	–	–
Mean SRI	43.5		76.1		40.9		61.5	

Source	DF	Type I SS	Mean square	F value	Pr > F
Erosion bridge					
Model	6	46193.18	7698.86	11.38	<0.0001
Error	116	78501.44	676.74		
Corrected total	122	124694.62			
Photogrammetry					
Model	4	16493.79	4123.45	12.70	<0.0001
Error	76	24682.50	324.77		
Corrected total	80	41176.29			

† Photogrammetrically-modeled surfaces for Long Creek and PB Creek were less than 90 % complete relative to the transect coverage, and so were not used for analyses

between 23 and 66 m; we chose unequal transect lengths in order to fully represent the various wetland cross sections. The stretched tape was staked at about 5-m intervals with 15-cm landscape fabric staples to keep it in place in wind and to anchor it to the ground across typically concave riparian meadows.

We used a systematic placement of the EB and photo plots along transects, such as at 2- or 5-m intervals, to obtain at least ten samples per transect. Some plots were photographed several times to ensure at least one high quality image, and in such cases the highest quality image was used for analysis, or in the case of equality, the first image was used. Each EB placement along a transect was the sampling unit for EB data analysis, and each 1 m^2 plot was the sampling unit for the photo method. Transect sample sizes ranged from nine (some digital images of data were unusable) to 11 for EB, and ten to 11 for photo. We analyzed our data using an unbalanced 2-way ANOVA with six (EB) or four (photo) sites and two levels of grazing.

Results

Erosion bridge measurements

The average EB SRI inside fences was 44 (Table 1). It was 76, or 1.7 times greater, outside ($p < 0.0001$, $n = 6$). The site with the longest period of conservation management (50+ years) had an inside SRI of 27, lower than any other site.

Photogrammetric (photo) measurements

Surface models were successfully created (>90 % for both transects) for four of the six sites (Fig. 5). PB Creek and Long Creek could not be modeled. Across the four successfully-modeled sites, grazed wetland surface roughness was 1.5 times higher than ungrazed wetland ($n = 4$, $p < 0.0001$, Table 1). SRI values were similar and correlated with EB SRI values ($R = 0.71$, $n = 8$; Table 1)

Discussion

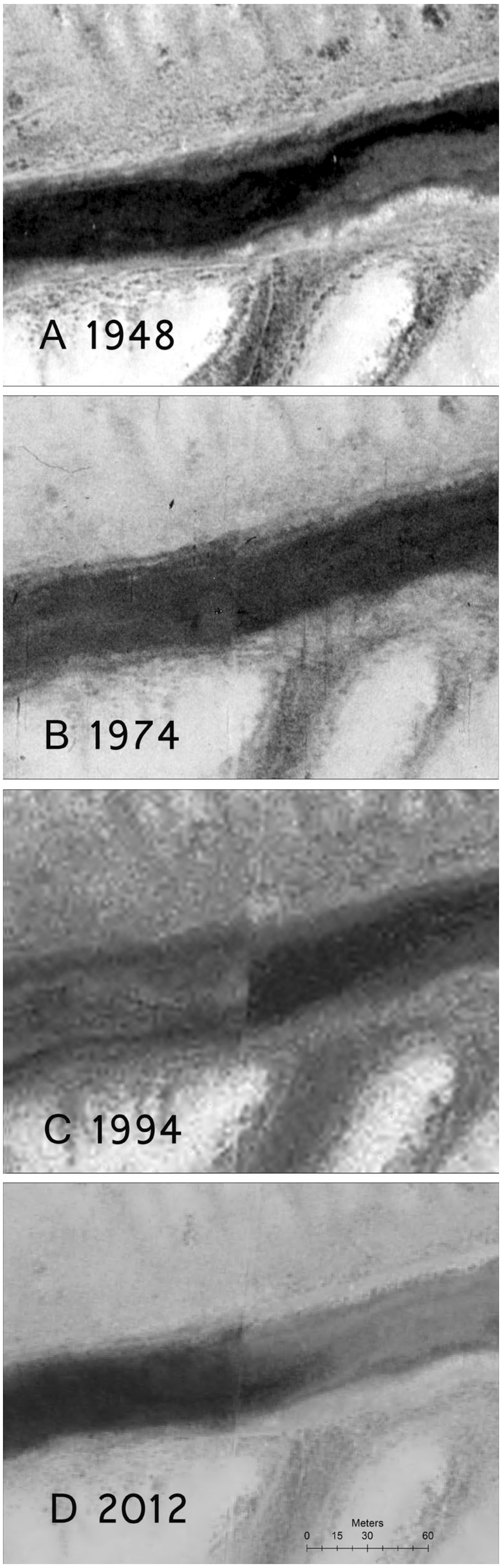
We used EB and photo methods to measure surface roughness at six and four fencelines, respectively, establishing that there are highly significant grazing-related differences in the fenceline contrasts. This is not proof that grazing causes hummocks; rather, it is very strong evidence that grazing significantly increases surface roughness—roughness that may result from hummock formation and/or deepening inter-hummock channels, and perhaps from other factors. We agree that macrotopography, weather,

Fig. 6 (Colour figures online) Photograph taken October 2009 looking upstream (west) on PB Creek wetland inside the private pasture. This kind of annual post-grazing-season ground cover is likely a significant factor in reduced surface erosion and in soil organic matter accumulation, thus leading to its present low SRI. Photo: J. C. Likins

hydrology, soil type, and climate are likely also factors in hummock formation (Smith et al. 2012); however, both sides of the fencelines were equally exposed to all of these factors. The advantage of our study sites was the difference in grazing management–in isolating one potential hummock-forming factor from others. We find our evidence consistent with—not antipathetic to—the thesis that hummocks of grazed wetlands are formed surface-down by inter-hummock channels resulting from trampling, trailing, and grazing by domestic livestock, and from soil erosion that follows these wetland disturbances. Domestic-livestock grazing is our principal suspect as the major contributor, and perhaps the major cause, of the hummocks and inter-hummock channels that are, by far, the dominant microtopographic features contributing to surface roughness outside the exclosures on the wetlands we studied (Figs. 1b, 3).

SRIs averaged 50 % higher outside exclosures based on the photo method of four sites, and 75 % higher based on the EB analysis of six sites (Table 1). SRI's from both methods were correlated ($R = 0.71$, $n = 8$). The two methods are not, however, strictly comparable, in that the EB measures soil elevation, whereas the DEM models vegetation elevation. Hairsine et al. (1992) defined microtopography as the "soil structure at the soil-atmosphere interface when dry". Therefore, the DEM-derived SRI should be seen not as a replacement of traditional pin-height measurements, but rather as a second indicator of surface roughness that allows additional measurements. Depression water storage can be measured from a single DEM and soil erosion, sediment transport, or other net change in surface elevation, can be measured by comparison of two temporally-separated DEMs (Ullah and Dickinson 1979; Warner and Kvaerner 1998; Chandler et al. 2002; Mathews 2008).

Open water and moving vegetation (wind) caused problems with image alignment during photo modeling. Of 12 transects, only five were modeled fully. The remaining transects were modeled partially, from 6 to 91 %. Only transects with at least 90 % of the surface modeled were used for analysis. Wet meadow sites with open water like PB Creek (many small puddles) and Atlantic W (pond) were not modeled well. Sites with tall, fine vegetation, such as the 50-cm-tall grass



◀**Fig. 7** Aerial photographs of the PB Creek fenceline, acquired in late July or early August, displayed in grayscale for the years 1948 (**a**), 1974 (**b**), 1994 (**c**), and 2012 (**d**). Note similar conditions along the length of the stream before the fence was constructed (**a**), compared to fenceline differences in **b**, **c**, and **d**. By 1974 (**b**) the wetland above (to the *left* of) the fence is wider and more dense than below the fence, and this trend is repeated in the 1994 and 2012 images. The wetland vegetation color is lighter inside the pasture in 1974 and 1994. We speculate this is due to high amounts of ungrazed, senesced vegetation that both insulates the soil and delays greenup. As 2012 was a particularly hot, dry year, vegetation phenology was more advanced by late July, and we think the wetland growth inside the pasture had overtopped the older, senesced vegetation. The obvious dryness downstream in the 2012 image further supports this conjecture

at Long Creek, were not modeled successfully when sampled during high wind. Tie point nail frequency was insufficient to overcome an absence of stable natural features at these sites. A wider-angle lens or higher camera height would likely improve model creation by including more natural tie points and higher stereo overlap between images, but this would not overcome moving vegetation and open water.

Historical aerial photographs provide corroborating evidence of our findings and of the claim that inter-hummock channels dewater wetlands (Girard et al. 1997; Corning 2002; Johnson and Carey 2004; Fig. 1b). The PB fenceline had the lowest inside EB SRI (Fig. 6), an outside EB SRI 2.4 times greater, and therefore provides a revealing contrast. Functioning (Fig. 6) wetlands, like those inside the PB Creek pasture fence, slow, spread, and store water and are highly effective at sequestering carbon (Heede 1978, Naiman and Decamps 1997, Chimner and Cooper 2003, Miller and Fujii 2010). Figure 7 shows the PB Creek fenceline in grayscale from pre-fence (1948; year of fence construction is not known) through 2012, revealing wetland improvement—including the healing of cattle trails—over time inside the fence with an increasingly proper-functioning-condition wetland. The change-over-time sequence adds context to 2012 and 2013 color images showing the contrast in fenceline differences that we interpret as increased water storage (green vegetation) where EB SRI = 27 versus 64 (Fig. 8a, b; Google Earth 2013). These images provide additional evidence that hummocked lands lose water more rapidly than intact wetlands. As is illustrated in Fig. 2, the Sweetwater River and its tributaries are part of the Platte River/Missouri River

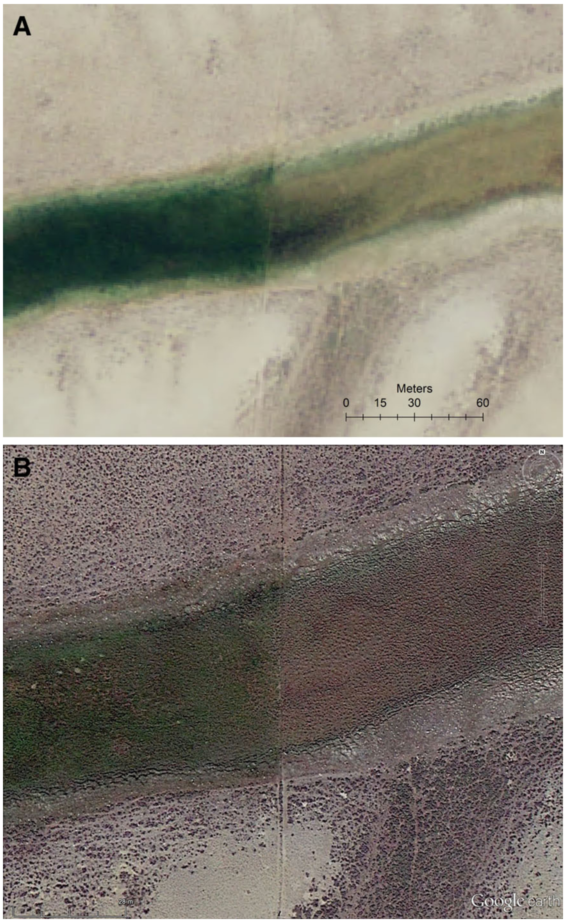


Fig. 8 (Colour figures online) **a** 2012 and **b** 2013 (drought-years) color aerial images of the PB Creek wetland showing fenceline differences. We interpret the images as showing greater water storage by the wetland with an SRI of 27 (on the *left*) compared to that with an SRI of 64 (on the *right*). **b** is a screen shot captured from Google Earth (2013).The fenceline differences are not due to herbage removal to the right of the fence since grazing unstressed vegetation would stimulate fresh green growth, which is not what the images depict. Rather, the vegetation to the right is largely dormant. We interpret the dormancy as resulting from lack of water

basins. During 2010 and 2011, nearly 3,700.5 million m^3 of water—enough water to fill Wyoming's Pathfinder Reservoir with its 188-km shore line, three times—crossed the Wyoming-Nebraska state-line gauge after all Wyoming North Platte reservoirs were full (personal communication, Matt Hoobler, Wyoming State Engineers Office, 7 Nov 2013). Water that leaves a region rapidly does not efficiently foster wildlife habitat, economic production, or aquifer recharge, and it can negatively impact downstream areas. Flood damage from western mountain streams and rivers in 2011 and 2013 was in the billions of dollars with damage in the Missouri and Souris River basins exceeding \$2 billion in 2011 (NOAA 2011A). Direct US-wide flood damages during water year 2011 (10/1/2010–9/30/2011) totaled a record \$8.4 billion (NOAA 2011B). Damage in Colorado from September 2013 flooding alone is estimated at \$2 billion (Coffman 2013). The more water stored in mountain wetlands and meadows, the less costly these types of floods will be and the more likely late-season, and drought-year streamflows will be sustained.

Conclusions

We reject the null hypothesis that grazing doesn't influence surface roughness and accept the alternative. The claims of Girard et al. (1997; northern Wyoming); Magnusson et al. (1998; Iceland), Jankovsky-Jones (1999; Idaho), Corning (2002; central Wyoming), and Johnson and Carey (2004; Colorado) are supported. There is a level of upland grazing that is consistent with conservation of associated wetland as is demonstrated by the condition of PB private pasture. Grazing intensities that annually leave wetland vegetation to senesce and build layer upon layer of organic matter are grazing intensities that will minimize wetland SRIs and maximize liquid water retention and storage (Fig. 6).

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