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Biogeochemical and ecological impacts of livestock grazing in semi-arid southeastern Utah, USA

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Abstract

Relatively few studies have examined the ecological and biogeochemical effects of livestock grazing in southeastern Utah. In this study, we evaluated how grazing has affected soil organic carbon and nitrogen to a depth of 50 cm in grasslands located in relict and actively-grazed sites in the Canyonlands physiographic section of the Colorado Plateau. We also evaluated differences in plant ground cover and the spatial distribution of soil resources. Results show that areas used by domestic livestock have 20% less plant cover and 100% less soil organic carbon and nitrogen compared to relict sites browsed by native ungulates. In actively grazed sites, domestic livestock grazing also appears to lead to clustered, rather than random, spatial distribution of soil resources. Magnetic susceptibility, a proxy for soil stability in this region, suggests that grazing increases soil erosion leading to an increase in the area of nutrient-depleted bare ground. Overall, these results, combined with previous studies in the region, suggest that livestock grazing affects both plant cover and soil fertility with potential long-term implications for the sustainability of grazing operations in this semi-arid landscape.

Keywords: Magnetic susceptibility; Moran's index; Nitrogen; Soil organic carbon

1. Introduction

Soil organic matter (SOM) is the organic fraction of soil consisting of plant and animal residues at various stages of decomposition, and the synthesized by-products of soil organisms. SOM influences cation exchange capacity (CEC), aggregate stability, and the energy supply central to the release and availability of nutrients for primary production and is therefore a key indicator of soil quality (Brady and Weil, 1999). Soil organic carbon (SOC), which directly relates to SOM, has been recognized as an indicator of rangeland health (NRC, 1994) because grazing affects SOC content (e.g. Milchunas and Lauenroth, 1993). However, the effect of grazing on SOC depends on many biotic and abiotic factors governed by climate and evolutionary history.

In the short-grass steppe of North America, SOC generally increases with the occurrence of grazing (Lecain et al., 2002; Manley et al., 1995; Schuman et al., 1999). This relation exists because the dominant

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bunchgrasses of the region co-evolved with large ungulate herds and possess adaptations that decrease surface disturbance impacts associated with grazing (Mack and Thompson, 1982; Stebbins, 1981). In contrast, landscapes in the inter-mountain west evolved without the presence of large ungulate herds, and consequently the dominant bunchgrasses of the region lack adaptations that impart resilience to surface disturbance. In the inter-mountain west, there is increasing evidence that grazing leads to widespread changes in the physical properties of soils (Belnap, 2003; Belnap and Gillette, 1998; Neff et al., 2005; Schwartzman and Volk 1991; Verstraete and Schwartz, 1991). However, the effect of livestock grazing on soil biogeochemistry and plant communities has been difficult to establish because few ungrazed areas remain in the region and those that do are difficult to access. In this study, we utilize relict areas that straddle multiple geologic substrates and soil types to compare soil and ecological properties to similar currently grazed settings. These relict sites have been minimally exposed to land use and domestic livestock grazing. A handful of studies have used relict areas to study the effects of grazing on vegetation composition (Brotherson et al., 1983; Harris et al., 2003; Jefferies and Klopatek, 1987; Kleiner and Harper, 1972); however, studies from relict areas emphasizing landscape-level gradients in soil properties are lacking. Understanding grazing and soil fertility interactions in the inter-mountain west should provide rangeland managers with additional tools for management of grazed lands.

In many cases, rangeland management decisions are based on the monitoring of vegetation cover and composition, indices that are responsive to livestock impacts and relatively simple to measure (Herrick et al., 2005). However, because vegetation indices are highly variable in arid and semi-arid ecosystems (Huenneke et al., 2002) measurement of soil biogeochemical properties may be an important integrative indicator of grazing impacts because progressive loss of soil fertility may have long-term implications for the sustainability of rangeland practices.

The goals of this study were to (1) assess differences in SOC, nutrient exchange capacity, vegetation cover, and the spatial distribution of soil resources between grazed and relict grasslands, as well as extent of soil erosion associated with grazing, and (2) investigate whether SOC and soil nitrogen (N) contents vary on the basis of soil parent material in the Canyonlands physiographic section of the inter-mountain west.

2. Materials and methods

2.1. Study area geology, ecology, and history

Our study sites were located in Utah, USA, in the Canyonlands physiographic section of the Colorado Plateau specifically. The Canyonlands physiographic section of the Colorado Plateau is approximately 1500 m above sea level and is characterized as a cold desert with a mean annual precipitation of 207 mm, mean annual maximum temperature of 20 °C, and mean annual minimum of 3 °C (http://www.wrcc.dri.edu/summary/climsmut.html). The soils of the area are derived from Quaternary sandstone and shale deposits primarily of Permian to Jurassic age.

In terms of grazing history, the region evolved in the absence of large herds of ungulate grazers (Mack and Thompson, 1982). The primary native ungulates of the region are mule deer and antelope that occur in small groups, preferring to browse rather than graze, and tend not to stay in a single location for too long (Armstrong, 1982). Domestic livestock grazing has occurred in the area since the 1880s (Hindley et al., 2000) and currently takes place on 90% of the region's land (http://www.fs.fed.us/land/pubs/ecoregions/ch36.html).

2.2. Site selection and location

An assessment of relict land-use areas developed by The Nature Conservancy (TNC) and the National Park Service (NPS) was used to identify relict and ungrazed sites (Van Pelt et al., 1992). Specifically, identification of study sites was done with the TNC and NPS assessment and by overlaying digitized geologic and soil maps of the region (Huntoon et al., 1982; US Department of Agriculture Soil Conservation Service, 1991). With this information we established and surveyed two relict and two grazed sites with soil derived from the Kayenta Formation and one relict and one grazed site on soil derived from Navajo Sandstone. In addition, we analyzed ungrazed and grazed soil derived from Cedar Mesa Sandstone from previously established sites.

All three relict sites were located in the Bridger Jack Mesa wilderness study area, an area administered by the Bureau of Land Management. Bridger Jack Mesa is approximately 15 km long and is 100–1000 m wide. Ranchers attempted to pasture horses on the mesa during the early 19th century, but animal casualties were high, so the practice was terminated. As a result, the area today is characterized as "relict" (Van Pelt et al., 1992). Since the mesa is accessible to native ungulates, its biological crusts have been partially disturbed; however, the visual impacts are not as severe as in surrounding livestock grazed areas. The two grazed Kayenta Formation settings were located at Hatch Point and Island in the Sky, and the single grazed Navajo Sandstone site was located in Shay Mesa. The ungrazed and grazed Cedar Mesa Sandstone sites were located in the Needles district of Canyonlands National Park. Hatch Point, Island in the Sky, Shay Mesa, and the Needles district of Canyonlands National Park are between 5 and 25 km away from Bridger Jack Mesa.

2.3. *Study design*

In the first component, we assess differences in the quantity of SOC and N between relict and grazed grasslands with soil derived from the Kayenta Formation. In addition, we evaluate vegetation cover, CEC, and the magnetic properties of these soils. We then examine the spatial distribution of SOC, soil magnetic properties, and soil fines (silt + clay) in order to assess how grazing affects the spatial distribution of soil resources.

In the second component of this study we compare SOC, N, for series of relict/ungrazed and grazed sites with soil derived from three different geologic substrates (Kayenta, Navajo, and Cedar Mesa) in order to examine broader landscape and land-use controls on SOM and soil physical properties in this region.

It can be very difficult to pair relict and grazed grasslands using USDA soil survey information because some of the attributes used to assign soil categories are themselves influenced by grazing (e.g. vegetation cover or composition). Accordingly, we use soil physical properties, chemistry, and soil profile morphology to establish similar sites. Our rationale is that similarities in soil texture, chemistry, and soil structure, combined with similarities in underlying bedrock geology and geomorphology, are the best ways to establish historic similarities among sites. Physical and botanical characteristics of our study sites are shown in Table 1, along with USDA soil-series names. Although paired sites in Kayenta and Navajo substrates have different USDA soil names, differences in the sub-surface physical, chemical, and morphological characteristics of these paired sites are minimal. For example, similarities in clay content between sites (Table 2) suggest that landscape setting and period of landscape stability are similar between site pairs. Additionally, calcic horizon development and soil color are similar across these Kayenta sites. Finally, differences in ecological site description are not apparent; *Stipa comata*, *Stipa hymenoides*, and *Sporobolus cryptandrus* are the dominant native plant species for all Kayenta Formation sites.

2.4. *Sampling method*

Prior to intensive sampling, a small set of samples was taken and analyzed for SOC and N. A power analysis conducted on this data indicated 37 samples from ungrazed and grazed sites would be needed to determine statistically significant site differences at $p < 0.05$. Additionally, a variogram was produced with this data in order to establish a sampling protocol. The variogram indicated that the majority of spatial variability without over-sampling would be with sample points separated by a distance of 9.7 m. As a result, sampling was done by establishing grids comprised of 10 × 10 m plots, in areas dominated by grass. Grids were 100–120 m long and 50–60 m wide in area.

At each plot, individual plant species were recorded as well as the percent cover of grass, forb, and shrub. From the center of each plot, a soil core representing the top 10 cm of the soil column was extracted with a volumetric soil corer (Soil Moisture Equipment Soil Core Sampler Model 0200). Soil cores were also taken 10–30 cm, and 30–50 cm from the same point as the shallow core. The 10–30 cm depth core was taken at every other plot, the 30–50 cm depth core was taken at every third plot.

The afore-mentioned sampling method was used on all Kayenta Formation and Navajo Sandstone sites. Sampling for Cedar Mesa Sandstone sites was accomplished by running belt transects and extracting soil cores every 20 m (Neff et al., 2005).

Table 1
Observed and mapped soil characteristics and vegetation cover for each site and NAD 1983 UTM northing (N) and easting (E) coordinates

Site name, geology, grazing history and UTM location	Slope (°)	Mapped USDA soil series name/taxonomic descriptor/ecological site descriptor	Dominant plant species
Kayenta 1, Relict, E: 620527, N: 4206422	4–5	Barx fine sandy loam/fine-loamy, mixed, mesic, Ustollic Haplargid/Basin Big Sagebrush	*Stipa comata*, *Stipa hymenoides*, *Bouteloua gracilis*, *Sporobolus cryptandrus*, *Poa secunda*, *Ceratoides lanata*, *Artemisia frigida*, *Atriplex canescens*, *Opuntia polyacantha*, *Sphaeralcea coccinea*, *Erodium cicutarium*, *Cryptanth tenuis*, *Guitierrezia sarothrae??*, *Senicio multilobatus*, *Phlox longifolia*, *Juniperus osteosperma*, *Pinus edulis*
Kayenta 1, Grazed, E: 617275, N: 4236520	4–5	Begay fine sandy loam/Coarse-loamy, mixed, superactive, mesic Ustic Haplocambids/Four-Wing Saltbrush	*Stipa comata*, *Stipa hymenoides*, *Bouteloua gracilis*, *Sporobolus cryptandrus*, *Hilaria jamesii Bromus tectorum*, *Ceratoides lanata*, *Artemisia tridenta*, *Atriplex canescens*, *Opuntia polyacantha*, *Sphaeralcea coccinea*, *Erodium cicutarium*, *Cryptanth tenuis*, *Snake grass*, *Salsola kali*, *Juniperus osteosperma*, *Pinus edulis*
Kayenta 2, Relict, E: 619120, N: 4204672	2–3	Barx fine sandy loam/fine-loamy, mixed, mesic, Ustollic Haplargid/Basin Big Sagebrush	*Stipa comata*, *Stipa hymenoides*, *Bouteloua gracilis*, *Sporobolus cryptandrus*, *Hilaria jamesii*, *Poa secunda*, *Bromus tectorum*, *Ceratoides lanata*, *Artemisia frigida*, *Opuntia polyacantha*, *Sphaeralcea coccinea*, *Erodium cicutarium*, *Cryptanth tenuis*, *Oenothera pallida*, *Phlox longifolia*, *Phlox austromontana*
Kayenta 2, Grazed, E: 609259, N: 4267023	2–3	Begay fine sandy loam/Coarse-loamy, mixed, superactive, mesic Ustic Haplocambids/Four-Wing Saltbrush	*Stipa comata*, *Stipa hymenoides*, *Bouteloua gracilis*, *Sporobolus cryptandrus*, *Hilaria jamesii Bromus tectorum*, *Ceratoides lanata*, *Artemisia tridenta*, *Opuntia polyacantha*, *Sphaeralcea coccinea*, *Erodium cicutarium*, *Cryptanth tenuis*, *Oenothera pallida*, *Salsola kali*
Navajo, Relict, E: 619333, N: 4205571	4–5	Barx fine sandy loam/fine-loamy, mixed, mesic, Ustollic Haplargid/Basin Big Sagebrush	*Stipa comata*, *Stipa Hymenoides*, *Bouteloua gracilis*, *Poa secunda*, *Poa fenestra*, *Bromus tectorum*, *Ceratoides lanata*, *Artemisia figida Ephedra viridis*, *Opuntia polyacantha*, *Sphaeralcea coccinea*, *Erodium cicutarium*, *Cryptanth tenuis*, *Delphinium andersonii*, *Pedicularis centranthera*, *Snake grass*, *Senicio multilobatus Juniperus osteosperma*, *Pinus edulis*
Navajo, Grazed, E: 629301, N: 4205324	4–5	Begay fine sandy loam/Coarse-loamy, mixed, superactive, mesic Ustic Haplocambids/Four-Wing Saltbrush	*Stipa comata*, *Stipa Hymenoides*, *Bouteloua gracilis*, *Poa secunda*, *Poa fenestra*, *Bromus tectorum*, *Ceratoides lanata*, *Artemisia tridenta Ephedra viridis*, *Opuntia polyacantha*, *Sphaeralcea coccinea*, *Erodium cicutarium*, *Cryptanth tenuis*, *Delphinium andersonii*, *Plantango patagonica*, *Snake grass*, *Senicio multilobatus*, *Draba cuneifolia Juniperus osteosperma*, *Pinus edulis*
Cedar Mesa, Ungrazed, E: 609345, N: 4222714	3–4	Coarse-loamy, mixed, superactive, mesic Ustic Haplocambids	*Stipa comata*, *Stipa hymenoides*, *Hilaria jamesii*, *Bromus tectorum*, *Ceratoides lanata*, *Artemisia tridenta*, *Opuntia polyacantha*, *Ephedra virdis*, *Atriplex canescens*, *Juniperous osteosperma*, *Pinus edulis*
Cedar Mesa, Grazed, N: 608423, E: 4225863	3–4	Coarse-loamy, mixed, superactive, mesic Ustic Haplocambids	*Stipa comata*, *Stipa hymenoides*, *Hilaria jamesii*, *Bromus tectorum*, *Ceratoides lanata*, *Artemisia tridenta*, *Opuntia polyacantha*, *Ephedra virdis*, *Atriplex canescens*, *Juniperous osteosperma*, *Pinus edulis*

Table 2
Means and standard error for SOC and N, percent sand, silt, clay, and total soil Al, Fe, Ca, P, Mg, Mn, and K for each Kayenta Formation site

Site	Kayenta 1 relict	Kayenta 1 grazed	Kayenta 2 relict	Kayenta 2 grazed
SOC (kg/m^2)	0.66 (0.02)	0.22 (0.01)	0.66 (0.02)	0.23 (0.01)
Interpolated SOC (kg/m^2)	0.66 (0.07	0.25 (0.05)	0.66 (0.05)	0.26 (0.05)
N (kg/m^2)	0.055 (0.002)	0.025 (0.002)	0.057 (0.002)	0.028 (0.001)
% Sand	65 (0.49)	69 (0.80)	57 (1.17)	58 (0.70)
% Silt	25 (0.41)	23 (0.47)	32 (0.89)	29 (0.44)
% Clay	9 (0.13)	9 (0.23)	11 (0.41)	13 (0.32)
Al (mg/g)	34.14 (0.53)	32.93 (1.11)	32.78 (1.60)	37.22 (0.98)
Fe (mg/g)	11.57 (0.24)	11.22 (0.40)	11.21 (0.56)	13.15 (0.33)
Ca (mg/g)	21.24 (2.47)	20.97 (1.46)	19.48 (2.24)	26.48 (1.27)
P (mg/g)	0.37 (0.02)	0.37 (0.02)	0.38 (0.02)	0.51 (0.04)
Mg (mg/g)	4.18 (0.12)	6.53 (0.21)	4.79 (0.21)	7.05 (0.22)
Mn (mg/g)	0.45 (0.01)	0.29 (0.01)	0.37 (0.01)	0.37 (0.02)
K (mg/g)	1.96 (0.06)	2.11 (0.05)	1.96 (0.04)	2.20 (0.06)

All values are for the 0–10 cm depth increment.

2.5. *Chemical and physical analyzes of samples*

For comparison of the grazed and relict Kayenta sites, all soil cores were analyzed for SOC and N content, soil texture, and magnetic susceptibility (MS). MS measures the concentration of ferrimagnetic and paramagnetic minerals but is always dominated by, magnetite when present. Recent investigations in the study region have shown that (1) sedimentary bedrock is essentially devoid of magnetite, but (2) soil made up of such bedrock contains relatively abundant silt-size magnetite introduced as atmospheric dust (Reynolds et al., 2001) and useful as a proxy for eolian soil erosion (Neff et al., 2005). In the studies by Reynolds et al. (2001) and Neff et al. (2005), soil magnetite content was determined with isothermal remanent magnetization (IRM), another measure of magnetite (Thompson and Oldfield, 1986). In this study, the use of MS was favored because measurement of MS is much more rapid than IRM. Only the 0–10 and 10–30 MS values are compared and presented. Additionally, three cores from each site, representing the 0–10, 10–30, and 30–50 cm depth increments, were used to measure total soil Al, Ca, Fe, K, Mg, Mn, and P content (Table 2) as well as the exchangeability of soil Ca, K, Mg, Mn, and P. Prior to soil analysis, soil cores were oven dried at 80 °C, weighed, and passed through a 2-mm sieve. The less-than-2-mm soil size fraction was then homogenously split for each analysis with a soil splitter.

2.6. *Organic C and N determination*

Soil organic carbon and N content was measured with an EA 1110 CNS combustion analyzer (Thermo Electron Corporation, Waltham, MA) at the Institute of Arctic and Alpine Research, University of Colorado. Prior to analysis, soil carbonate was removed by adding 15% HCl solution until effervescence was no longer observed. Soils were then pulverized with a ball mill (Spex Industries Inc., Metuchen, NJ).

2.7. *Soil texture measurement*

Soil texture was determined on a volume–percent basis with a Mastersizer 2000 (Malvern Instruments Ltd, Southborough, MA, USA). The Mastersizer 2000 uses a laser-light scattering method capable of measuring particles between 0.05 and 3840 μm and has an accuracy and reproducibility of ±1%. Prior to analysis, carbonate and organic matter were removed. Carbonate was removed by adding a 15% HCl solution as done for SOC and N analysis. Large organic particles were removed manually with tweezers and small particles were digested out with 30% H_2O_2. The Wentworth scale was used to assign class percentage breakdown for sand, silt, and clay.

2.8. Soil total element and exchangeable cation content

Total soil element concentrations were determined with inductively coupled plasma mass spectroscopy (ICP-MS) at the USGS laboratories in Denver, Colorado. Samples were ground to less than 150 μm and a 0.2 g aliquot of each sample was dissolved using a four acid (HF, HCl, HNO_3, and $HClO_4$) total digestion procedure.

Exchangeable cation concentrations (P, Mg, Mn, Ca, K) and total CEC were determined by washing soil with sodium acetate and then ammonium acetate as outlined by Hesse (1972). The sodium acetate washing was used to determine the exchangeability of specific cations and total CEC was determined with the ammonium acetate solution. Concentrations from each washing were determined at the Laboratory for Environmental and Geological Studies, University of Colorado, with the use of inductively coupled plasma atomic emission spectroscopy (ICP-AES).

2.9. Soil magnetic measurements

Soil MS measurements were made at the USGS laboratories in Denver. Magnetic measurements were performed by, placing lightly ground soil in 3.2 cm^3 plastic cubes and normalizing each cubed sample for mass. MS was measured in a 0.1 mT induction at a frequency of 600 Hz with a Sapphire II susceptometer (Sapphire Instruments, Ruthven, Ont., Canada) capable of measuring a magnetic field smaller than $4 \times 10^{-7}\,m^3/kg$.

2.10. Data and statistical analysis

Statistical analyzes were done with Statistica version 7.1 (Statsoft, Tulsa, OK) and ArcGIS (ESRI, Redlands, CA). Statistica was used for conducting nested multivariate analyzes of variance (MANOVA) and *T*-tests for independent samples by group. ArcGIS was used for interpolating SOC data and determining Moran's index for spatial autocorrelation. For all MANOVA analyzes, significantly different means and interactions were determined to be honestly different with Tukey's unequal N post-hoc test for honestly significant differences (HSD) at an alpha of 0.05. Standard errors (S.E.) are reported after each mean in brackets.

2.11. Differences between relict and grazed Kayenta Formation grasslands

Soil organic carbon, N, and plant cover density differences between relict and grazed Kayenta Formation sites were assessed with three separate MANOVAs. The first model, a nested factorial MANOVA, was used to determine differences in SOC and N. In this model, grazing history and soil depth acted as categorical variables and interactions. In the second model, a one-way MANOVA, plant cover density differences were assessed. In this second MANOVA model, percent grass, forb, shrub, and total cover acted as categorical variables. In the third MANOVA, a nested factorial, differences in MS were determined. In this model, grazing history and soil depth acted as categorical variables and interactions. Differences in CEC and exchangeable cations were assessed by, conducting *T*-tests for independent samples by group. In this analysis, independent samples were grouped on the basis of land-use history. Soil depth was not used as a category in this analysis; therefore, the results represent values for the top 50 cm of the soil sampled. To examine differences among the spatial distribution of SOC, soil magnetic properties, and soil fines between relict and grazed Kayenta Formation grasslands, we used Moran's index for spatial autocorrelation. Moran's index measures the spatial autocorrelation of geo-referenced variables and evaluates whether their distribution is clustered, dispersed, or random. A Moran's index value near $+1.0$ indicates clustering, a value near -1.0 indicates dispersion, and a value near zero indicates a random distribution. Each calculated Moran's index value has a calculated *z*-score. The statistical significance of clustered or dispersed distribution is determined by comparing *z*-scores to a range of confidence intervals. For example, in order for a clustered or dispersed distribution to be statistically significant at a *p* of 0.05 or 0.01, the *z*-score has to be between -1.96 and 1.96 or -2.58 and 2.58, respectively. Additionally, we used kriging to better understand differences in the spatial distribution of surface SOC and better estimate and illustrate site-level SOC stocks.

2.12. Parent material controls on soil responses to grazing

A nested MANOVA analysis was done in order to determine variation in SOC and N content for soil derived from different parent material. In this analysis, the categorical variables were grazing history and soil-parent material (Kayenta, Navajo, and Cedar Mesa). For this analysis, only surface values (0–10 cm) of SOC and N are compared. We additionally conduct linear regressions between soil fines and SOC for each site and the entire data set.

3. Results

3.1. Differences between relict and grazed Kayenta Formation grasslands

Relict Kayenta Formation grassland SOC and N means were significantly higher than those of grazed settings (Wilks = 0.418, $F = 199$, effect d.f. = 2, error d.f. = 286, $p = <0.00$). The differences in SOC and N were also significant with grazing history and soil depth as interactions (Wilks = 0.507, $F = 28.9$, effect d.f. = 8, error d.f. = 572, $p = <0.00$).

Across all soil depths, relict sites had more SOC than grazed sites. Relict grasslands had 124%, 112%, and 100% more SOC for the 0–10, 10–30, and 30–50 cm soil horizons, respectively (Fig. 1, panel A). In surface 0–10 cm horizons, relict grasslands had 0.66 (0.014), whereas grazed had 0.25 (0.005) kg C/m^2. At 10–30 and 30–50 cm below the surface, relict grassland SOC measured 0.41 (0.017) and 0.36 (0.017) kg C/m^2, whereas grazed grasslands had 0.18 (0.004) and 0.18 (0.008) kg C/m^2 at 10–30 and 30–50 cm, respectively.

Differences in soil N between relict and grazed grasslands followed the same trend as SOC. Soil N in relict grasslands was 106%, 92%, and 92% higher than in grazed at 0–10, 10–30, and 30–50 cm (Fig. 1, panel B). At 0–10, 10–30, and 30–50 cm relict grassland N values were, respectively, 0.062 (0.001), 0.043 (0.001), and 0.039 (0.002) kg N/m^2, whereas grazed grasslands soil N at the same depths, respectively, measured 0.029 (0.001), 0.023 (0.001), and 0.021 (0.001) kg N/m^2.

3.2. Kayenta Formation relict and grazed differences in vegetation cover

Relict and grazed grasslands had essentially the same plant-species composition (Table 1); however, these settings had significant differences in ground cover of grass, forb, shrub, and total (grass + shrub + forb) cover (Wilks = 0.294, $F = 146.39$, d.f. = 3, $p = <0.001$, d.f. = 3) (Fig. 2). According to univariate results from the one-way MANOVA, the difference in total cover contributed most to the overall F-test value ($F = 371.74$).

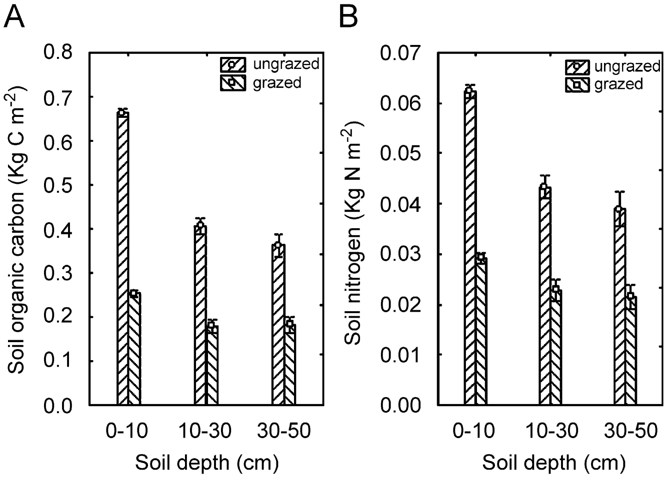

Fig. 1. Nested factorial MANOVA results showing differences in soil organic carbon (panel A) and nitrogen (panel B) with grazing history and soil depth as interactions for Kayenta Formation grasslands. Error bars show standard error.

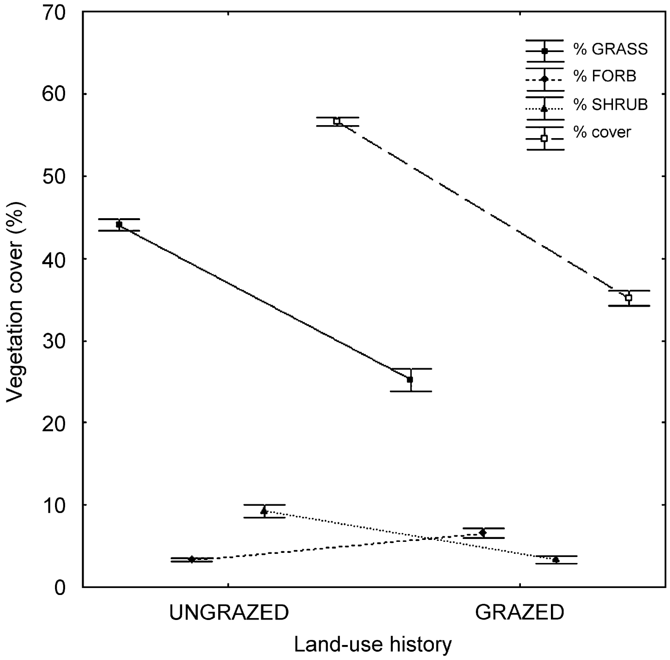

Fig. 2. One-way MANOVA results showing differences in ground, grass, forb, and shrub cover (in %) between ungrazed and grazed landscapes.

Mean total cover in relict grasslands measured 56.57% (0.52) but only 35.09% (0.96) in grazed grasslands, 38% lower. In terms of plant functional type, differences in grass cover were greatest between relict and grazed grasslands (univariate result of the one-way MANOVA, $F = 131.51$), followed by shrub ($F = 37.01$) and forb cover ($F = 23.49$). Grass cover in the relict grasslands was approximately two times greater (44.01%, S.E. = 0.76) than in grazed (25.21%, S.E. = 1.42). Shrub cover in the relict grasslands was approximately three times higher than in grazed (9.24% (S.E. = 0.87) vs. 3.33% (S.E. = 0.46)). Forb cover in the relict grasslands was lower (3.31%, S.E. = 0.25) than in grazed (6.54%, S.E. = 0.59).

3.3. Kayenta Formation relict and grazed differences in MS

Magnetic measurements indicate that grazed sites have experienced more erosion than relict. Differences in MS between ungrazed and grazed sites were significantly different for the 0–10 and 10–30 cm depths ($F = 174.93$, d.f. = 2, $p < 0.00$). Relict grassland MS values at 0–10 and 10–30 cm depths, respectively, measured 2.96×10^{-7} (0.057) and 2.75×10^{-7} (0.100) m^3/kg (Fig. 3). Grazed grassland MS values at these depths measured 1.83×10^{-7} (0.037) and 1.75×10^{-7} (0.036) m^3/kg, respectively, 38% and 36% lower than relict grassland MS. Differences in MS between relict and grazed pairings decreased with soil depth. Mean MS values for ungrazed Kayenta 1 compared to grazed Kayenta 1 were 42% and 37% higher at 0–10 and 10–30 cm, respectively. Mean MS values for the Kayenta 2 pairing follow the same trend as that of the Kayenta 1 pairing. MS for ungrazed Kayenta 2 was 38% and 24% higher than that of grazed Kayenta 2 at 0–10 and 10–30 cm, respectively.

3.4. Relict and grazed CEC and exchangeable cation differences

Mean CEC was significantly higher for relict Kayenta Formation grassland soil than grazed (Table 3). Although mean total soil P and Mg values were higher for grazed grasslands, exchangeable P, Mg, and Mn values were greater for relict grassland soil than grazed. Differences in exchangeable Ca and K were not significant on the basis of land-use history.

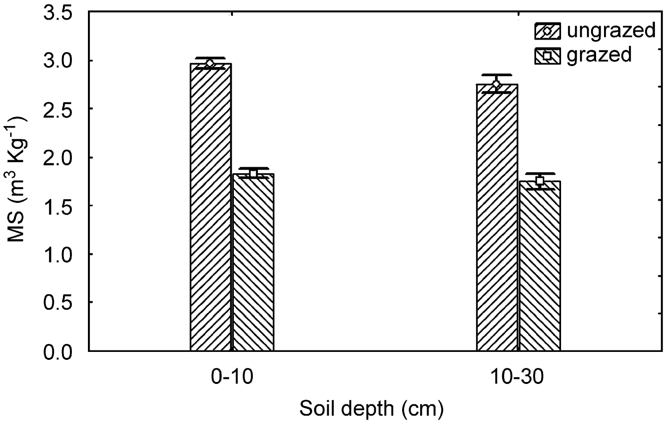

Fig. 3. Nested factorial MANOVA results showing differences in soil MS with grazing history and soil depth as interactions for Kayenta Formation grasslands. Error bars show standard error.

Table 3
T-test results for soil CEC and exchangeable P, Mn, Mg, Ca, and K for ungrazed and grazed Kayenta Formation settings

Variable	Mean and S.E. (ungrazed)	Mean and S.E. (grazed)	*T*-test value	d.f.	*p*	S.D. (ungrazed)	S.D. (grazed)
CEC m.e./100 g soil	15.46	12.68	6.37	24	<0.00	1.4	0.8
Exchangeable P (mg/g)	0.0040	0.0029	4.93	24	<0.00	0.0003	0.0007
Exchangeable Mn (mg/g)	0.0017	0.0008	2.66	24	0.013	0.0012	0.0002
Exchangeable Mg (mg/g)	0.075	0.061	2.70	24	0.013	0.0101	0.015
Exchangeable Ca (mg/g)	0.64	0.64	0.047	24	0.962	0.15	0.09
Exchangeable K (mg/g)	0.12	0.11	0.3966	24	0.695	0.03	0.03

Values represent means for the 0–50 cm depth section of the soil profile.

3.5. Spatial distribution of soil properties

The spatial distribution of SOC and MS on all ungrazed sites was random (unclustered) according to Moran's index for spatial autocorrelation, (Table 4). In contrast, SOC and MS on grazed sites spatially clustered in distribution, except for SOC in the grazed Kayenta 2 site, where it was random, but at a *p* of 0.1. The spatial distribution of soil fines was clustered on all sites, except for the ungrazed Kayenta 2 site where the distribution of soil fines was random.

Soil organic carbon means for interpolated data were similar to the geometric mean (Table 1). Interpolated results show that SOC is higher throughout relict sites (Fig. 4). Additionally, interpolation maps show SOC to be more uniformly distributed in relict areas; but the contrast between relict and grazed settings is more evident where the slope is greater.

3.6. Variation in SOC and N for grassland soils derived from different parent material

Soil organic carbon and nitrogen concentrations were significantly higher in all relict and ungrazed grasslands (Wilks = 0.45, $F = 182.49$, effect d.f. = 2, error d.f. = 304, $p<0.00$). Each relict site had approximately twice as much SOC and N than its grazed counterpart (Fig. 5). Differences in SOC and N were also evident amongst the soils derived from different parent material (Wilks = 0.82, $F = 7.93$, effect d.f. = 8, error d.f. = 608, $p<0.00$). Grasslands on Navajo Sandstone soil had significantly more SOC and N under both relict and grazed conditions than other grasslands. Mean SOC and N for relict Navajo, relict Kayenta, and ungrazed Cedar Mesa grasslands measured 0.75 (0.026) and 0.077 (0.002), 0.66 (0.014) and 0.062

Table 4
Moran's Index value, z-score, p, and statistically assigned spatial distribution for surface (0–10 cm) soil organic carbon (SOC), magnetic susceptibility (MS), and soil fines

Variable	SOC	MS	% Fines	SOC	MS	% Fines
Site & History	Kayenta 1 ungrazed	Kayenta 1 ungrazed	Kayenta 1 ungrazed	Kayenta 1 grazed	Kayenta 1 grazed	Kayenta 1 grazed
Moran's index	−0.02	−0.03	0.03	0.10	0.09	0.11
z-Score	0.03	−0.03	2.7	2.5	4.2	6.5
p	NA	NA	0.01	0.05	0.01	0.01
Distribution	Random	Random	Clustered	Clustered	Clustered	Clustered
Site and history	Kayenta 2 ungrazed	Kayenta 2 ungrazed	Kayenta 2 ungrazed	Kayenta 2 grazed	Kayenta 2 grazed	Kayenta 2 grazed
Moran's index	−0.04	−0.04	−0.02	0.03	0.09	0.10
z-Score	−0.05	−0.07	0.04	−0.05	5.8	2.2
p	NA	NA	NA	0.1	0.01	0.05
Distribution	Random	Random	Random	Clustered	Clustered	Clustered

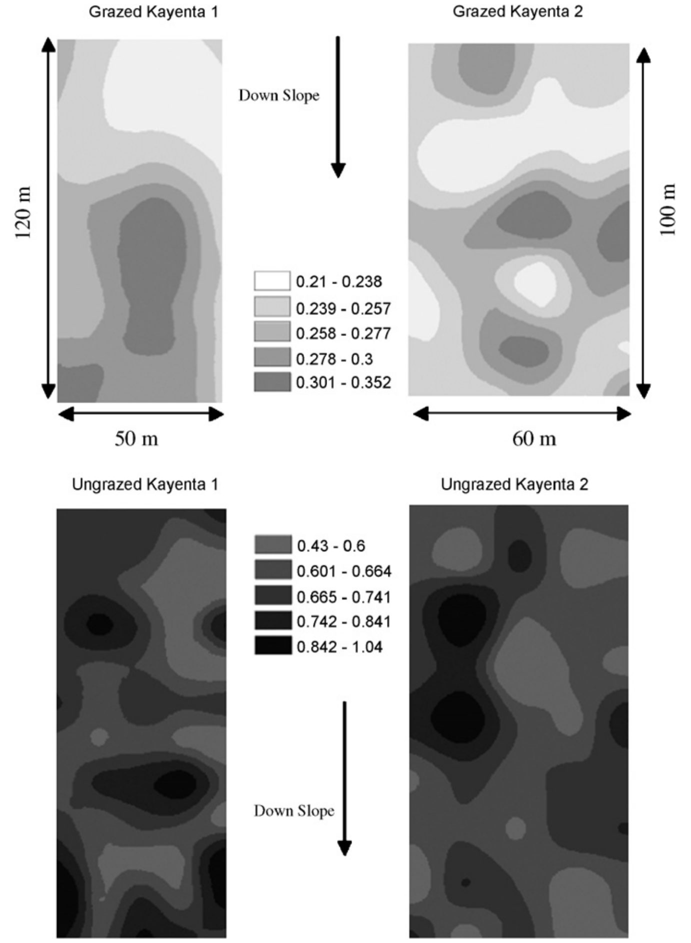

Fig. 4. Krig interpolated SOC maps for Kayenta Formation grasslands.

(0.001), and 0.54 (0.057) and 0.051 (0.001), respectively. Mean SOC and N for grazed Navajo, Kayenta, and Cedar Mesa grasslands measured 0.35 (0.009) and 0.034 (0.001), 0.25 (0.004) and 0.029 (0.001), and 0.23 (0.033) and 0.022 (0.005), respectively.

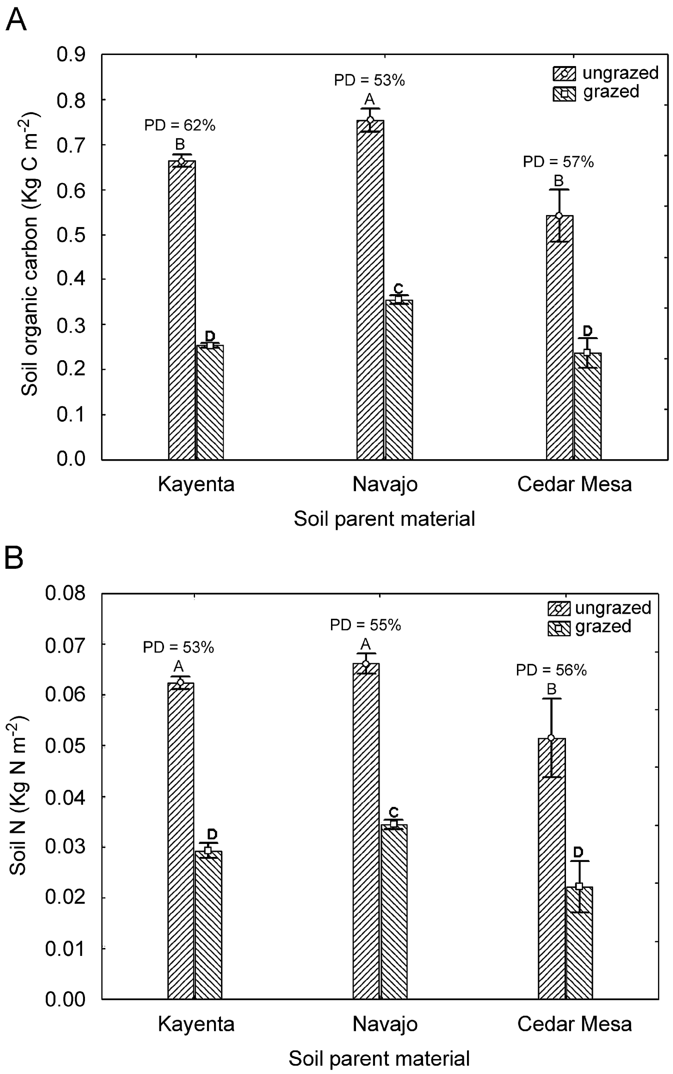

Fig. 5. Nested factorial MANOVA results showing differences and percent decrease (PD) in SOC and N for relict/ungrazed and grazed grasslands of different parent material. Bars with the same letter are not significantly different according to Tukey's unequal N post-hoc test for HSD.

For each individual grassland, soil fines and SOC correlated positively; however, the relationship was weak in every case (Table 5). A stronger correlation between soil fines and SOC occurred under relict/ungrazed land-use than grazed. Overall, the regression cloud shows that relict/ungrazed and grazed grassland SOC clusters within the same range of soil fines but that ungrazed/relict grassland SOC clusters above grazed and has a greater range (Fig. 6).

4. Discussion

Soil organic carbon, N, vegetation cover, MS, and the exchangeability of soil cations appear to be influenced by grazing history in the Canyonlands area. All of these indicators of soil fertility are consistently higher in grasslands where domestic livestock grazing does not occur. On average, SOC and N values were approximately two times higher without the occurrence of grazing regardless of soil parent material. There were also differences in the spatial distribution of soil resources with grazing history of sites. Relict grasslands derived from Kayenta Formation parent material had randomly distributed SOC and MS, but livestock

Table 5
R^2 and p-values for percent soil fines (silt + clay) and soil organic carbon linear regressions

Soil parent material and history	R^2	p
All parent materials and both histories	0.10	<0.00
All parent materials only ungrazed	0.12	<0.00
All parent materials only grazed	0.01	0.014
Ungrazed Kayenta Formation	0.17	<0.00
Grazed Kayenta Formation	0.01	0.17
Ungrazed Navajo Sandstone	0.06	0.03
Grazed Navajo Sandstone	0.08	0.04
Ungrazed Cedar Mesa Sandstone	0.001	0.93
Grazed Cedar Mesa Sandstone	0.35	0.01

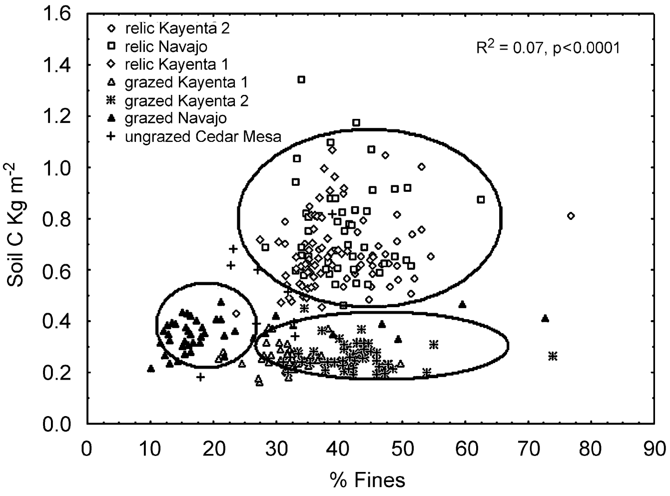

Fig. 6. Scatterplot showing correlation between SOC and soil fines for the 0–10 cm soil depth increment.

grazed sites were spatially clustered. This study and others suggest that decreases in plant density, SOC, and N in arid ecosystems are at least in part due to destabilization of soil by domestic livestock that causes soil to be redistributed by wind and water (Huenneke et al., 2002; Neff et al., 2005; Schlesinger et al., 1990). In this study, differences in MS between relict and grazed grasslands reflect soil erosion. However, this study also suggests that the net depletion of SOC and N associated with grazing induced soil erosion may be mediated by soil-parent material chemistry.

4.1. Differences between relict and grazed Kayenta Formation grasslands

In grasslands located on the Kayenta Formation, for each soil-depth increment evaluated, SOC and N were approximately two times greater in relic than grazed settings. Grazed areas also had roughly 50% less grass and shrub cover and 38% less total vegetation. These results suggest that productivity is lower in grazed Kayenta grassland compared to relict. Declines in productivity are generally related not only to a decrease in vegetation but to deterioration of soil as well (Dregne, 1986). For example, studies have shown that as vegetation cover decreases, susceptibility to soil erosion and loss of rock-derived nutrients increases (Ali, 1998; Leys, 2002; Palis et al., 1997; Schlesinger et al., 2000). However, in most studies, it is difficult to establish clearly whether affected settings undergo net loss of nutrients (e.g. Neff et al., 2005) or redistribution of nutrients (e.g. Schlesinger et al., 1990).

Research by Reynolds et al. (2006) indicates that nutrients delivered as atmospheric mineral dust are a source of soil nutrient pools in the study area and that far-traveled eolian dust accounts for 40–80% of rock-derived soil nutrients for near-surface soil in undisturbed areas of this region. Reynolds et al. (2001) also shows that magnetic properties of surficial deposits of the region serve as a proxy for the addition far-traveled eolian dust. Inputs of far-traveled eolian dust in surface soil should be similar across landscapes with similar geomorphology and in close proximity. For these reasons, lower soil MS in grazed vs. relict Kayenta Formation grasslands are interpreted as the result of more soil erosion in grazed settings. Previous work by Neff et al. (2005), in this region, used magnetic mineral content of soil to show how livestock grazing has resulted in soil erosion and a net loss of nutrients for the top 10 cm of soil. In this study, MS measurements suggest the top 30 cm of soil has had a net loss of nutrients.

Research by Hook et al. (1991) shows that in xeric grasslands and shrublands, soil resources are concentrated in vegetated areas surrounded by resource-depleted bare ground; however, vegetation and soil resources are more spatially homogeneous in grasslands than shrublands (Schlesinger et al., 1996; Smith et al., 1994). Nonetheless, how surface disturbance effects the spatial distribution of soil nutrients in drylands is variable. In some cases, soil nutrients become more concentrated per unit area (Bolton et al., 1993), with or without a net loss of nutrients from the system (Schlesinger et al., 1990; Whitford, 1995). In the grasslands studied here, grazing appears to have induced SOC and MS to become spatially clustered, leading to an increase in nutrient-depleted bare ground along with a large net loss of SOC and rock-derived nutrients. For example, results from component one of this study show that grazed sites have 38% more bare ground, approximately two times less SOC and N, and MS has decreased by approximately 33%. The effects of nutrient redistribution and spatial clustering, which have been described as ‘‘islands of fertility’’, may be more accurately described by reference to the surrounding oceans of nutrient-depleted soil in those sites.

An additional issue with SOM status in these ecosystems is the lack of soil textural control on SOM pools (Fig. 6). Typically protected (and thus resistant to disturbance) SOM is located on silt and clay mineral surfaces or in aggregates. In this region, SOM appears to be mostly found in a particulate form partially explaining why soil SOM stocks are so highly susceptible to soil erosion and decomposition following disturbance.

4.2. Variation in SOC and N for grassland soils derived from different parent material

In our study area, the distribution SOM appears to be controlled primarily by land-use and to a lesser extent by soil-parent material. In the Canyonlands region, the elemental content of parent material varies widely, so that there are areas of relatively high- and low-nutrient availability distributed across the region (Neff et al., 2006). Phosphorus availability, in particular, varies with bedrock type primarily because of how P interacts with Fe, Al, and Ca content in soil (Jurinak et al., 1986; Lajtha and Bloomer, 1988, Lajtha and Schlesinger, 1988a). This variation may be important to range management because P availability can limit plant productivity in arid ecosystems (Lajtha and Schlesinger, 1988b; Whitford, 2002). Across all substrates studied here, Navajo Sandstone has very low Ca, Al, and Fe content and higher P availability compared to soil derived from different parent material in the area (Neff et al., 2006). In this study, Navajo Sandstone grassland has the smallest grazed/relic differences in SOC and N pools (Fig. 5) suggesting that these settings may be less susceptible to grazing-induced changes in organic matter cycling. At this stage, we can only speculate on the potential role of bedrock in ecosystem response to land use, but these findings suggest that an improved understanding of the geologic and geochemical framework of the ecosystems could potentially help inform land-management decisions.

5. Conclusion

Research from relict landscapes provides baseline indices for assessing how land-use practices affect ecosystem properties. In this study, we found SOC and N to be two times greater in relict than in currently grazed settings. Neff et al. (2005) found the same SOC and N result when comparing an ungrazed setting to one having 30 years of recovery from grazing. Gardner (1950) compared an arid landscape area free from grazing for 30 years to an adjacent grazed site and found 46% more plant cover in the ungrazed site. Although declines in plant cover, SOC, and N associated with livestock grazing have been observed elsewhere (see Asner et al., 2003; Huenneke et al., 2002) there are very few comparisons of grazed and relict setting on the Colorado

Plateau. Combined with previous research, findings from this study indicate that recovery from grazing disturbance requires more than 30 years, significantly longer than in more mesic regions.

Existing indicators of rangeland health are primarily qualitative and temporally variable in the arid southwest. Use of SOC and MS (where mineralogically feasible) combined with Moran's index for spatial autocorrelation may prove useful for assessing ecosystem structural change in a more quantitative manner. In addition, more extensive use of temporally stable variables such as SOC and N would permit quantitative long-term monitoring of range condition. Moreover, monitoring and comparing MS, SOC, N, and soil nutrients in range soils derived from different parent materials should be performed to ensure sustainability of all portions of the landscape. These types of measurements can also provide useful information on the potential resilience of different sites to grazing disturbance. Additional research is needed to understand the interactions among stocking rate, grazing duration, the fertility and texture of soil parent material, and duration of recovery.

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