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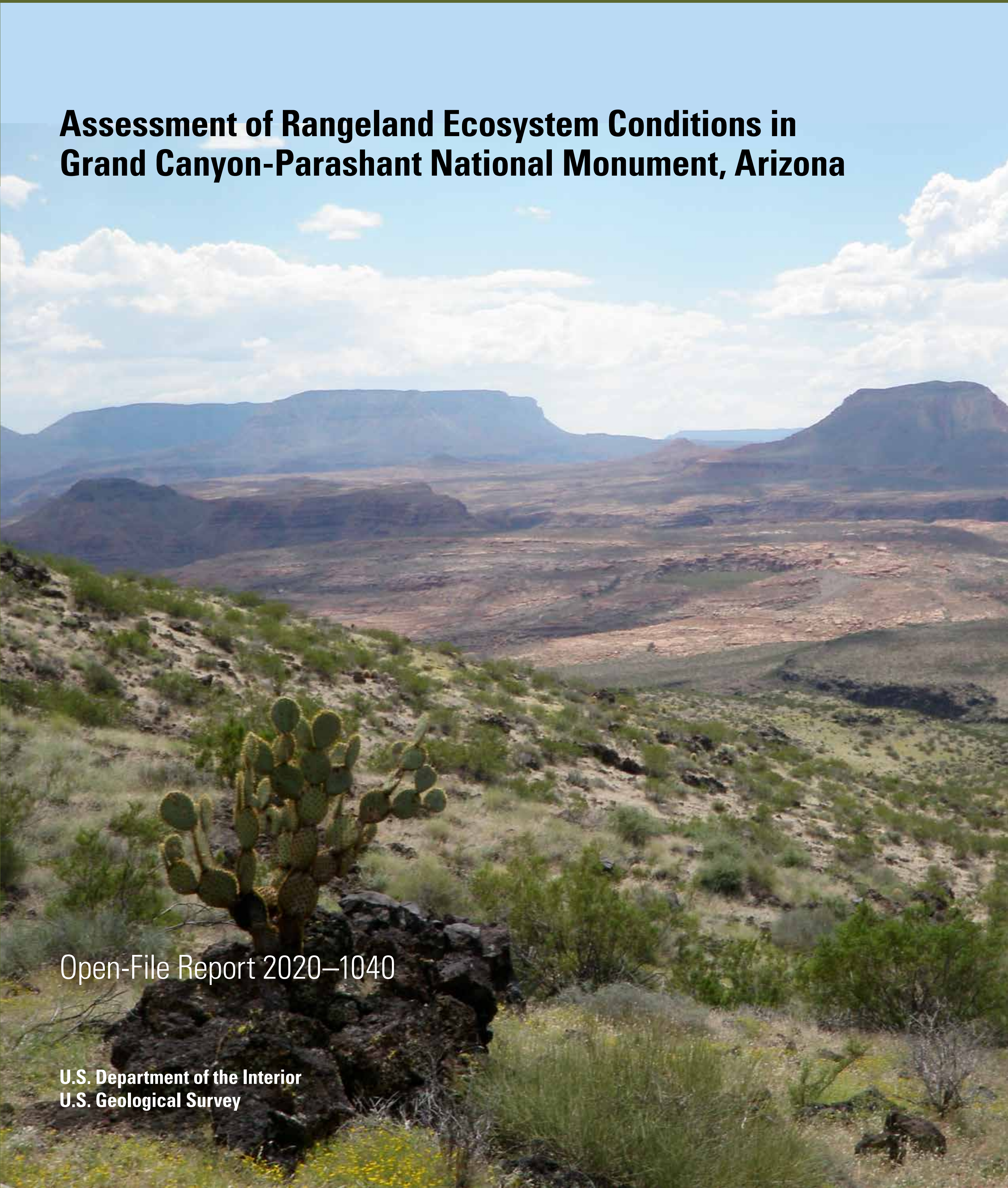

Assessment of Rangeland Ecosystem Conditions in Grand Canyon-Parashant National Monument, Arizona

Open-File Report 2020–1040

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph of the southern part of Whitmore Canyon, Grand Canyon-Parashant National Monument, Arizona. Photograph by E.C. Palmquist.

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By Michael C. Duniway and Emily C. Palmquist

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as

$$°C = (°F - 32) / 1.8.$$

Abbreviations

BLM	Bureau of Land Management
ca.	circa
cm	centimeters
CRA	Conservation Resource Area
DEM	Digital Elevation Model
DIMA	Database for Inventory, Monitoring, and Assessments
ESD	ecological site description
ESG	ecological site groups
GMP/RMP	Joint NPS Grazing Management Plan/BLM Resource Management Plan
GPS	Global Positioning System
GRTS	general randomized tessellation stratification
ha	hectares
LPI	line point intercept
m	meters
mm	millimeters
MLRA	Major Land Resource Area
N	number
NMS	nonmetric multidimensional scaling
NPS	National Park Service
NRCS	Natural Resources Conservation Service
p	probability value
r	correlation coefficient
spp.	species
TWI	topographic wetness index
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

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Abstract

Sustainability of dryland ecosystems depends on the functionality of soil-vegetation feedbacks that affect ecosystem processes, such as nutrient cycling, water capture and retention, soil erosion and deposition, and plant establishment and reproduction. Indicators that represent these fundamental processes are central to many approaches for ecosystem assessment and monitoring in drylands—collectively they are referred to as "rangeland health." Evaluation of rangeland health relies on describing the condition and sustainability of these individual, measurable, or observable indicators that are linked to important ecosystem processes. Useful, common indicators can provide information on soil and site stability, hydrologic function, and biotic integrity. Quantitative approaches to rangeland health evaluations allow for robust and reliable evaluations of trends through time (that is, monitoring) and serve as the basis for several national rangeland monitoring programs. However, management-relevant interpretations of rangeland health assessments require contextual information on how soils, landscape, and climate setting are shaping ecosystem qualities and some estimate of what constitutes target values of a healthy system.

The approximately one-million-acre Grand Canyon-Parashant National Monument is located in the northwest corner of Arizona and co-managed by the Bureau of Land Management (BLM) and National Park Service (NPS). This report focuses on the circa (ca.) 200,000 acres of NPS-administered lands in the monument—one of the largest NPS units where livestock grazing is a permitted land-use activity. Many ecosystems in the monument are characterized by a low degree of resilience to improper grazing because of low and variable precipitation. Grand Canyon-Parashant National Monument is marked by a high degree of environmental heterogeneity, including a large elevation gradient, widely differing precipitation patterns, a diversity of geologic substrates, and unique combinations of plant species.

The objective of this report is to (1) increase our understanding of the underlying landscape, soil, and climate setting factors that affect Grand Canyon-Parashant National Monument dryland ecosystem structure and function (also referred to as land potential) and (2) characterize the condition of Grand Canyon-Parashant National Monument ecosystems in relation to management concepts, such as rangeland health. The results discussed here on ecosystem condition, coupled with the increased understanding of soil-geomorphic controls on vegetation distribution within Grand Canyon-Parashant National Monument, provide information to help managers develop appropriate livestock management strategies.

Locations for rangeland assessments were selected using a stratified, spatially balanced random sampling method based on allotment, soil type, slope, distance to cattle water locations, and accessibility. A total of 155 plots were established and sampled between March and November of 2012 and 2013. Data collection at each plot included soil-geomorphic setting descriptions, plant and soil cover, and soil aggregate stability. Data were analyzed by elevation zone using both univariate and multivariate approaches. Survey results document the high level of diversity within the study area, including 15 unique soil taxa (to great group level) and 271 species of plants. We collected three new plant species for Grand Canyon-Parashant National Monument and 17 new species for the NPS portion of Grand Canyon-Parashant National Monument.

Results also document a strong association between rangeland health indicators and elevation, topographic setting, and soils. Soil factors found to explain important variation across plots include the amount of exposed bedrock, soil rockiness, soil texture (and associated hydrologic properties), and soil depth. We also found that dominant species turnover across elevation may represent species' differences in adaptation to climates, including *Larrea tridentata*, *Coleogyne ramosissima*, and *Artemisia* spp. *Bromus rubens* is the most common invasive species of concern recorded in this study, but other common invasive species are *Bromus tectorum*, *Erodium cicutarium*, and *Schismus arabicus*. Correlations between an index of cattle use and indicators of rangeland health suggest that areas with high cattle use have increased bare ground, decreased ground cover, increased frequency of *Schismus arabicus*, decreased cover of *Coleogyne ramosissima* and *Ephedra* spp., and increased cover of *Gutierrezia* spp. The few strong correlations observed between indicators of vascular plant community cover or abundance and indicators of cattle activity support rangeland assessment and monitoring strategies that do not rely solely on plant-based indicators are needed.

This work supports management of dryland ecosystems, including Grand Canyon-Parashant National Monument, using concepts of land potential. Land-potential-based classification systems use climate, soils, and topographic properties to classify landscapes based on potential productivity, composition, and response to climate and management. We conclude the report with recommendations on improving existing land-potential-based classification systems, associated interpretations, and methods for moving forward with a Grand Canyon-Parashant National Monument rangeland monitoring program.

Introduction

Sustainability of dryland ecosystems, including ecosystem resilience to climate disturbances and anthropogenic stressors, depends on ecosystem capacity for capturing and retaining scarce resources (Whitford, 2002). This capacity is largely controlled by soil-vegetation feedbacks that affect ecosystem processes, such as nutrient cycling, water capture and retention, and soil erosion and deposition, as well as plant demographic processes, such as establishment and reproduction (Tongway and Ludwig, 1997; Whitford, 2002). Because of their importance for the functionality and dynamics of dryland ecosystems, as well as their sensitivity to land-use impacts (Tongway and others, 2003; Neff and others, 2005), indicators of these processes are central to many approaches for ecosystem assessment and monitoring in drylands and collectively referred to as "rangeland health" (National Research Council, 1994; Pyke and others, 2002; Tongway and Hindley, 2004; Herrick and others, 2005; Pellant and others, 2005).

Evaluation of rangeland health does not rely on one single response variable, but rather a suite of fundamental attributes that describe the condition and sustainability of drylands. Three attributes are increasingly recognized as fundamental to condition and sustainability: soil and site stability, hydrologic function, and biotic integrity (National Research Council, 1994; Pyke and others, 2002). Soil and site stability refers to the capacity of a plot or area to minimize redistribution and otherwise retain soil resources against the erosive forces of wind and water. Hydrologic function pertains to a plot or area's ability to capture, store, and safely release incoming precipitation or overland flow. Biotic integrity refers to a plot or an area's biotic community, including plants, animals, insects, and soil biota, and its ability to support ecological processes and recover these processes when disturbed. Assessment of rangeland health attributes uses individual, measurable indicators that are linked to important ecosystem processes, such as amount of foliar cover or exposed bare ground. Evaluation of the three attributes of rangeland health utilizes both qualitative assessments (Pyke and others, 2002; Herrick and others, 2010) and quantitative approaches (Herrick and others, 2005; Duniway, Herrick, and others, 2010; Duniway and Herrick, 2013) (table 1).

Quantitative approaches to rangeland health evaluations allow for robust and reliable evaluation of trends through time (monitoring) and serve as the basis for several national and regional rangeland monitoring programs (Nusser and Goebel,

Table 1. Indicators of rangeland health, association with attributes, and brief description (adapted from Pellant and others [2005] and Duniway, Herrick, and others [2010]).

[SSS, soil and site stability; HF, hydrologic function; BI, biotic integrity; cm, centimeters; mm, millimeters; m^2, square meters]

Quantitative indicator	Expected correlation[1]	Attribute SSS	Attribute HF	Attribute BI	Description
Basal gaps >200 cm	−	●	●		Fraction of plot in basal gaps >200 cm
Canopy gaps >100 cm	−	●	●		Fraction of plot in canopy gaps >100 cm
Bare ground	−	●	●		Fraction of plot with no foliar, litter, or soil cover
Ground cover	+	●			Fraction of plot with ground cover (biological soil crust, litter, rock, basal)
Biological soil crust	+	●			Summed cover of dark cyanobacteria, lichen, and moss
Lichen	+	●		●	Fractional soil cover of lichens
Moss	+	●		●	Fractional soil cover of mosses
Soil surface (top few mm) resistance to erosion	+	●	●	●	Average soil aggregate stability index (1–6) measure of water stable aggregates
Functional/structural groups	+/−		●	●	Fractional cover by plant life form and duration
Species cover	+/−			●	Species diversity and fractional cover of important native species
Litter cover	+		●	●	Fractional cover of litter (herbaceous or woody)
Total foliar cover	+			●	Total fraction of plot with foliar cover
Invasive species	−			●	Rooted frequency (1 m^2 quadrat) of species of concern

[1]Expected correlation (positive, negative, or both) with indicators of rangeland health.

1997; Toevs and others, 2011; National Park Service, 2016), though this type of approach can be difficult to implement for some soil and site stability and hydrologic function indicators (Duniway, Herrick, and others, 2010). Standard methods for collecting rangeland data that allow for quantitative estimates of rangeland health indicators are now well established (Herrick and others, 2005; Toevs and others, 2011) and widely used. These quantitatively derived indicators can be then used for management-relevant interpretations, such as data-driven state-and-transition models (Miller and others, 2011), evaluating risk of accelerated erosion (Webb and others, 2014), and detection of leading indicators of state change (Bestelmeyer and others, 2013). However, interpretation of indicator values and meaningful assessment of rangeland health attributes requires contextual information on how soils, landscape, and climate setting are shaping ecosystem qualities and some estimate of what constitutes target values of a healthy system.

Risks of persistent, undesirable changes in ecosystem structure and function are dependent on inherent properties that confer resistance and resilience to drivers of change, as well as the degree of exposure to drivers (for example, livestock grazing; Archer and Stokes, 2000; Herrick and others, 2006). Whereas ecosystem resistance and resilience can change in relation to varying climatic conditions and dynamic ecosystem properties affected by climate, land use, and management (Bestelmeyer and others, 2015), they are also strongly controlled by ecosystem properties that are generally stable through time. Inherent soil properties (for example, rock content, texture, depth, mineralogy) and geomorphic setting are among the most important factors controlling ecosystem resistance and resilience to land-use activities (Duniway, Bestelmeyer, and others, 2010), but specific relations between soil-geomorphic properties and ecosystem dynamics are poorly understood on a regional basis (Duniway and others, 2016).

The Grand Canyon-Parashant National Monument is one of the largest National Park Service (NPS) units where livestock grazing is a permitted land-use activity (fig. 1). The Bureau of Land Management (BLM), which co-manages the monument, administers nine allotments on the NPS portion of the monument, some of which are closed to grazing and some of which are actively grazed. Like many arid regions globally, some ecosystems in Grand Canyon-Parashant National Monument are characterized by a low degree of resilience to improper grazing. Unique to Grand Canyon-Parashant National Monument is the high degree of environmental heterogeneity encompassed by these nine allotments. Situated on the northwestern edge of the Grand Canyon, these allotments contain a large elevation gradient, widely differing precipitation patterns, a diversity of geologic substrates, and unique combinations of plant species. This area is also remote and difficult to travel in. Combined, these ecosystem characteristics make this area particularly complex to understand and therefore manage. Despite the broad spatial extent of grazing activity in Grand Canyon-Parashant National Monument, and the sensitivity of dryland ecosystems to associated impacts, monument managers have little information regarding effects of past and current livestock grazing on the condition of rangeland resources within the monument.

Rigorous scientific information documenting the current condition of rangeland ecosystems in relation to land use and climate is needed to make progress towards achieving resource protection goals (for example, those identified in the 2008 joint NPS General Management Plan/BLM Resource Management Plan for the monument [GMP/RMP]). One goal specifically called for in the GMP/RMP is the identification of "vital signs" (indicators and attributes of ecosystem health) and the implementation of a long-term program to monitor vital signs as a means of evaluating grazing effects on vegetation, soil, and watershed conditions. The GMP/RMP prescribes an adaptive management approach to grazing, whereby monitoring results are evaluated against applicable indicators and associated standards and are used to refine NPS and BLM grazing management. Refinement may include changes to season of use or timing, rest, grazing intensity, more active herd management within pastures, deferment, or other actions. Adaptive management would be aimed at retaining or restoring ecosystem resilience and resource sustainability while minimizing risks of impairment to resources or ecological processes.

This project focuses on two scientific issues: (1) understanding the underlying landscape, soil, and climate setting factors that affect Grand Canyon-Parashant National

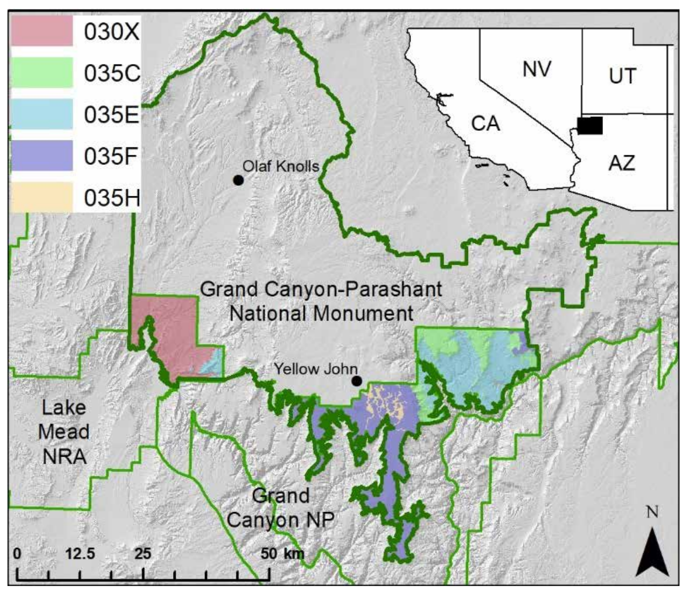

Figure 1. Map showing the study area in the Grand Canyon-Parashant National Monument in the southwestern United States. The monument is outlined in dark green. Land management agency boundaries are shown in light green. Natural Resources Conservation Service (NRCS) Major Land Resource Areas and Land Resource Units within the study area are shown by various colors (Lindsay and others, 2003; Natural Resources Conservation Service, 2006); land resource codes are defined in table 3. Black dots indicate weather station locations. NRA, National Recreation Area; NP, National Park; km, kilometers.

Monument dryland ecosystem structure and function (also referred to as land potential) and (2) characterizing ecosystem condition in relation to management concepts, such as rangeland health. This assessment project aims to provide information required to facilitate prioritization for restoration, monitoring, or other activities that support resource protection goals and thereby allow for further evaluation of the adequacy of current grazing management practices on NPS lands. The specific objectives of this work were to collect rangeland ecological condition inventory data from the nine allotments within the NPS-managed portion of the monument, provide interpretations on these results as they pertain to monument management, and include some suggestions for the next steps. The results included here on ecosystem condition, coupled with the increased understanding of soil-geomorphic controls on vegetation distribution within Grand Canyon-Parashant National Monument, will enable managers to develop appropriate livestock management strategies.

Materials and Methods

Study Location

Field studies were conducted on NPS-administered lands within Grand Canyon-Parashant National Monument (fig. 1). This area comprises more than 200,000 acres (80,937 hectares [ha]) of the approximately 1,000,000-acre (404,686 ha) monument located in the northwest corner of Arizona. This area is bordered on the south and east by Grand Canyon National Park, to the north by BLM-administered lands of Grand Canyon-Parashant National Monument, and to the west by the BLM's Southern Nevada District and Lake Mead National Recreation Area. Elevation ranges from approximately 400 to more than 2,000 meters (m). The low-elevation western side of the study area is characterized by Mojave Desert flora (Major Land Resource Area [MLRA] 030, Mohave Basin and Range; Natural Resources Conservation Service, 2006). The eastern side of the study area is dominated by large canyon benches with diverse vegetation communities because of the influence of the Mojave Desert, the Great Basin, and the Sonoran Desert, and to a lesser degree the Colorado Plateau (MLRA 035). The high-elevation parts in the center of the study area are largely pinyon-juniper stands with some ponderosa pine occurring in patches. Of the 1,095 plant species recorded in Grand Canyon-Parashant National Monument to date, 681 species are listed for the NPS-managed land, of which 135 only occur on NPS-managed lands, and new species records are regularly reported (Hildebrand and Fertig, 2012). Climate regimes vary from arid in the low reaches to mesic at high elevations. Average annual precipitation ranges from 204 to 405 millimeters (mm). Low elevation areas are warm to hot (monthly average ranges from a low of 8 °C in December to a high of 32 °C in July) and higher reaches of Grand Canyon-Parashant National Monument are cool to cold (monthly average ranges from a low of −1.4 °C in December to a high of 21 °C in July) with significant snow accumulation in some winters (fig. 2).

The monument straddles the Colorado Plateau and Great Basin physiographical provinces, separated by the Grand Wash Cliffs (Billingsley and others, 2004). Eastern Grand Canyon-Parashant National Monument falls within the Colorado Plateau (the Sanup and Shivwits Plateaus) and is dominated by structural benches and mesas formed from Paleozoic limestones, sandstones, and gypsiferous mudstones. Soils in these settings are formed from residuum, colluvium, and alluvium of varying geologic sources. To the west of the Grand Wash Cliffs lies the lower Basin and Range Province (Grand Wash trough), which is dominated by Tertiary and Quaternary sedimentary deposits (Billingsley and others, 2004). There are several prominent Tertiary-aged basalt flows that occur in both the western and eastern parts of the study area (Billingsley and others, 2004). The diversity of climatic conditions and variety of geologic substrate of Grand Canyon-Parashant National Monument together have produced a wide range of soil types. The most recent soil survey (Lindsay and others, 2003), though done at a coarse scale (1:24,000 scale mapping), includes 65 unique soil map unit components in the study area.

As in much of the western United States, grazing in this area has been an important land-use activity since the 1880s (Rider and Paulsen, 1985; Godfrey, 2008) with likely profound ecosystem impacts (Fleischner, 1994). Prior to the Taylor Grazing Act of 1934, grazing across the western United States was largely unregulated, with stocking rates generally higher than sustainable (Godfrey, 2008). After the establishment of the BLM and subsequent grazing management, stocking rates have generally been reduced. Grazing in low-elevation areas on the west side of Grand Canyon-Parashant National Monument is typically permitted year round, and, because of low forage availability, at fairly low intensities. In the mid-elevation areas, grazing occurs during the winter and into early summer. High elevation reaches were used historically in the summer (table 2). The study area is currently divided into nine allotments, some of which are separated into pastures for grazing management. There are several allotments where grazing does not currently occur. These include the Tassi allotment on the western edge, in which cattle use was disallowed in 2001 because of endangered species concerns (*Gopherus agassizii*; fig. 3). There were several wild burro and trespassing cattle in the Tassi allotment, but most cattle were rounded up in 2013. In the eastern study area, one allotment (Lone Mountain) has not experienced appreciable grazing by domestic livestock because of inaccessibility, however we were not able to collect field data from this allotment. Finally, there has been no domestic grazing in the Home Ranch allotment since 2003.

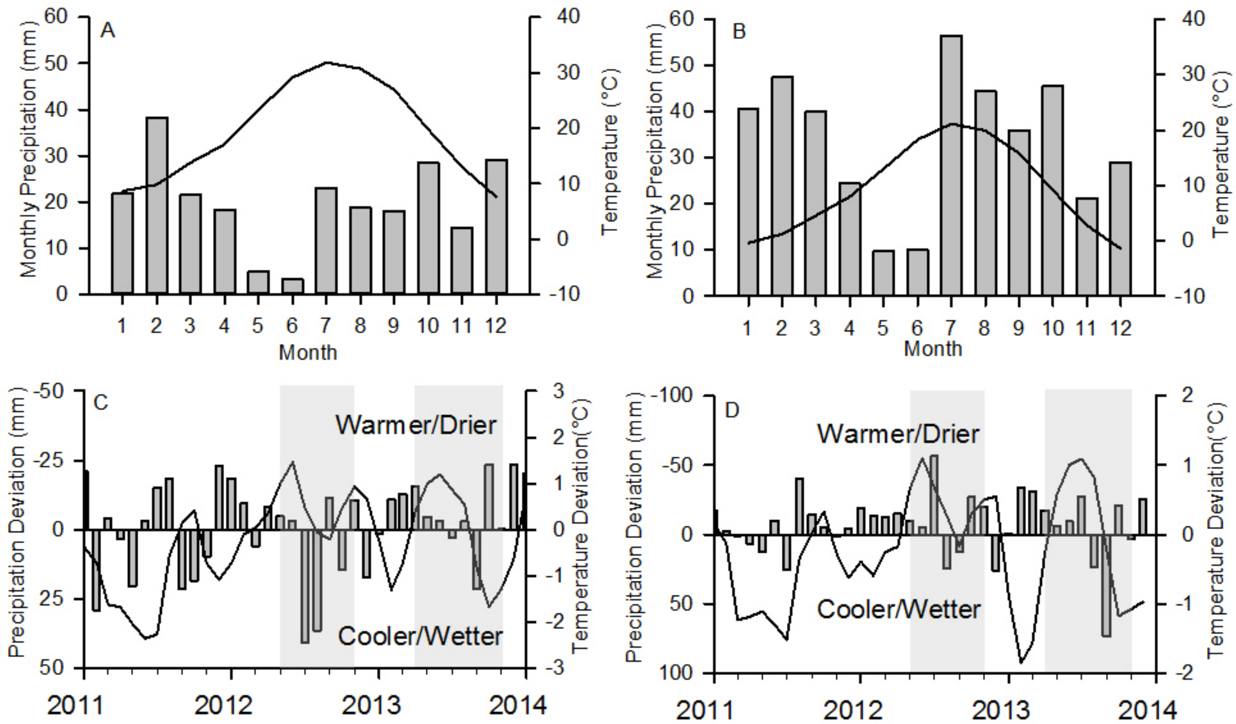

Figure 2. Plots showing the study area average monthly climatic conditions (*A* and *B*) and weather deviation from normal for 2011–14 (*C* and *D*). Weather deviation is shown for one year prior to and during the two-year sampling period (sample periods indicated by gray fill). Plots *A* and *C* show data from a low-elevation weather station (884 meters; Olaf Knolls in fig. 1). Plots *B* and *D* show data from a high-elevation weather station (1,878 meters; Yellow John in fig. 1). Data from the Western Regional Climate Center (http://www.wrcc.dri.edu); long-term average based on the record period from 1985 to 2016. mm, millimeters; °C, degrees Celsius.

Table 2. Study area allotments, size, permitted stocking rates, and season of use.

[Data from Bureau of Land Management Rangeland Administration System Reports, accessed June 25, 2019, at https://reports.blm.gov/reports/RAS. Billed animal unit months (AUMs) are averaged for 1990 to 2014; data accessed October 15, 2015, at https://reports.blm.gov/reports/RAS. NA, not applicable]

Allotment	Area, in hectares[1]	AUMs[2]	Billed AUMs[3]	Season of use
Big Spring Pipeline	23,358	2,789	1,266	Year round[4]
Dripping Spring	4,690	448	323	Nov.–May
Home Ranch	30,890	-	1,152	NA
Mt. Trumbull	13,463	1,825	1,175	Year round
Mule Canyon	7,022	585	338	Nov.–May[5]
Pa's Pocket	3,518	479	276	Dec.–Apr.[6]
Red Pond	22,280	2,508	1,144	Year round
Tassi	45,150	-	1,024	NA

[1]Hectares totaled within allotment corresponding to AUMs from Rangeland Administration System Reports.

[2]Animal unit months, based on authorized use as of June 25, 2019.

[3]Dripping Spring data missing 2003–2005, Pa's Pocket data only available 2001–2014, Home Ranch data ends in 2003, and Tassi data ends in 2000.

[4]Numbers reduced by about one-third for Oct.–Feb.

[5]Numbers reduced by about one-third for Mar.–May.

[6]Numbers reduced by about one-third for Mar.–Apr.

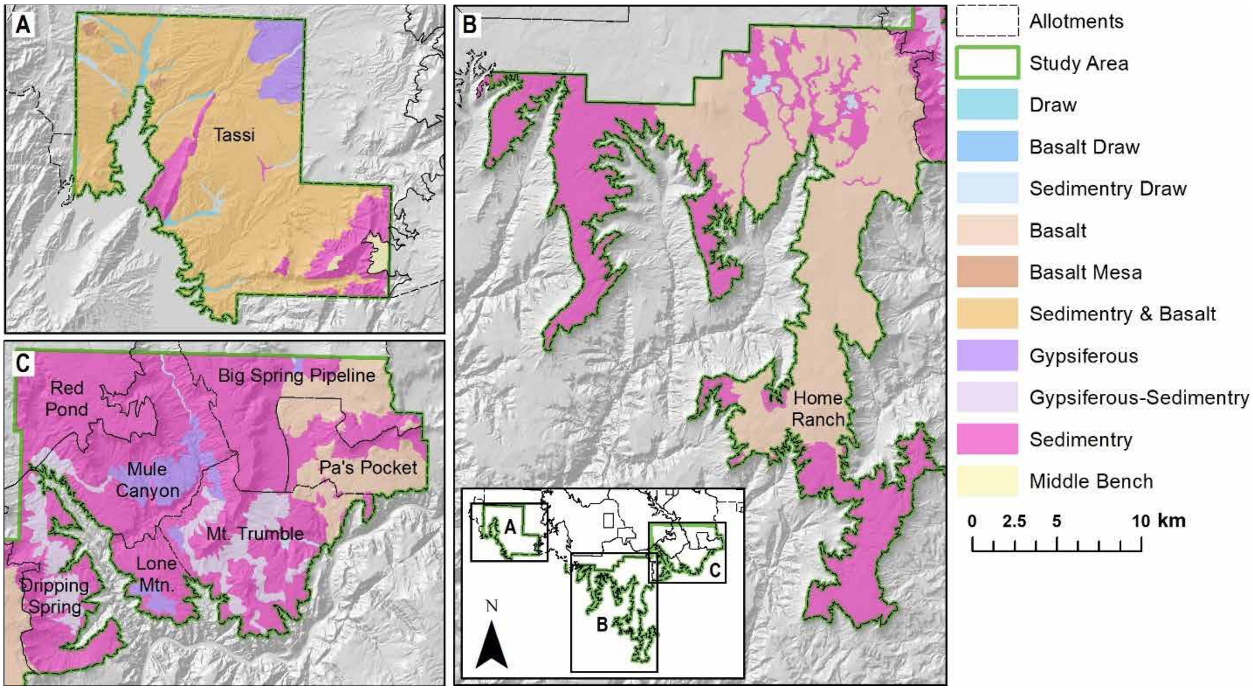

Figure 3. Maps of topographic-geomorphic units showing allotment and study area boundaries. Soil-geomorphic units based on soil survey map unit descriptions (Lindsay and others, 2003). Map inset shows the part of the Grand Canyon-Parashant National Monument that the National Park System administers (outlined in green). km, kilometers.

Site and Plot Selection

To account for the high degree of heterogeneity imposed by abiotic factors in the study area, we employed a stratified random sampling scheme based on climate, soil, and topographic factors. We first attempted to use Natural Resources Conservation Service (NRCS) ecological site descriptions (ESDs), which are assigned to soil survey map unit components (Lindsay and others, 2003; Duniway, Bestelmeyer, and others, 2010). However, there were too many unique ESDs in the study area to use as strata (N >60). Given the importance of soil parent material and topographic setting in controlling dryland ecosystem dynamics, we used geologic parent material groups and topographic setting as soil-geomorphic strata. We used the soil parent material data (as described in the soil survey map units; Lindsay and others, 2003), to create three geologic groups (table 3). Given the importance of slope in governing plant community dynamics and cattle distribution, we further subdivided soil map units by slope (into three groups). Slope and other terrain derivatives were calculated using Spatial Analyst in Esri's ArcGIS ver. 10.1 and a 10-m digital elevation model (DEM) from the U.S. Geological Survey (USGS) National Elevation Dataset (https://nationalmap.gov).

To capture areas that are likely more productive, and therefore important from a livestock forage perspective, we used a simple supervised classification approach to pick out shallow slope areas (<8°) that likely accumulate overland flow from the surrounding landscape ("run-in") (Rango and others, 2006). Methods used to map these hydrologically enhanced areas are described in appendix 1. To further reduce the number of strata, we did not cross slope and topographic setting with parent material for the run-in and steep-slope strata (fig. 3). For both run-in and steep-slope locations, we anticipated that the influence of topographic setting would most often overwhelm that of surficial geology.

To ensure an adequate number of study plots in each livestock management unit, we further stratified our sampling by Grand Canyon-Parashant National Monument allotment. Two allotments spanned large precipitation gradients (Big Spring Pipeline and Pa's Pocket) and for these two allotments we further divided the strata by zones identified in the soil survey (Common Resource Areas [CRAs] precipitation zones: 6–10, 10–14, 13–17, and 17–25 inches annually; fig. 1). Sample draws were done for each strata within each allotment separately using the general randomized tessellation stratification (GRTS) method to generate random, spatially balanced plot locations (Stevens and Olsen, 2004) with the geostatistical analysis tools in ArcGIS ver. 10.1. Not all strata occurred in each allotment, resulting in a variable number of strata in each allotment (fig. 4). We allocated more sampling effort to large allotments and landscape settings likely to receive high use by livestock (run-in and other shallow-slope sites; table 4). The GRTS approach provides a random order of selection for each sample draw, allowing users to not sample all selected points either because of predefined rejection criteria or inadequate time.

We used a variable probability surface with a 10-m pixel size (snapped to the DEM) within each allotment and strata to increase the probability of obtaining a grazing gradient in

Table 3. Topographic classes and geologic parent material used in stratified random sampling design and extent mapped in study area (in hectares).

Topographic class	Geologic parent material	030X[1]	035C[2]	035E[3]	035F[4]	035H[5]	Total
Shallow slopes (<8°)		2,951	3,581	8,298	24,145	2,039	45,905
	Run-in	2,325	719	2,202	4,992	966	11,204
	Mixed geology			212			5,104
	Basalt	51	219	954	11,722		12,946
	Gypsiferous	518		1,756			2,274
	Sedimentary	58	2,644	3,173	7,430	1,073	14,377
Medium slopes (8° to 19.5°)		11,589	6,580	14,938	5,344	43	38,495
	Mixed geology	6,993					6,993
	Basalt	53	586	902	1,880		3,422
	Gypsiferous	476		543			1,019
	Sedimentary	349	1,815	6,194	2,288	39	10,685
Steep slopes (>19.5°)		3,718	4,178	7,299	1,176	4	16,375
Total		19,432	10,161	23,236	29,489	2,082	84,400

[1]030X, Mohave Basin and Range, elevations range from 400 to 3,000 feet and precipitation averages 6 to 10 inches per year.

[2]035C, Colorado Plateau, elevations range from 4,500 to 6,000 feet and precipitation averages 10 to 14 inches.

[3]035E, Colorado Plateau, elevations range from 1,600 to 4,500 feet and precipitation averages 6 to 10 inches per year.

[4]035F, Colorado Plateau, elevations range from 5,500 to 7,000 feet and precipitation averages 13 to 17 inches per year.

[5]035H, Colorado Plateau, elevations range from 6,800 to 8,500 feet and precipitation averages 17 to 25 inches per year.

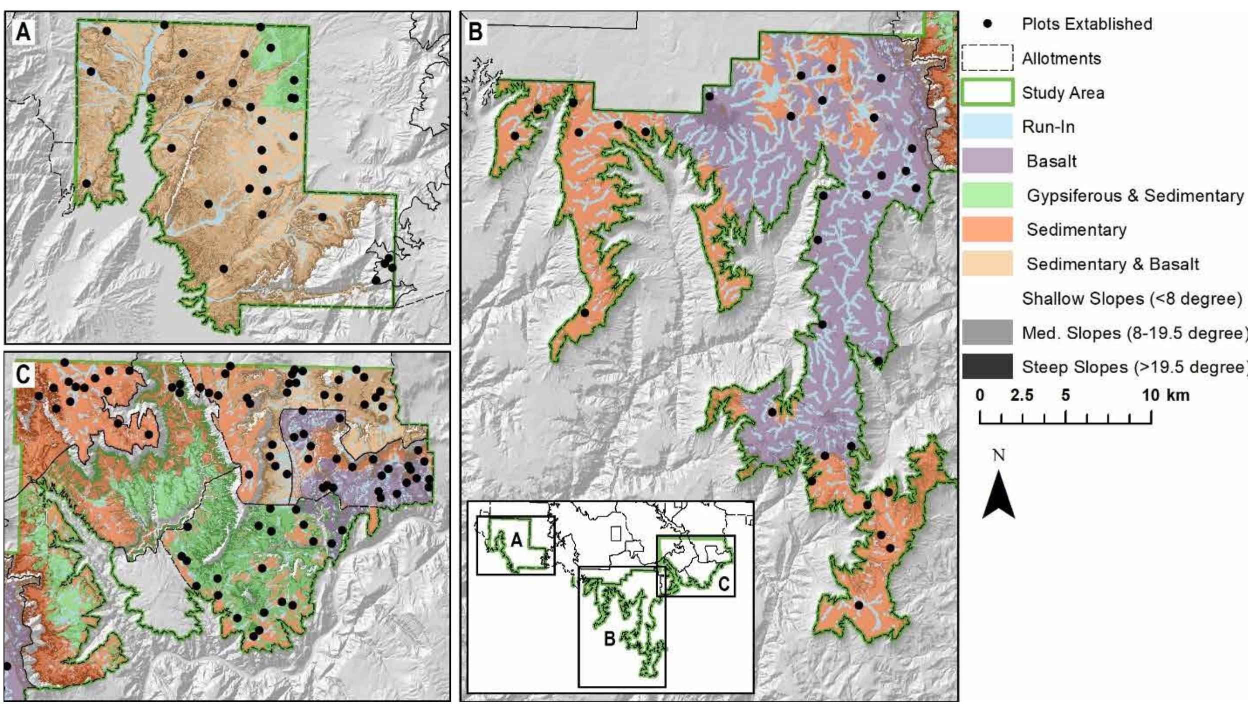

Figure 4. Maps of soil-geomorphic strata used for locating plots in the study area (locations sampled indicated by black dots). The geologic parent material classes were based on soil map unit descriptions and terrain subdivisions based on digital elevation model analyses. Map inset shows the part of the Grand Canyon-Parashant National Monument, northwestern Arizona, that the National Park System administers (outlined in green). km, kilometers.

Table 4. Final distribution of plots sampled by allotment and topographic-geologic grouping.

Topographic class	Geologic parent material	Big Spring Pipeline	Home Ranch	Mt. Trumbull	Mule Canyon	Pa's Pocket	Red Pond	Tassi	Total
Shallow slopes (<8°)		18	26	9	2	15	9	18	97
	Run-in	7	10	4		5	4	8	38
	Basalt		8			4			12
	Gypsiferous							3	3
	Mixed	11				3		7	21
	Sedimentary		8	5	2	3	5		23
Medium slopes (8° to 19.5°)		7	5	3	1	8	4	6	34
	Basalt		2			2			4
	Mixed	7				3		6	16
	Sedimentary		3	3	1	3	4		14
Steep slopes (>19.5°)		2	1	2		2	2	2	11
Mixed slopes				7				6	13
	Basalt			3					3
	Gypsiferous			4				2	6
	Middle bench							4	4
Total		27	32	21	3	25	15	32	155

our sample and to increase efficiency of field work. This was done because of the large size of each allotment (table 2) and the importance of landscape features and distance to water for governing cattle distribution in arid rangelands (Bailey and others, 1996). Distance to water was used as a proxy for likely grazing intensity and distance to accessible roads was used to estimate field sampling costs. For both distance to water and distance to roads, we created a cost-distance model that considered impassible cliffs and terrain steepness using the Spatial Analyst extension in ArcGIS. Cliffs were defined using a ruggedness index (Riley and others, 1999) where cells with ruggedness >2.3 were defined as impassible; for distance to water, allotment fence lines were defined as impassible. The monument is characterized by remote and rugged terrain. To increase efficiency of field work, we used the same travel-cost surface as used for grazing intensity to calculate distance from roads for field sampling. For each strata within each study area allotment, we created one variable probability surface based on these two cost-distance models. The goal of the livestock cost-distance to water model was to increase the likelihood of obtaining samples from varying distances to water (even if those distances are not evenly represented on the landscape). This was achieved by binning the data for each strata and then making the selection probability inversely proportional to the area represented by each bin (scaled from >0 to <1). For the distance from roads probability, we scaled the cost-distance values for each strata from near zero (very far from roads) to near 1 (very near roads). These two probability surfaces were then averaged, and the final probability sampling surface represents a compromise between obtaining a grazing gradient and increasing field work efficiency (fig. 5).

Vegetation and Soil Assessments

A total of 155 plots were established and sampled between March and November of 2012 and 2013 (table 4, fig. 4). Mojave Desert sites were sampled in the early spring (March and April), high-elevation pinyon-juniper and ponderosa sites were sampled May through July, and the eastern canyon benches were sampled between August and October. Each 50×50-m plot consists of three parallel 50-m transects spaced 25 m apart. Transects were placed so that they followed the topography, with transects following topographic contours rather than running up or down slope. Plots were marked with blue painted rebar at each end of the center transect. The locations of all transect ends and the plot centers were recorded by Global Positioning System (GPS; Garmin eTrex, Vista HCx, accuracy 3 m). Six plots intended for sampling were not established because the slopes were too steep to work on safely (four plots) or they were inaccessible (two plots). Only three plots were established in Parashant Canyon and no plots were established in Andrus Canyon and the surrounding benches (Mule Canyon and Dripping Spring allotments) because of extensive road damage during the sampling period in both 2012 and 2013. No plots were established in Lone Mountain owing to inaccessibility.

At each study plot, the NRCS soil map unit component was determined using soil properties and geomorphic setting (Lindsay and others, 2003). At a representative location near the plot center, a small soil pit or auger hole was excavated to a depth of at least 50 centimeters (cm) in rocky soils and 100 cm in nonrocky soils or until a restrictive layer was reached. Soil pedogenic horizons were identified and described following Schoeneberger and others (2012). Soil properties descriptions include soil textural class, clay percentage, effervescence in response to 1 normal HCl, coarse fragment content (percentage by volume), and carbonate stage. Structure (shape, grade, and size) was added in 2013 for horizons occurring within ~30 cm of the soil surface. Plot parent material, landform, elevation, slope, slope shape, and aspect were also recorded. Additionally, digital photographs were taken at both ends of each transect following Herrick and others (2005) methods for a total of six photographs per plot. Each photograph contains a photograph board with the allotment, plot name, date, transect number, and direction of image.

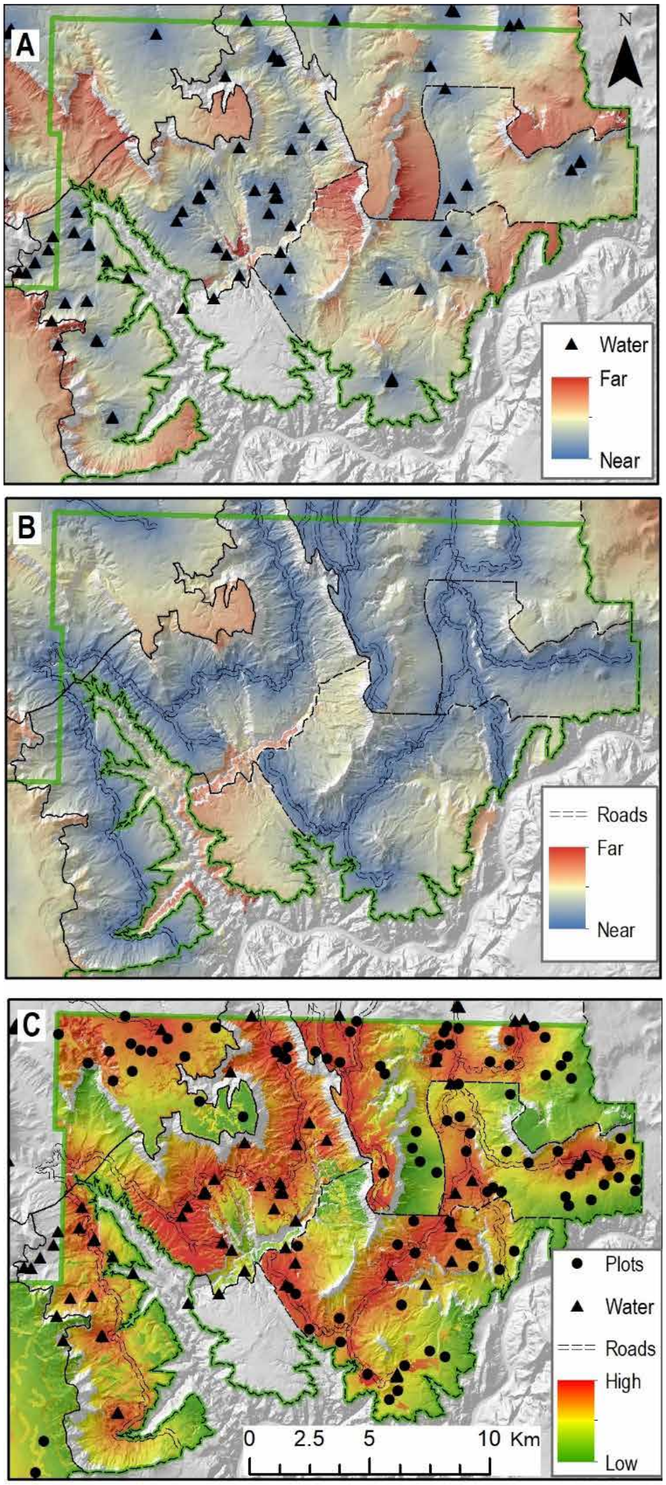

Figure 5. Maps showing example variable probability surfaces created for the eastern allotments in the study area in Grand Canyon-Parashant National Monument, northwestern Arizona,for (*A*) distance to livestock water sources, (*B*) distance from roads, and (*C*) the final combined probability surface used in plot selection.

We used soil and landscape property data, along with climate zone, and plot photographs to assign each plot to a soil map unit component (Lindsay and others, 2003). We did not restrict possible soils to those described for the map unit in which the plot occurred but included surrounding map units as well. We then identified the plot ecological site using the map unit component-ESD correlation provided in the NRCS soil survey database (Lindsay and others, 2003).

To assess plot ecological condition, we collected data on soil and site stability, hydrologic function, and plant community cover and composition. Foliar cover by species, ground cover, and plant composition were assessed using the line-point intercept method (LPI; Herrick and others, 2005) with a point spacing of 1 m, for a total of 150 points per plot. Plant species frequency was assessed using a nested frequency frame containing a 10×10 cm and 40×40 cm quadrat (rooted frequency for herbaceous species and canopy frequency for woody species). Frames were placed every 5 m along each transect, resulting in 30 frames per plot. Potential for wind and water erosion, run-off, and perennial community structure were assessed on each transect using the perennial plant canopy and basal gap intercept method (Herrick and others, 2005). Surface soil aggregate stability was measured using a soil stability test, which ranks stability from 1 to 6, with 6 being the most stable (Herrick and others, 2001; Herrick and others, 2005). Six soil surface samples were collected at randomly selected points along each transect (18 per plot). Relative cattle use was assessed using frequency of dung. The presence or absence of cattle dung was recorded for ten 1×1-m quadrats per transect (placed every 5 m, 30 total per plot). It is not possible to use cattle dung frequency counts to estimate absolute use (Fuller, 1991), but dung counts have been used in many studies as an index of relative use (Augustine, 2003; Veblen, 2012; Kimuyu and others, 2017).

All soil and vegetation data were entered into the Database for Inventory, Monitoring, and Assessment (DIMA; Courtright and Van Zee, 2011) either directly using a field computer (LPI, canopy and basal gap) or afterward (soil stability, frequency, and soil pedon descriptions). Basic summary reports were generated in DIMA for further data analysis. Dung frequency data were entered and stored separately.

Data Analyses

We used four general approaches to data analysis. First, we provide general descriptions and summaries of soils, plants, and cattle activity across the Grand Canyon-Parashant National Monument. Second, we summarized quantitative indicators of rangeland health (table 1) by generalized ecological site type and then conducted analyses for differences in indictors between these soil groups. Third, within the four climate zones, we conducted community-scale analyses using multivariate approaches to understand how plot soil and plant composition vary across the landscape, looking for natural floristic groups. Fourth, we examined the univariate and multivariate data for the relations among indicators of rangeland health, abiotic gradients, and indicators of cattle activity.

Plot-level averages of species foliar cover, soil cover, plant canopy and basal gap distribution, and other indicators of rangeland health were derived using the reporting functions provided by DIMA (table 1; Courtright and Van Zee, 2011). Plant species were categorized in three ways: growth form (tree, shrub, grass, or forb), woody or herbaceous, and perennial or annual. Category determinations follow the U.S. Department of Agriculture PLANTS database. For species that can take on multiple growth forms (for example, can either be a forb or subshrub), the form that was most commonly seen in the study area was used. These categories were used to broadly describe plant structure. Although frequency was collected for all plant species, we only analyzed frequency of exotic species here. Species lists with associated classifications and all frequency data is available in Duniway and Palmquist (2020).

Trends in rangeland ecosystem indicators with elevation were examined using cubic local regression (SAS software ver. 9.4, LOESS procedure). Relations between cattle dung frequency and environmental covariates were examined using a quantile regression approach (QUANTREG procedure). Quantile regression provides an approach for examining relations between independent and dependent variables that is robust to outliers (Cade and Noon, 2003). A final index of relative cattle use was developed based on a multiple quantile regression using frequency of cattle dung (dependent variable) and a suite of environmental covariates (independent variables). Environmental covariates examined included cost-distance to water (as described in the survey design), plot ruggedness (using the ruggedness index described above), and soil survey estimated forage production (representative value) for the correlated soil map unit component. Forage production is an attribute in NRCS soil surveys based on soil profile properties and climate that can be used to estimate appropriate stocking rates.

We created site climate zones based on NRCS precipitation groups and natural elevation breaks and grouped ESDs in each climate zone into generalized ecological site groups (ESGs) based on similarity in soil properties and (or) soil parent materials (fig. 6; Duniway and others, 2016). Descriptive statistics of plant and soil communities were done using SAS ver. 9.4 (MEANS procedure) and examination of differences in indicators was done using a mixed model with ESGs as fixed effects (MIXED procedure).

To conduct multivariate analyses, two data matrices were created from plot data in each of the four climate zones, one containing the foliar and ground cover data and the other environmental and cattle use variables. The foliar and ground cover data matrices were used for the cluster and multivariate analyses, and the environmental and cattle use matrices were used to examine correlations. The foliar and ground cover matrices consisted of the cover values for each plant species, biological soil crust, litter, and bare soil, as well as frequency values instead of LPI cover values for *Bromus rubens*, *Bromus tectorum*, *Erodium cicutarium*, and *Schimus arabicus*. Frequency values were used for these four nonnative invasive species because their cover values were commonly low but their presence or absence was considered an important indicator of ecosystem change. The correlation matrices consisted of the physical characteristics of the plot (slope, aspect, and elevation), characteristics of the soil (parent material, percentage of cover by rock fragments on the surface, percentage of rock by volume of the first horizon, surface texture, and percentage of sand and silt estimates), cattle dung frequency, the cattle use index, and distance to the nearest road (table 5).

Multivariate analyses, richness, and diversity measures (Simpson's diversity index and Shannon's diversity index) were generated using PC-ORD ver. 6.08 (McCune and Mefford, 2011). Both measures of diversity are reported here to facilitate comparisons across geographic regions and studies. Prior to multivariate analysis, species that occurred in less than 5 percent of plots were removed (McCune and Grace, 2002). Cover values were converted to compositional cover (cover of species within the total foliar cover) for all species other than the four nonnative species listed above. Data was otherwise untransformed, except where transformation clarified relations. In the one case where data transformation improved analyses (middle desert), a square root transformation was applied to all columns. Two plots were removed from analyses for which outlier analysis using the Sørensen distance measure indicated that they fell more than two standard deviations from the mean and including these outliers obscured further interpretation of data. One of these outliers occurs in a burned ponderosa forest, which now has very little living ponderosa overstory and has high amounts of very large woody material owing to dead and downed ponderosa. The other outlier occurs in a drainage through bedrock with very little soil and consequently very little foliar cover.

Plots were classified using hierarchical cluster analysis (flexible beta [$\beta = -0.25$] linkage and a Sørensen distance matrix) and indicator species analysis (9,999 randomizations and quantitative response). The number of clusters that generated the highest indicator values and had a reasonable amount of information remaining was chosen to define floristic groups. Those groups were also cross-checked with plot photographs to make sure the communities were recognizable.

Nonmetric multidimensional scaling (NMS) using the Sørensen distance measure was used to illustrate variability within climate zones and correlations between floristic groups and explanatory variables (environmental and land use factors). The "slow and thorough" method in autopilot was chosen, which uses a random starting configuration, 250 runs of real and randomized data with a maximum of 500 iterations, and an instability criterion of 0.0000001. The best

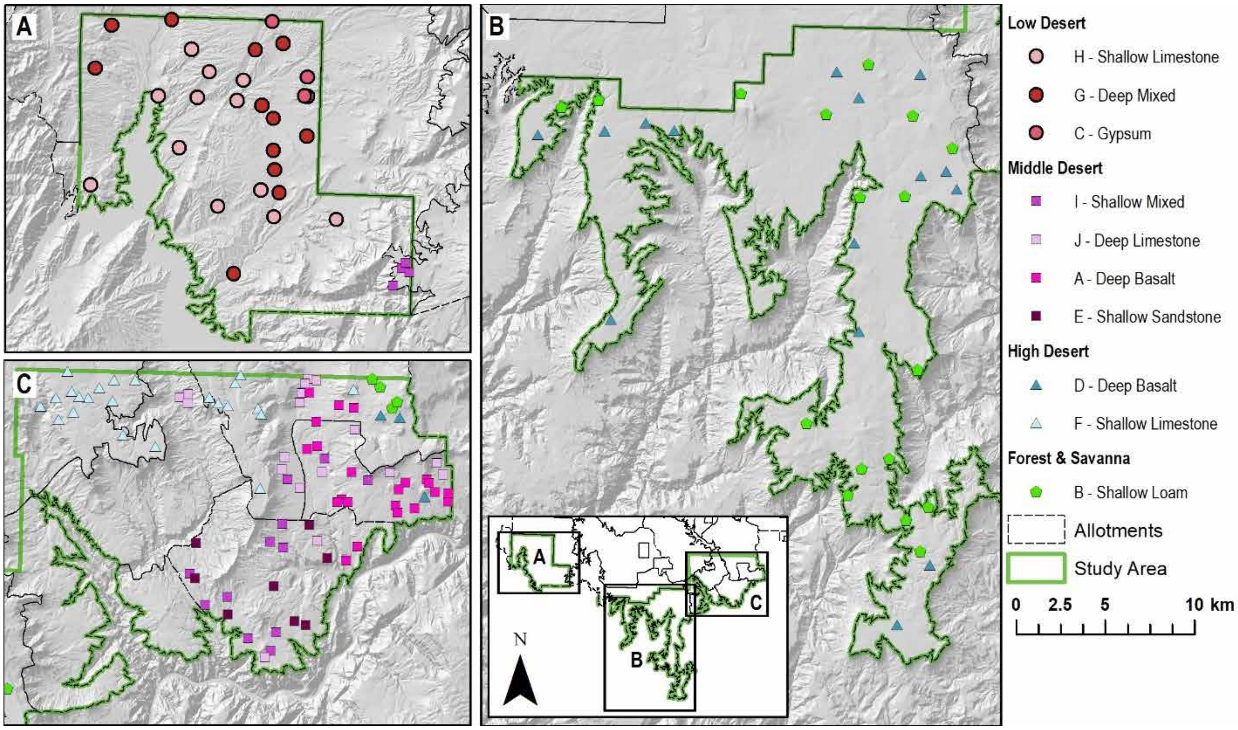

Figure 6. Maps showing the distribution of identified ecological site groups (table 6). Map inset shows the part of the Grand Canyon-Parashant National Monument, northwestern Arizona, that the National Park System administers (outlined in green). km, kilometers.

Table 5. Landscape setting, soil, and cattle use variables hypothesized to control indicators of rangeland health and community ordinations in the Grand Canyon-Parashant National Monument, northwestern Arizona.

[m^2, square meters; Wm^{-2}, watts per square meter]

Variable	Description	Source[1]
	Landscape setting	
Elevation	Plot elevation, in meters	DEM
TWI	Topographic wetness index (Sörensen and others, 2006)	DEM
Flow accumulation	Contributing area, measure of hydrologic connectivity (log transformed)	DEM
Slope	Plot average slope (degrees)	DEM
Curvature	Plot compound curvature	DEM
Solar insolation	Plot annual solar insolation (in Wm^{-2})	DEM
	Soil surface properties	
Bedrock	Cover of exposed bedrock	LPI
Cobble	Cover of surface cobbles	LPI
Gravel	Cover of surface gravels	LPI
All Rock	Total rock cover	LPI
A-horizon fragment	Rock fragments in surface soil horizon A	Soil
Sand	Estimated sand content of surface horizon	Soil
Clay	Estimated clay content of surface horizon	Soil
Saturated conductivity	Saturated conductivity of surface horizon based on texture	Soil
AWC	Available water capacity of surface horizon based on texture	Soil
Field cap.	Field capacity of surface horizon based on texture	Soil

Table 5. Landscape setting, soil, and cattle use variables hypothesized to control indicators of rangeland health and community ordinations in the Grand Canyon-Parashant National Monument, northwestern Arizona.—Continued.

Variable	Description	Source[1]
	Cattle	
Cow dung	Frequency of cow dung in 1-m^2 quadrats	Freq.
Distance to water	Cost-distance to water source (log transformed)	Derived
Cattle index	Cattle index based on multiple quantile regression	Derived
	Soil classes	
Depth	Generalized soil depth class (very shallow, shallow, and moderately deep or deeper)	Soil
Texture	Generalized soil textural class	Soil
Soil taxonomy	Generalized soil taxonomic class	Soil

[1]DEM, calculated from 10-meter digital elevation model; LPI, line-point intercept model; Soil, data from soil pedon observation or derived soil variable (using pedotransfer function or soil survey; Schapp and others, 2001); Freq., quadrat frequency data; Derived, variable calculated using multiple sources (see Materials and Methods section).

number of dimensions was assessed by substantial reductions in stress and a Monte Carlo test (McCune and Grace, 2002). Pearson's *r* was used to analyze correlations between axis scores and explanatory variables.

To examine for structure in the cross-tabulation of ESGs and floristic groups, chi-square tests were done by climate zone (SAS ver. 9.4; FREQ procedure). Analysis of association between rangeland health indicators, NMS axis, and edaphic explanatory variables were done by climate zone using correlation for continuous variables (SAS ver. 9.4; CORR procedure) and mixed model analysis of variance for class variables (MIXED procedure). Edaphic variables included DEM-derived landscape setting indices, surface soil rockiness indicators, soil texture, and estimates of soil hydrologic properties (table 5; Schaap and others, 2001). The various field data as well as new data generated using geographic information systems and statistical analysis are available in Duniway and Palmquist (2020).

Results

Soils, Ecological Sites, and Vegetation Communities Sampled

In the 155 plots, we sampled 15 unique soil taxa (to great group level) and 52 unique soil map units components (table 6). Soil taxa represented in the plot data are dominated by aridisols but include mollisols and alfisols at high elevations, entisols in active alluvial settings, and some vertisols in locations dominated by shrink-swell clays. These 52 soil map unit components were correlated to 31 unique ecological sites in the soil survey (Lindsay and others, 2003). We used the NRCS MLRA and CRA classifications (primarily delineated by elevation breaks) as an initial ecological site grouping factor. We then looked within these groups for similarities in soil parent material, slope, and texture to develop potential soil-geomorphic units that will share commonalities in soil-plant relations. This resulted in a total of ten ESGs that were distributed among four climate zones (table 6); three in the low desert, four in the middle desert, two in the high desert, and one in the forest and savanna climate zones (fig. 6).

A total of 271 species were recorded in the study area (based on nested frequency and LPI). This includes new vouchered collections of three species for Grand Canyon-Parashant National Monument and 17 species for the NPS-administered part of the monument. All collections are located at the Grand Canyon-Parashant National Monument Herbarium. The new species recorded and vouchered for Grand Canyon-Parashant National Monument are *Eriastrum sparsiflorum*, *Thlaspi montanum*, and *Trichoptilium incisum*. Cluster analysis and indicator species analysis identified a total of 11 different floristic groups (table 7) distributed among the four climate zones (fig. 7). Details of cluster analysis and ordination results are provided by climate zone below.

Cross tabulation of plot tallies by the ESGs assigned a priori and data-driven cluster analysis of vegetation composition suggests a strong concordance between the two approaches in most instances (table 8), indicating close links between soils and vegetation. Notable exceptions include the splitting of the Mojave shrub, desert grassland, and blackbrush floristic groups into two primary ESGs and some significant spread among floristic groups within the deep basalt, shallow limestone, and shallow loam ESGs. Details of the underlying properties driving these results are given by climate zone.

Table 6. Ecological site groups identified in the study area.

[ft, feet; in., inches; LRU, Land Resource Unit; m, meters; MLRA, Major Land Resource Area; N, number of plots sampled; NRCS, Natural Resources Conservation Service; %, percent]

Ecological site group	Description	N	NRCS ecological sites	Elevation range (m)	Slope range (%)	Soil taxonomy	Allotment
			Low desert (MLRA 030)				
H	Shallow limestone.—Ecological sites with 6–9 in. precipitation, limestone parent material, shallow soils, elevations of 1,500–3,200 ft, and sandy soil textures.	12	R030XB212AZ, R030XB214AZ	432–695	9–37	Petrocalcids, haplocambids, haplocalcids	Tassi
G	Deep mixed.—Ecological sites with a mix of limestone, basalt, and granite parent materials, deep soils, shallow to moderate slopes, elevations of 400–3,000 ft, and sandy soil textures	12	R030XA109AZ, R030XA115AZ, R030XB215AZ, R030XB218AZ, R030XB221AZ	430–623	1–7	Torriorthents, haplocalcids, torripsamments	Tassi
C	Gypsum.—Ecological sites with gypsum parent material, deep soils, elevations of 1,600–3,400 ft, and sandy loam to loamy soil textures.	4	R030XB222AZ	590–630	6–44	Torriorthents	Tassi
			Middle desert (MLRA 035, LRU E)				
I	Shallow mixed.—Limestone and sandstone parent material, shallow soils, typically moderate to steep slopes, elevations of 3,500–5,000 ft, and sandy to loamy soil textures.	16	R035XE503AZ, R035XE505AZ, R035XE517AZ, R035XE519AZ	1,067–1,463	1–45	Petrocalcids, haplocalcids, haplogypsids, torriorthents	Big Spring Pipeline, Mt. Trumbull, Pa’s Pocket, Tassi
J	Deep limestone.—Mostly limestone (some sandstone) parent material, deep soils, typically shallow to moderate slopes, elevations of 3,500–5,000 ft, and sandy to loamy soil textures.	18	R035XE511AZ, R035XE514AZ, R035XE518AZ	1,022–1,574	3–30	Haplocalcids, calcigypsids, torriorthents	Big Spring Pipeline, Mt. Trumbull, Mule Canyon, Pa’s Pocket
A	Deep basalt.—Primarily basalt parent material, moderately deep to deep soils, elevations between 2,800–5,000 ft, and loamy to clayey loam soil textures.	22	R035XE501AZ, R035XE520AZ	874–1,537	3–47	Haplargids, calciargids, argigypsids	Big Spring Pipeline, Mt. Trumbull, Pa’s Pocket
E	Shallow sandstone.—Sandstone parent material, shallow soils, shallow slopes, elevations of 1,600–4,600 ft, and sandy loam and loamy sand soil textures.	8	R035XE510AZ	1,021–1,230	2–23	Torriorthents	Mt. Trumbull
			High desert (MLRA 035, LRU C and F)				
D	Deep basalt.—Primarily basalt parent material, generally shallow to moderate slopes, moderately deep to deep soils, elevations of 5,000–6,600 ft, and loamy to clayey loam soil textures.	18	F035XF611AZ, R035XC301AZ R035XC303AZ, R035XF604AZ	1,437–1,953	1–24	Paleustolls, argiustolls, haplusterts, haplargids, haplocambids, haplustalfs	Big Spring Pipeline, Home Ranch

Table 6. Ecological site groups identified in the study area.—Continued

Ecological site group	Description	N	NRCS ecological sites	Elevation range (m)	Slope range (%)	Soil taxonomy	Allotment
	High desert (MLRA 035, LRU C and F)—Continued						
F	Shallow limestone.—Primarily limestone parent material, mostly shallow to moderate slopes, shallow soils, elevations of 4,500–6,000 ft, and loamy to clayey soil textures.	24	R035XC302AZ, R035XC319AZ, R035XC331AZ_1, R035XC350AZ	1,523–1,724	0–63	Haplocalcids, torriorthents, petrocalcids, haplustalfs	Big Spring Pipeline, Red Pond
	Forest and savanna (MLRA 035, LRU F and H)						
B	Shallow loam.—Shallow soils, elevations of 5,500–7,500 ft, and loamy to clayey soil textures. Typically, *Pinus edulis*/*Juniperus osteosperma* or *Pinus ponderosa* sites.	21	F035XF613AZ, F035XF620AZ, F035XF624AZ, F035XH805AZ	1,718–1,977	1–40	Argiustolls, calciustolls haplustalfs, haplusterts, paleustolls	Big Spring Pipeline, Home Ranch

Table 7. Floristic groups identified in the study area.

[m, meters; N, number of plots sampled; NRCS, Natural Resources Conservation Service; %, percent]

Floristic group	Description	N	NRCS ecological sites	Elevation range (m)	Slope range (%)	Allotment
	Low desert					
Mojave shrub	Characterized by *Ambrosia dumosa* and *Schimus arabicus*, typically low plant cover, and a high proportion of annual species cover. Graminoid cover is low, particularly perennial grasses. Generally shallow slopes.	25	R030XA115AZ, R030XB221AZ, R030XB215AZ, R030XB218AZ, R030XA109AZ, R030XB212AZ, R030XB222AZ, R030XB214AZ,	430–695	1–37	Tassi
Mojave gypsum	Characterized primarily by very low foliar cover and high biological soil crust cover and development. *Lycium andersonii* and *Mentzelia affinis* are low cover and frequency indicator species. Restricted to gypsiferous soils.	3	R030XB222AZ	590–609	6–44	Tassi
	Middle desert					
Desert grassland	Characterized by typically high grass cover and all grass indicator species: *Hilaria rigida*, *Muhlenbergia porteri*, *Bouteloua eriopoda*, *Sporobolus cryptandrus*, and *Tridens muticus*. Total foliar cover is variable but tends to be higher than other groups. Mostly occurs on shallow slopes (gradients <20%).	32	R035XE518AZ, R035XE514AZ, R035XE501AZ, R035XE511AZ, R035XE505AZ, R035XE520AZ, R035XE517AZ	985–1,574	3–47	Big Spring Pipeliine, Mt. Trumbull, Mule Canyon, Pa's Pocket

Table 7. Floristic groups identified in the study area.—Continued

Floristic group	Description	N	NRCS ecological sites	Elevation range (m)	Slope range (%)	Allotment
			Middle desert—Continued			
Blackbrush shrubland	A mix of grasses and shrubs characterized by *Coleogyne ramosissima* and *Mortonia utahensis*. Shares many species with low and high desert groups, which have affiliations with the Mojave Desert and the Colorado Plateau. Mostly on shallow slopes (gradients <20%).	26	R035XE520AZ, R035XE517AZ, R035XE510AZ, R035XE519AZ, R035XE503AZ, R035XE505AZ, R035XE501AZ, R035XE514AZ	1,021–1,418	1–45	Big Spring Pipeline, Mt. Trumbull, Pa's Pocket, Tassi
Creosote slopes	Primarily woody shrubs with little understory or an understory of annual, nonnative grass. *Larrea tridentata* is the primary indicator species and *Pectis papposa* is a weak indicator. Mostly on shallow slopes (gradients <15%).	6	R035XE514AZ, R035XE501AZ, R035XE520AZ, R035XE519AZ	874–1,191	3–35	Mt. Trumbull, Pa's Pocket
			High desert			
Mixed shrublands	*Bromus rubens, Atriplex canescens, Ephedra viridis*, and *Yucca baccata* characterize this group. Shrubs are the primary cover, but grass cover can also be codominant. Strongly correlated with steep slopes and high amounts of surface rock. At lower elevations than the pinyon-juniper woodlands.	7	R035XC331AZ, R035XC302AZ, R035XC303AZ, R035XC319AZ	1,437–1,704	7–63	Big Spring Pipieline, Pa's Pocket, Red Pond
Sagebrush shrublands	Characterized by *Artemisia tridentata*, *Bromus tectorum*, and *Sphaeralcea grossulariifolia*. Foliar cover primarily from shrubs; some annual grasses. Mostly on shallow slopes (gradients <25%) and lower elevation than the pinyon-juniper woodlands.	16	R035XC319AZ, R035XC331AZ_1, R035XC301AZ, R035XC302AZ, R035XC350AZ	1,523–1,790	0–51	Big Spring Pipeline, Red Pond
Pinyon-juniper woodland	Characterized by tree cover from *Juniperus osteosperma*, *Pinus monophylla*, and *Pinus edulis* and low amounts of *Eriogonum umbellatum*. Low covers of perennial grass are present. Mostly above 1,800 m in elevation on very shallow slopes (gradients <10%).	19	F035XF611AZ, R035XC302AZ, R035XF604AZ, R035XC350AZ, R035XC319AZ	1,658–1,953	1–21	Big Spring Pipeline, Home Ranch, Red Pond
			Forest and savanna			
Pinyon woodland	Primarily characterized by tree cover from *Pinus edulis*, with some *Artemisia tridentata*. Very low amounts of understory cover. Strongly correlated with surface rock fragments.	4	F035XF620AZ, F035XF624AZ	1,718–1,977	3–36	Big Spring Pipeline
Juniper woodland	Characterized by *Juniperus osteosperma*, little shrub understory, and *Elymus elymoides*. Understory cover is low, particularly annual species. Positively correlated with high cattle index values. Occurs on shallow slopes.	11	F035XF613AZ, F035XF620AZ, F035XF624AZ	1,815–1,955	1–10	Home Ranch
Forest shrubland	Highest foliar cover of all groups, mostly a mix of tree and shrub cover. *Poa fendleriana*, *Garrya flavescens*, *Quercus turbinella*, and *Purshia stansburiana* are characteristic. Annual cover is almost zero. Typically on steep slopes (gradients >25%).	4	F035XF620AZ, F035XF613AZ	1,788–1,871	3–40	Home Ranch

Trends Across Elevation

Indicators of soil and site stability and hydrologic function show contrasting trends with elevation (fig. 8). Vegetation gap indicators signify increasing stability and function (decrease in cover of large basal and canopy gaps and increase in protective litter cover) with increasing elevation, and total amount of exposed bare soil is generally unchanged across elevations (fig. 8*A*). There is a large increase in litter cover between 1,700 and 1,800 m, likely associated with an increase in tree cover (fig. 8*A*). Soil surface biologic indicators (biological soil crusts and soil aggregate stability) show a decrease with elevation whereas rock cover increases slightly to a peak between 1,400 and 1,500 m before reaching lower values at higher elevations (fig. 8*B*). The average aggregate soil stability index is highest in the low elevations (ca. 4), with a pronounced dip in soil aggregate stability to minimum smoothed index value of ca. 2 near 1,700 m. Total biological soil crust cover decreases between the low-elevation Tassi allotment and the next elevation zone with data (1,100 m).

Trends in indicators of biotic integrity demonstrate the importance of elevation (and associated climates) on plant communities in Grand Canyon-Parashant National Monument (fig. 9). Plant diversity is highest in the lower and upper reaches of the study area (table 9), with an evident dip in the local regression line and many field plots that have very low diversity between 1,000 and 1,400 m elevation (fig. 9*A*). Average total foliar cover increases with increasing elevation; the lowest cover value is for the low desert zone (ca. 0.2) and the highest is for the forest and savanna zone (ca. 0.5). Understory herbaceous and shrub cover peaks at the boundary between the low and high desert elevations (1,400–1,500 m), which coincides with marked increase in tree cover (starting at ca. 1,600 m; fig. 9*A*). Trends in dominant woody species cover with elevation show both elevation distinction and overlap among species (fig. 9*B*). *Ambrosia dumosa* and *Larrea tridentata* are both dominants in the lowest elevations and *L. tridentata* occurs at high cover values as high as about 1,200 m, whereas *A. dumosa* is limited to elevations below 700 m. *Coleogyne ramosissima* and *Ephedra* spp. overlap in elevation with *L. tridentata*, with average cover peaking at ca. 1,400 and 1,500 m, respectively. *Artemisia* spp. cover begins at ca. 1,400 m, peaks at ca. 1,600 m, and decreases at higher elevations. For the common tree species, *Juniperus* spp. and pinyon, cover starts at 1,500 and 1,600 m, respectively. *Juniperus* spp. are the dominant species at high elevations, with a sharp increase in cover between 1,700 and 1,800 m.

Occurrence of invasive species is an important part of biotic integrity, and frequency of invasive species of concern shows strong trends with elevation (fig. 9*C*). The annual grass *Bromus rubens* is the most common invasive species at most elevations. *Schismus arabicus*, also an annual grass, has similar, if not higher, frequency in the lowest elevations but observations of this species were infrequent above 700 m. The biennial forb *Erodium cicutarium*, a nonnative weed, occurs at low to mid-elevations (500–1,600 m). Average frequencies are low (local area regression line), but there are several plots across elevations that have high frequency. *Bromus tectorum*, another regionally important annual invasive grass, is also prevalent in the high elevation sites (1,400 to 1,900 m).

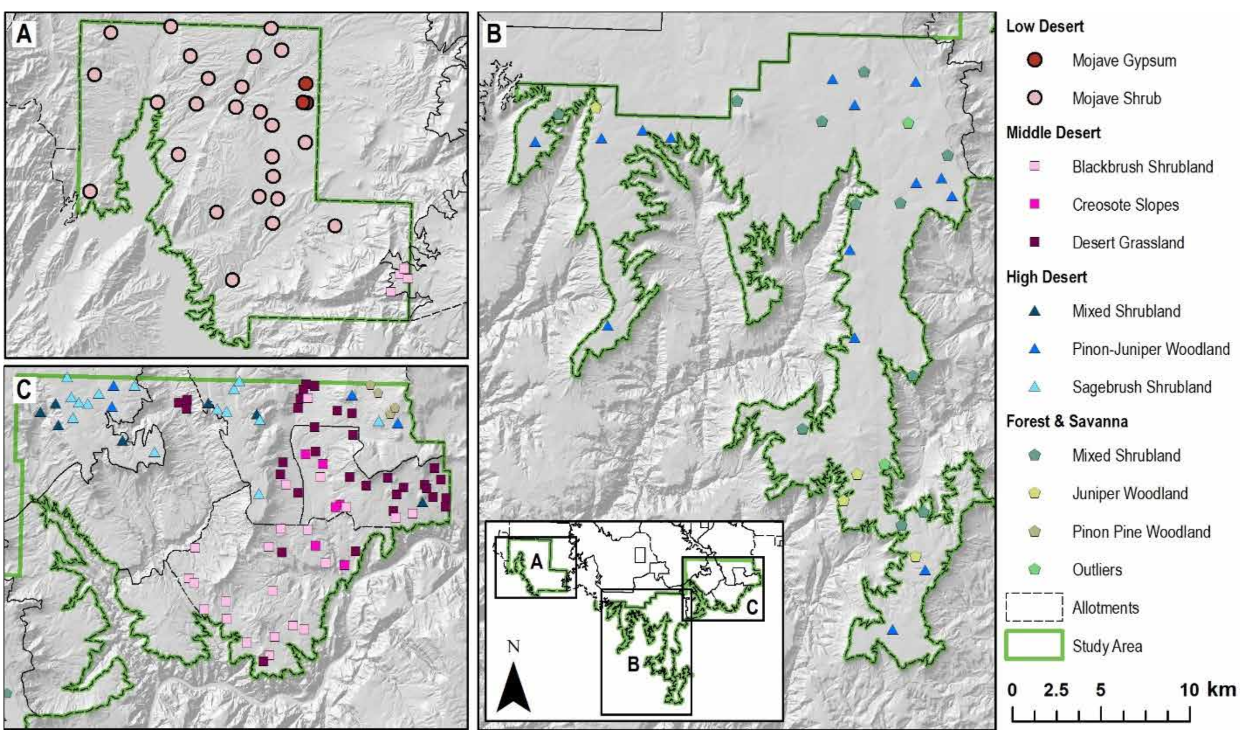

Figure 7. Maps showing the spatial distribution of identified floristic groups (table 7). Map inset shows the part of the Grand Canyon-Parashant National Monument, northwestern Arizona, that the National Park System administers (outlined in green). km, kilometers.

Table 8. Cross tabulation of ecological site groups (ESGs) (fig. 6) and cluster analysis floristic groups (fig. 7).

[Values are number of plots in each combination of ESGs and floristic groups. ESG and cluster groups show significant association (chi-square test for independence in all climate zones except forest and savanna, where there is only one ESG). Low desert $p = 0.001$, middle desert $p < 0.001$, and high desert $p < 0.001$]

Cluster analysis floristic groups	Low desert			Middle desert				High desert		Forest and savanna
	C	G	H	A	E	I	J	D	F	B
Mojave shrub	1	12	12							
Mojave gypsum	3									
Desert grassland				14		2	16			
Blackbrush shrubland				4	8	13	1			
Creosote slopes				4		1	1			
Mixed shrublands								1	6	
Sagebrush shrublands								1	15	
Pinyon-juniper woodland								16	3	
Pinyon woodland										4
Juniper woodland										11
Forest shrubland										4
Outliers										2

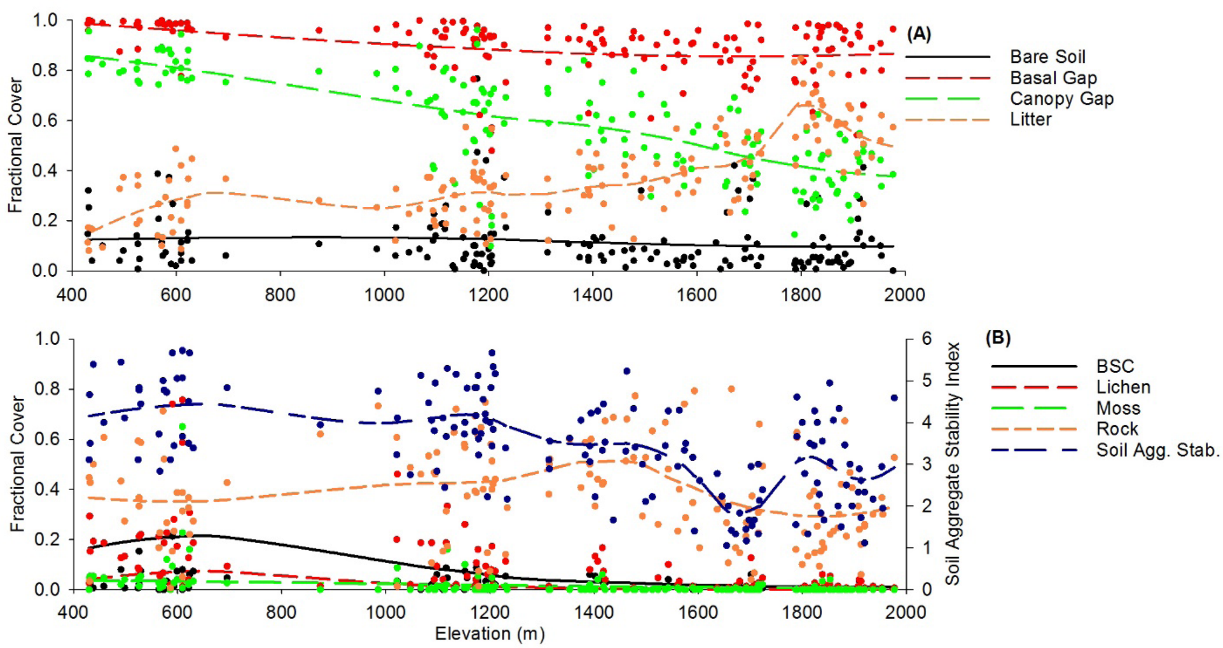

Figure 8. Plots showing trends in indicators of (*A*) soil and site stability and (*B*) hydrologic function with elevation (in meters [m]). Dots are observations, lines are loess cubic fit (SAS ver. 9.4, LOESS procedure). Plot *A* shows cover of bare soil, proportion of large basal (>200 centimeters [cm]) and canopy (>100 cm) gaps, and cover of litter (herbaceous and woody). Plot *B* shows indicators of soil cover, total biological crust cover (BSC), lichen cover, moss cover, rock cover, and soil aggregate stability.

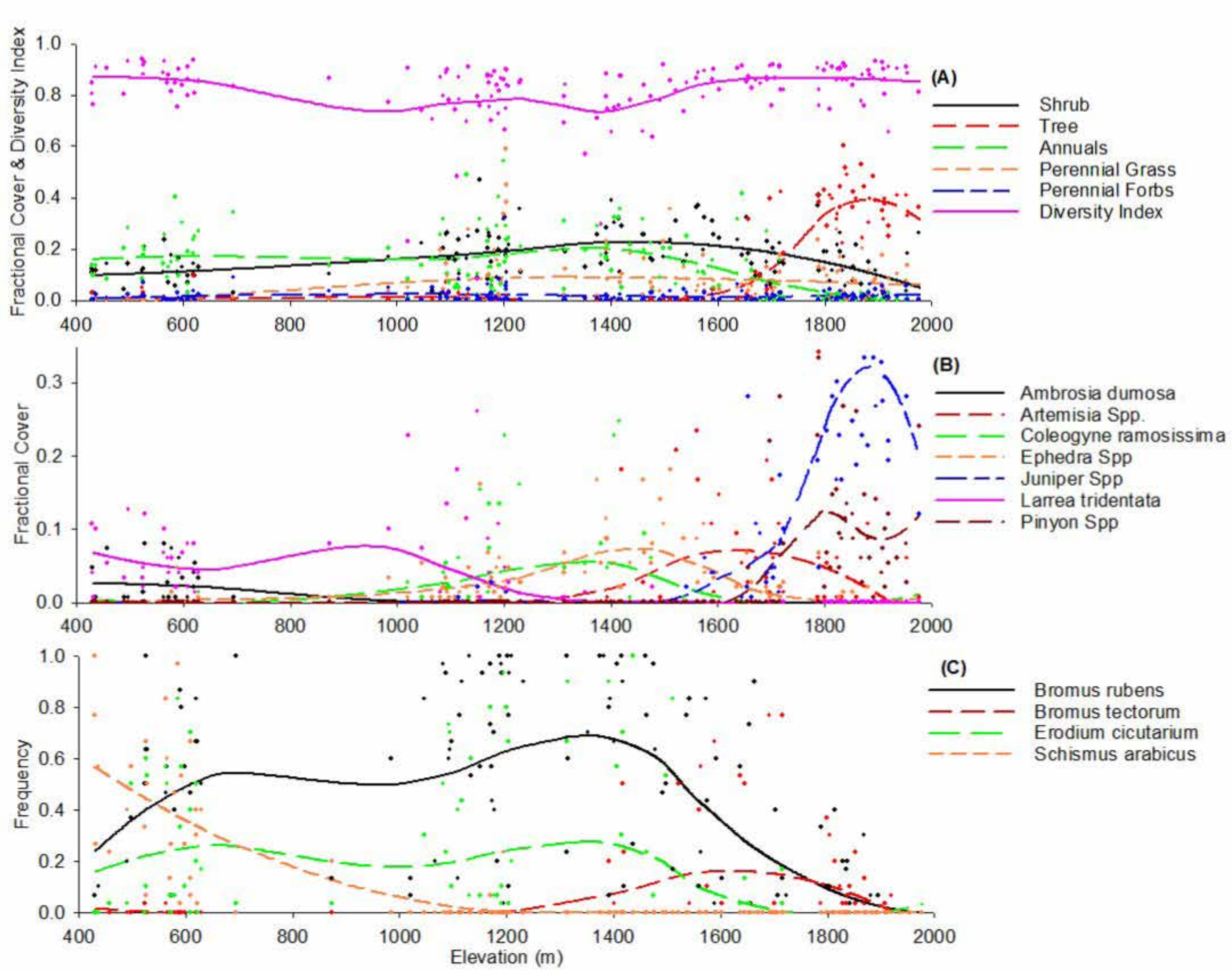

Figure 9. Plots showing trends in indicators of biotic integrity with elevation (in meters [m]). Dots are observations, lines are loess cubic fit (SAS ver. 9.4, LOESS procedure). *A*, Shrub cover, tree cover, annual cover, perennial grass cover, perennial forb cover, and Simpson's diversity index. *B*, Cover of dominant woody species. *C*, Frequency of invasive species (using a 0.16 square meter frame).

Table 9. Richness and diversity indices for climate zones and floristic groups within.

Floristic group	Avg. number of species per plot	Total number of species recorded	Avg. Simpson's diversity index	Avg. Shannon's diversity index
Low desert	10.3	62	0.78	1.85
Mojave shrub	10.6	56	0.78	1.87
Mojave gypsum	7.7	17	0.76	1.68
Middle desert	11.1	107	0.75	1.81
Desert grassland	13.2	84	0.81	2.03
Blackbrush shrubland	9.5	65	0.74	1.70
Creosote slopes	6.8	19	0.52	1.12
High desert	11.0	82	0.70	1.68
Mixed shrublands	15.7	52	0.84	2.25
Sagebrush shrublands	10.6	37	0.74	1.74
Pinyon-juniper woodland	9.7	41	0.62	1.42

Table 9. Richness and diversity indices for climate zones and floristic groups within.—Continued

Floristic group	Avg. number of species per plot	Total number of species recorded	Avg. Simpson's diversity index	Avg. Shannon's diversity index
Forest and savanna	10.9	51	0.69	1.61
Pinyon woodland	7.2	14	0.65	1.36
Juniper woodland	11.2	36	0.64	1.50
Forest shrubland	12.2	22	0.82	1.97

Cattle Use

Comparison of cow dung frequency to cost-distance from water in active grazing allotments indicates factors other than distance to water are also important for determining cattle distribution within NPS-managed allotments in Grand Canyon-Parashant National Monument (fig. 10*A*). Looking at the relation between cattle dung frequency and cost-distance to water, we observed a generally better fit to the upper quantiles of the dung frequency distribution (log-linear; $p = 0.003$; 90th percentile better than 75th or 50th), which suggests that the cost-distance to water variable provides a robust estimate of the upper bound on cattle dung frequency and is less suited to predicting more central tendencies or lower bounds of the distribution (fig. 10*A*). The 90th quantile of dung distribution also has a significant positive relation with estimated forage production (based on soil survey data; fig. 10*B*; $p = 0.029$) and negative relation with plot ruggedness index (DEM-derived ruggedness index; fig. 10*C*; $p = 0.023$). The model fit was improved by conducting a multiple-90th-quantile regression that includes all three independent variables (log cost-distance, potential forage production, plot ruggedness, and an interaction of plot potential forage production and ruggedness; table 10, fig. 10*D*). Such multiple predictor models have been used in other cattle distribution studies (Senft and others, 1983; Wade and others, 1998; Brock and Owensby, 2000; Ganskopp and Bohnert, 2009). The results presented here suggest a quantile regression approach may be more suited to estimating potential cattle use than a least-squares approach.

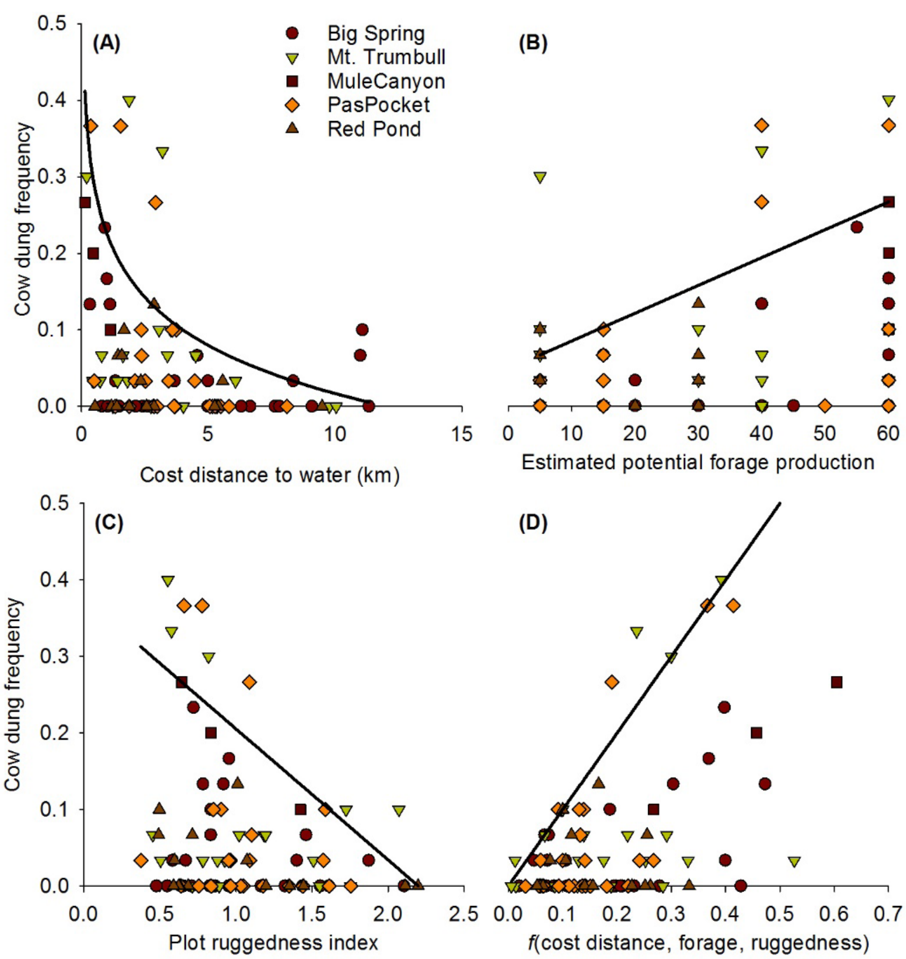

Figure 10. Plots showing the relation between observed cow dung frequency and (*A*) cost-distance to water, (*B*) predicted forage production based on correlated soil map unit component (in pounds per acre), (*C*) plot ruggedness index, and (*D*) a multiple regression of all three explanatory variables. Data for each allotment are shown. Black line depicts a 90-percent quantile regression fit. km, kilometers.

Low Desert

Landscape Setting, Soils, and Rangeland Indicators

Ecological site groups in the low desert are primarily distinguished by soil parent material, soil depth, soil horizons, slope, and landscape position (table 6, fig. 11). The four plots established in the gypsum hill area of the Tassi allotment were all classified to the same ESD and were placed in one ESG (gypsum). The other two groups (shallow limestone and deep mixed) are distinguished primarily by soil depth, soil horizon development, rock fragments, and landscape setting (slope and topographic wetness index [TWI]; fig. 11). The shallow limestone group is generally sloping with shallow soils and includes ESDs with these as the primary descriptor. The deep mixed group includes a variety of ESDs because of the range of soils included, however most plots in this group had little soil horizon development (entisols). Very little cattle dung was observed in this allotment (fig. 11*G*), however, plots in the shallow-slope and low-rock-content deep mixed group had the highest occurrence. This is expected since this allotment was officially closed to grazing at the time of this study and only trespassing cattle were present.

These differences in soils and topography among groups created few significant differences in indicators of site stability, hydrologic function, and plant functional groups (fig. 12). The deep mixed group has the highest bare ground and lowest soil aggregate stability, likely caused by low biological soil crust and rock cover (fig. 12*A*). The gypsum group has significantly higher biological soil crust cover (cyanobacteria, lichens, and mosses). Examination of plant functional group cover shows that the deep mixed group has a high cover of perennials, driven by high woody cover (fig. 12*B*). Looking at individual species, *Ambrosia dumosa* and *Larrea tridentata* occur across all groups with some among-group trends evident but no significant differences detected. The deep mixed sites had a high frequency of the invasive annual grass *Schismus arabicus* (fig. 12*C*).

Indicators of site stability and hydrologic function in the low desert show strongest correlation with measures of plot topographic setting and plot rockiness (fig. 13). Run-in areas (high TWI, high flow accumulation, and shallow slope) have high bare ground and low ground cover, potentially because of less protective rock cover. There is also a trend of high bare ground and low ground cover on warm aspects (high solar insolation). Soil aggregate stability followed similar trends. Total biological soil crust cover and cover of lichens was positively correlated with amount of exposed bedrock but negatively correlated with surface rockiness. Only proportion of large canopy gaps and soil aggregate stability showed correlation with soil texture variables, with more large gaps but also greater soil stability on fine-textured soils characterized by high water retention at field capacity. Though there is no cattle use currently permitted in the low desert (Tassi allotment), there is still a significant correlation with distance to water, which suggests areas more accessible to water sources have higher bare ground and lower ground cover than more distant parts of the Tassi allotment. This could be caused by historic cattle use, feral cattle and wild burro use (animals were present when field data was collected), or both.

Indicators of biotic integrity in the low desert show high correlation with soil texture and soil depth (fig. 13). Areas with high curvature (run-off location, hill tops, and shoulders) have low cover of woody vegetation, low cover of all perennial species, and low plant diversity. Areas with less exposed bedrock and deep soils tended to have more total cover, and areas with less exposed bedrock, few rocks in the soil profile, and deep soils tended to have high woody and shrub cover. Perennial species in general, and woody species in particular, show a positive correlation with coarse, well-drained surface soil textures. Though cover of perennial grasses and forbs is generally not very high in the low desert, there is significantly high cover of these functional groups in the shallow soil sites.

There is surprisingly little correlation among the two dominant shrubs of the low desert (*Ambrosia dumosa* and *Larrea tridentata*) and the suite of edaphic variables (fig. 13). There are no significant relations detected for *A. dumosa*. *L. tridentata* tends to occur on soils with high gravel cover and soil types that demonstrate some weak level of development (not entisols). Frequency of the two invasive annual species of concern show more correlation with soil and landscape variables. *Bromus rubens* is correlated with high elevations and deep soils. *Schismus arabicus* occurs at low elevations and is more common in areas that receive run-in moisture (high TWI) and have coarse surface textures. There is also a significant negative correlation between *S. arabicus* and distance to water sources, suggesting areas that historically have had high cattle use have high frequency of *S. arabicus*.

Ordinations

Only two floristic groups were identified for the low desert in the cluster analysis: the Mojave shrub and the Mojave gypsum (table 11). The final NMS has three axes, stress of 9.61, and instability of 0.00000. Cover in the Mojave shrub group is a mix of annual and woody species, characterized by *Ambrosia dumosa* and *Schismus arabicus*. Annual grasses compose the bulk of the graminoid cover in this group. Average richness is moderate (10.6), as is Simpson's diversity (0.78). The Mojave gypsum group is identifiable by its very well developed biological soil crust and sparse vegetation. It supports few species (average richness = 7.7, Simpson's diversity = 0.76) and low foliar cover (average total foliar cover = 0.13), but *Lycium andersonii* and *Mentzelia affinis* are indicators. Sparse vegetation leads to low indicator values and low average richness since no species occur regularly.

Table 10. Parameter estimates from multiple quantile regression estimating the 90-percent quantile of cattle dung frequency in active grazing allotments.

[Each estimate has 1 degree of freedom. %, percent]

Parameter	Estimate	Standard error	90-percent quantile		*p*-value
			Min.	Max.	
Intercept	0.6699	0.1689	0.3891	0.9507	<0.001
Log cost-distance to water	−0.1969	−0.2787	−0.1151	−4.00	<0.001
Soil survey perennial grass production	0.0079	0.0023	0.0040	0.0118	0.001
Ruggedness	0.0737	0.0755	−0.0518	0.1992	0.332
Ruggedness × perennial grass production	−0.0044	0.0020	−0.0078	−0.0011	0.029

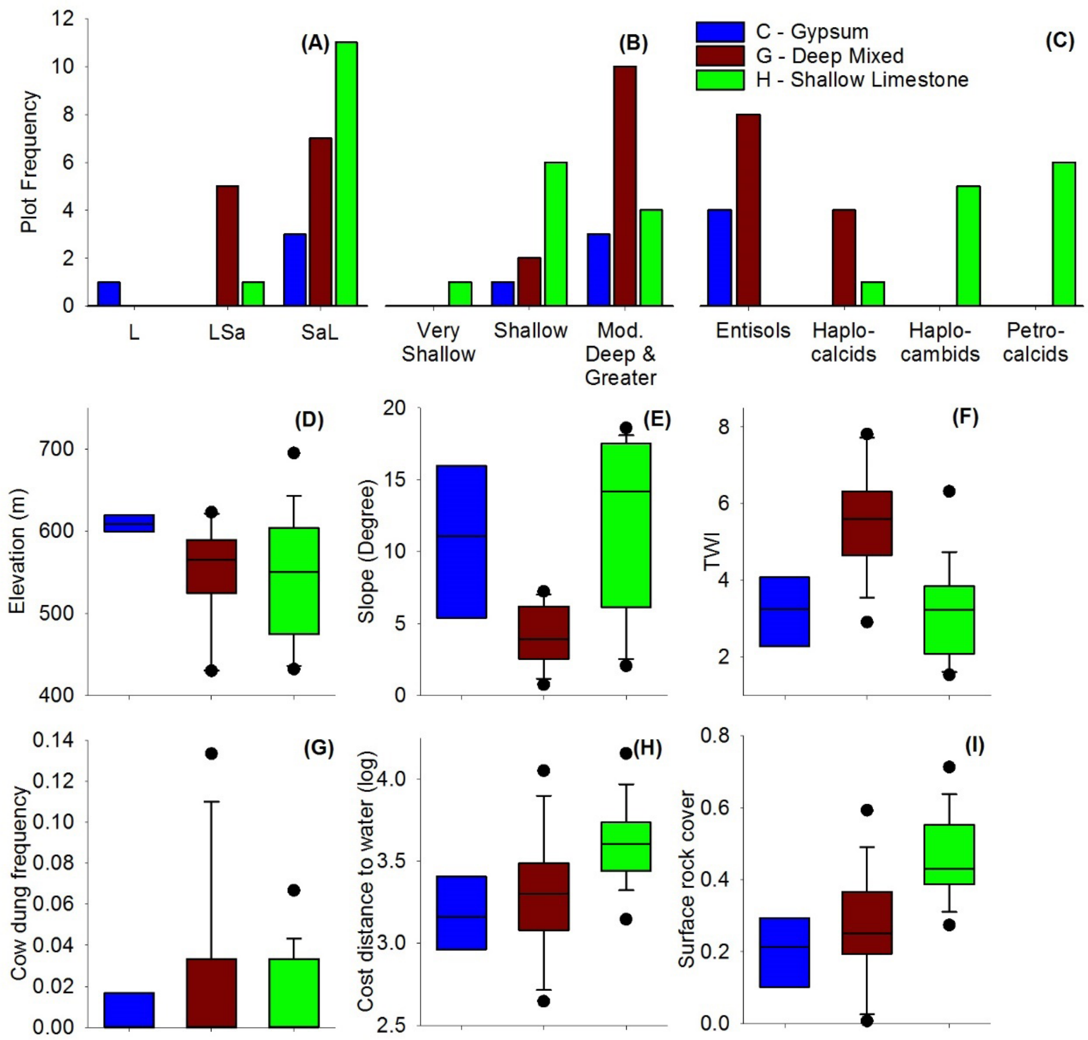

Figure 11. Plots characterizing the low desert ecological site groups. See figure 6 and table 6 for more information. Plots show the frequency of (*A*) surface soil texture class (L, loam; LSa, loamy sand; SaL, sandy loam), (*B*) soil depth class, (*C*) soil taxonomy, (*D*) elevation (in meters [m]), (*E*) slope, (*F*) topographic wetness index (TWI), (*G*) observed cow dung, (*H*) log cost-distance to water, and (*I*) surface rock cover. Box and whisker plots are shown for continuous variables, denoting 25th, 50th, and 75th quantiles (boxes); 10th and 90th quantiles (whiskers); and outliers (dots).

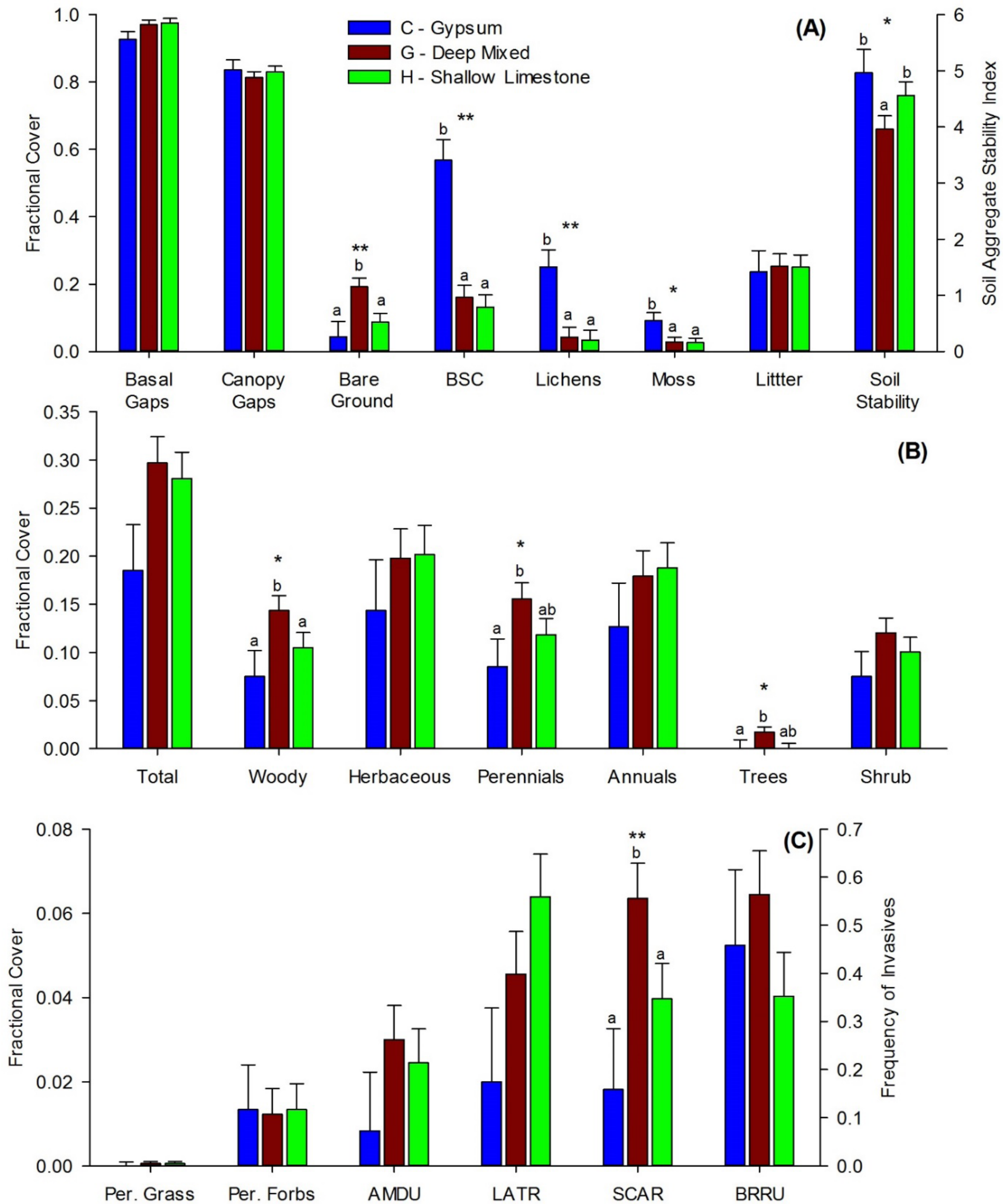

Figure 12. Plots showing fractional cover of the low desert ecological site groups. See figure 6 and table 6 for more information. *A*, Soil and hydrologic function indicators; *B*, plant community functional group cover; and *C*, dominant species cover and invasive species frequency. * indicates $p<0.10$; ** indicates $p<0.05$ for ecological site group differences from mixed model analysis of variance. Where analysis of variance detected differences among ecological site groups, bars with the same letter (a or b) do not differ. BSC, biological soil crust; per., perennial; AMDU, *Ambrosia dumosa*; LATR, *Larrea tridentata*; SCAR, *Schismus arabicus*; BRRU, *Bromus rubens*.

	Landscape setting						Soil surface properties										Cattle		Soil Classes		
Indicators	Elev.	TWI	Flow Acc.	Slope	Curv-ature	Solar Insol.	Bed-rock	Cob-ble	Gra-vel	All Rock	A-Hor. Frag.	Sand	Clay	Sat. Con	AWC	Field Cap	Cow Dung	Dist. Water	Dep-th	Tex-ture	Soil Tax.
Soil and site stability and hyrdologic function																					
Basal Gaps	-0.15	0.29	0.29	-0.26	**-0.42**	0.13	**-0.67**	0.11	0.31	0.27	-0.24	0.01	-0.01	0.05	-0.02	-0.01	0.02	0.03	0.78	0.80	0.60
Canopy Gaps	-0.15	0.02	-0.04	-0.09	0.03	0.15	-0.01	0.04	0.01	0.06	0.05	**-0.47**	**0.48**	**-0.41**	**0.45**	**0.47**	**-0.46**	0.01	0.09	**0.03**	0.51
Bare Ground	-0.16	**0.61**	**0.49**	**-0.50**	-0.28	**0.38**	-0.01	**-0.39**	**-0.45**	**-0.45**	-0.31	0.35	-0.31	0.34	-0.37	-0.34	0.15	**-0.48**	0.73	0.26	0.15
Ground Cover	0.09	**-0.53**	**-0.39**	**0.47**	0.19	**-0.38**	0.08	**0.43**	**0.48**	**0.50**	0.20	-0.27	0.24	-0.22	0.27	0.26	-0.06	**0.54**	0.64	0.44	0.24
BSC	0.17	-0.23	-0.21	0.21	0.09	-0.12	**0.51**	-0.22	**-0.44**	**-0.41**	-0.21	-0.26	0.32	-0.19	0.22	0.27	-0.10	-0.16	0.78	0.12	0.33
Lichens	0.20	-0.24	-0.21	0.23	0.15	0.01	**0.85**	-0.25	**-0.39**	-0.35	0.07	-0.25	0.27	-0.21	0.23	0.25	-0.17	-0.15	0.57	0.36	0.65
Moss	0.17	-0.26	-0.23	0.22	0.18	-0.35	-0.18	0.05	-0.13	-0.11	-0.05	-0.26	0.27	-0.26	0.26	0.27	0.07	0.17	0.29	0.38	0.63
Litter	**0.44**	-0.07	-0.08	0.06	0.02	-0.09	-0.18	-0.27	-0.21	-0.26	0.10	-0.03	-0.02	-0.11	0.06	0.02	0.08	-0.12	0.51	0.19	0.81
Soil Stability	0.12	**-0.53**	**-0.47**	**0.51**	0.34	**-0.40**	0.08	0.14	-0.05	0.03	0.05	**-0.38**	**0.42**	-0.37	0.36	**0.39**	-0.14	0.24	0.80	0.09	0.16
Plant diversity and functional groups																					
Diversity	0.01	**0.40**	**0.49**	-0.18	**-0.52**	0.15	-0.36	0.27	0.29	0.25	-0.32	0.21	-0.20	0.32	-0.23	-0.22	0.24	-0.13	0.19	**0.04**	**0.03**
Total	0.24	0.21	0.20	-0.05	-0.25	-0.14	**-0.50**	-0.17	-0.10	-0.14	-0.20	0.26	-0.30	0.19	-0.23	-0.27	**0.44**	0.02	0.07	0.15	0.59
Woody	-0.12	0.26	0.27	-0.21	**-0.39**	0.01	**-0.49**	0.15	0.17	0.08	**-0.38**	**0.48**	**-0.46**	**0.51**	**-0.48**	**-0.48**	**0.43**	-0.04	**0.03**	**0.02**	0.23
Herbaceous	**0.41**	0.10	0.09	0.04	-0.10	-0.14	-0.29	-0.30	-0.27	-0.27	-0.05	0.04	-0.09	-0.05	0.00	-0.05	0.28	-0.05	**0.02**	0.17	0.68
Perennial	-0.03	0.24	0.28	-0.17	**-0.42**	-0.02	**-0.49**	0.18	0.16	0.11	-0.31	**0.47**	**-0.46**	**0.49**	**-0.47**	**-0.47**	**0.50**	0.04	**0.05**	**0.03**	0.37
Annual	**0.38**	0.10	0.07	0.03	-0.06	-0.15	-0.30	-0.33	-0.26	-0.28	-0.08	0.03	-0.08	-0.07	0.01	-0.04	0.25	-0.06	0.13	0.13	0.69
Tree	0.02	**0.38**	**0.45**	-0.22	-0.31	0.19	-0.09	0.22	-0.02	0.04	-0.17	**0.46**	**-0.43**	**0.52**	**-0.48**	**-0.46**	0.08	-0.14	0.30	**0.01**	0.17
Shrub	-0.10	0.15	0.17	-0.13	-0.31	-0.05	**-0.48**	0.06	0.21	0.08	**-0.38**	0.34	-0.34	0.36	-0.34	-0.34	**0.39**	-0.05	0.09	0.17	0.20
Per. Grass	0.36	0.02	0.05	0.02	-0.07	-0.01	-0.07	-0.24	-0.06	-0.02	-0.08	0.16	-0.17	0.18	-0.16	-0.17	0.12	-0.08	**0.00**	0.61	0.37
Per. Forbs	0.26	-0.03	0.07	0.13	-0.13	-0.13	-0.10	0.10	-0.02	0.10	0.11	0.05	-0.09	0.04	-0.04	-0.06	0.29	0.26	**0.00**	0.83	0.49
Dominant species and species of concern																					
AMDU	0.04	0.10	0.03	-0.13	-0.13	-0.02	-0.23	0.03	0.10	0.03	-0.27	0.27	-0.26	0.25	-0.27	-0.27	0.30	-0.04	0.81	0.41	0.21
LATR	-0.36	-0.15	-0.06	0.18	-0.05	-0.27	-0.33	0.05	**0.43**	0.26	-0.08	0.10	-0.13	0.07	-0.09	-0.11	0.17	0.13	0.40	0.73	**0.02**
BRRU	**0.58**	0.30	0.37	-0.08	-0.37	-0.01	-0.37	-0.18	-0.25	-0.24	-0.28	-0.02	-0.02	0.00	0.03	0.01	0.21	-0.16	**0.01**	0.99	0.46
SCAR	**-0.40**	**0.42**	0.37	-0.31	-0.31	0.18	-0.26	-0.35	-0.20	-0.32	-0.25	**0.39**	-0.34	0.37	**-0.40**	**-0.38**	0.17	**-0.42**	0.07	0.20	0.62
NMS Axis Scores																					
Axis-1	-0.28	**0.61**	**0.59**	**-0.46**	**-0.50**	0.27	**-0.58**	-0.02	0.10	-0.01	**-0.49**	**0.43**	**-0.39**	**0.50**	**-0.46**	**-0.43**	0.23	-0.32	**0.01**	**0.02**	0.27
Axis-2	**-0.44**	-0.12	-0.14	0.00	0.14	0.03	0.22	0.35	0.33	0.33	0.02	-0.04	0.11	0.04	0.00	0.06	-0.19	0.22	0.05	0.16	0.74
Axis-3	**-0.44**	-0.05	-0.16	-0.05	0.28	0.06	0.27	-0.11	0.02	0.00	**0.40**	0.12	-0.14	-0.01	-0.08	-0.11	-0.23	-0.05	0.09	0.06	0.29

Figure 13. Plot showing correlations between rangeland health indicators, ordination axes (nonmetric multidimensional scaling [NMS]), and landscape setting, soil, and cattle factors for low desert settings. See table 1 for descriptions of rangeland health indicators (left column) and table 5 for descriptions of edaphic factors (top row). Cell values are Pearson correlation coefficients (for continuous variables; bold values indicate *p*-values <0.05) or *p*-values from ANOVA tests (for soil classes). Cell color shading provides further emphasis on correlation strength (dark green, strong positive; yellow, near zero; and dark red, strong negative) or ANOVA *p*-value strength (dark green is strong and white is weak).

Table 11. Floristic groups in the low desert climate zone identified by cluster analysis and indicator species analysis.

[In addition to functional indicators, species with statistically significant (*p* <0.05) indicator values are listed, followed by indicator value in parentheses. SD, standard deviation; N, number]

Indicator	Mean (SD)	Min.	Max.
Mojave shrub (N = 25)			
Total foliar cover	0.29 (0.09)	0.12	0.43
Woody cover	0.12 (0.05)	0.03	0.23
Graminoid cover	0.10 (0.08)	0.00	0.30
Annual cover	0.19 (0.09)	0.08	0.40
Avg. soil stability	4.22 (0.84)	2.83	5.67
Ambrosia dumosa (84)	0.03 (0.03)	0.00	0.08
Schimus arabicus (82)	0.03 (0.04)	0.00	0.13
Bare soil (75)	0.14 (0.11)	0.01	0.39

Indicator	Mean (SD)	Min.	Max.
Mojave gypsum (N = 3)			
Total foliar cover	0.13 (0.09)	0.07	0.24
Woody cover	0.06 (0.05)	0.00	0.11
Graminoid cover	0.04 (0.07)	0.00	0.12
Annual cover	0.08 (0.07)	0.03	0.15
Avg. soil stability	5.49 (0.36)	5.07	5.72
Biological soil crust (82)	0.69 (0.09)	0.59	0.76
Lycium andersonii (67)	0.01 (0.01)	0.00	0.02
Mentzelia affinis (67)	0.00 (0.00)	0.00	0.01

There is evidence for the importance of landscape and soil setting as controlling factors for indicators of plant community composition. There is strong agreement between Mojave gypsum floristic group and the gypsum ESG, whereas the Mojave shrub group was evenly split between the deep mixed and shallow limestone ESGs (table 8). Examination of relations among diversity, NMS axes, and edaphic gradients suggests local topographic setting (TWI, flow accumulation, slope, and curvature) plays an important role in controlling the primary axis of community composition (axis-1; fig. 13). Proportion of exposed bedrock, A-horizon rockiness, properties associated with soil texture, and soil depth are all also significantly correlated with the primary axis. The other two axes identified in the NMS (axis-2 and axis-3), show less correlation with measured landscape and soil factors, with significant correlations only observed for elevation (for both axes) and sand percentage (for axis-3).

Middle Desert

Landscape Setting, Soils, and Rangeland Indicators

The four ESGs of the middle desert are distinguished primarily by parent material (basalt, sandstone, and limestone), soil depth (shallow to deep), and slope (table 6, fig. 14). There are two ESGs that are characterized by shallow soils but have contrasting soil diagnostic horizons (and taxonomy; fig. 14*C*). Shallow limestone plots are all torriorthents, which are soils that have very little soil development, whereas shallow mixed plots generally are in taxonomic classes that require calcic horizon development. The other two ESGs are moderately deep to deep and generally not steeply sloping but have contrasting parent materials and resulting texture and mineralogy. Deep basalt plots are generally finer in texture than deep limestone plots, though deep limestone plots tend to be more hydrologically enhanced (high TWI; fig. 14*F*). Cattle dung frequency is highest in the deep limestone plots (fig. 14*G*).

Groups in the middle desert exhibit large and consistent differences in ecosystem indicators of site stability and hydrologic function (fig. 15*A*) and plant functional and species occurrence (fig. 15*B*, *C*). The deep limestone group has lower cover of large basal (>200 cm) and canopy (>100 cm) gaps than other ESGs. The shallow sandstone group has the highest biological soil crust cover and the deep basalt and deep limestone groups have the lowest. Soil aggregate stability is highest in the shallow mixed and deep limestone groups, shallow sandstone groups have an intermediate level of aggregation, and the deep basalt group has the lowest aggregate stability. ESG plant functional group and species cover indicate differences in basal and canopy gaps are driven by very high perennial grass cover in the deep limestone group. The shallow mixed group has significantly higher cover of *Coleogyne ramosissima*, leading to an overall higher cover of shrubs, than the other ESGs, whereas the shallow sandstone group has intermediate cover. *Gutierrezia* spp. cover is also high in the deep limestone group. *Bromus rubens* frequency shows some specificity to ESGs, with the deep limestone group having the lowest and deep basalt and shallow mixed both showing similarly common occurrence. Frequency of the invasive species *Erodium cicutarium* was highest in the deep limestone group and lowest in the deep basalt group.

In the middle desert, site stability and hydrologic function indicators associated with soil cover (bare ground, ground cover, and biological soil crusts) show the most correlation with landscape and soil setting variables (fig. 16). Sites with high TWI, shallow slopes, and low rock cover tend to have more bare ground and less ground cover. Total cover of biological soil crusts as well as cover of lichens and mosses are significantly positively correlated with proportion of exposed bedrock, negatively correlated with most rock cover indicators, and positively correlated with coarse soil textures. Together, these suggest that biological soil crusts are most prevalent on shallow, sandy soil settings. Soil stability and biological soil crust cover both showed decreasing trends with elevation. Moss cover and soil stability are negatively correlated with solar insolation, indicating they are high in the cool aspects. Correlations with cow dung frequency, distance to water, and the cattle index suggest areas with high cattle activity have high bare ground and low ground cover.

There are fewer associations among biotic integrity indicators, landscape, and soil setting variables in the middle desert than in indicators of soil and site stability and hydrologic function (fig. 16). There is less total cover in sites with high amounts of exposed bedrock and less cover of herbaceous and annual functional types on coarse well-drained soils. Similarly, few correlations were detected between functional group cover and the three measures of cattle use. There is some evidence of high shrub cover where cattle use is low (cow dung correlation) and high tree and annual cover where cattle use is low, but the lack of consistent trends among other functional group indicators suggests these correlations may be spurious.

Cover of dominant species and species of concern demonstrate more correlation with landscape and soil factors than functional group cover in the middle desert (fig. 16). *Ephedra* spp. cover is positively correlated and *Larrea tridentata* cover is negatively correlated with elevation. *Ephedra* cover is also positively correlated with steep slope and negatively correlated with run-in positions (TWI). *Ephedra* is the only dominant species that shows any correlation with soil properties, preferring soils with high rock cover but that are not excessively drained (negative correlation with soil conductivity). *Bromus rubens* frequency is also positively correlated with soil rockiness (rock cover as well as A-horizon rock content) and soil textures that afford high water retention (high clay, low conductivity, and high

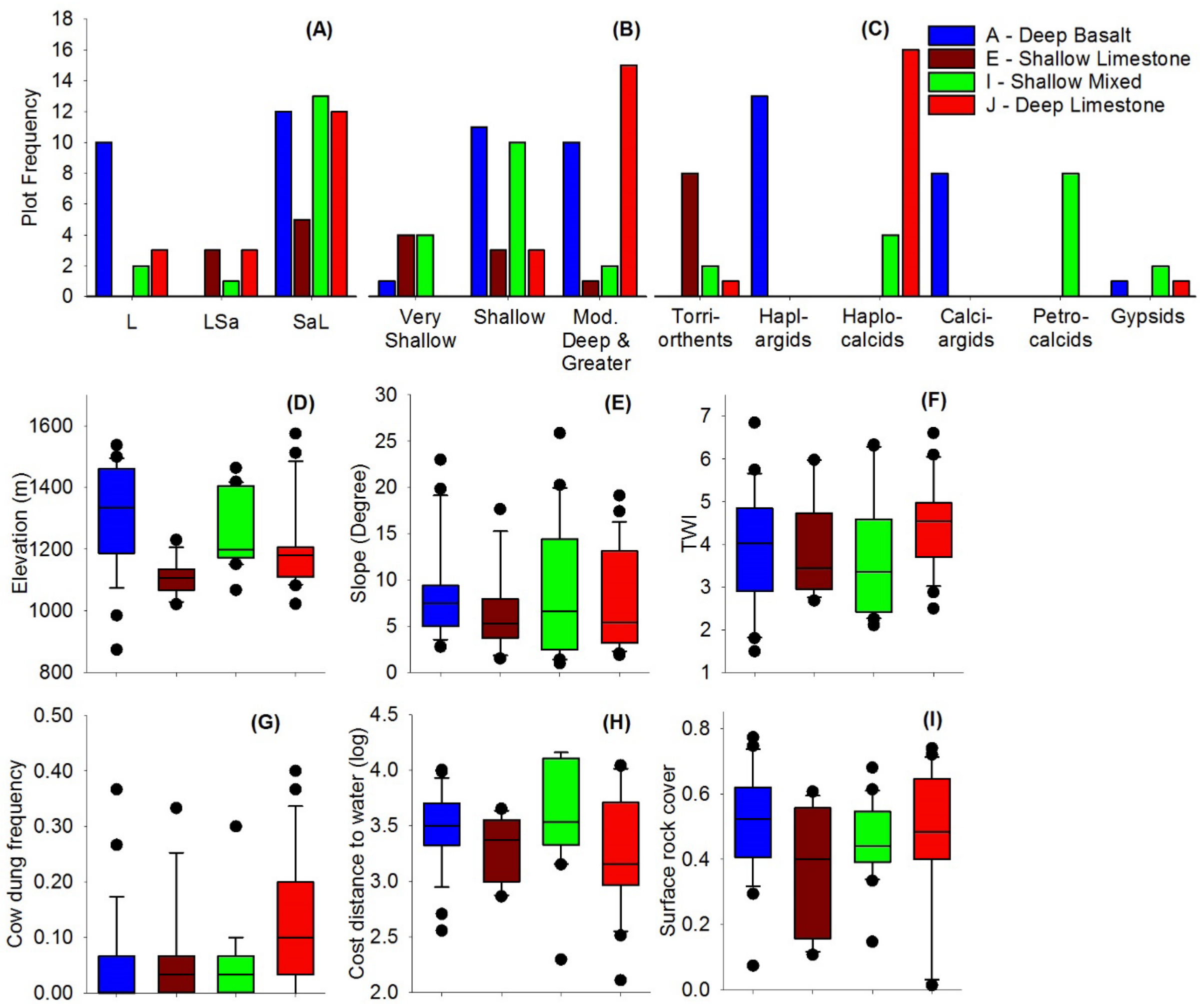

Figure 14. Plots characterizing the middle desert ecological site groups. See figure 6 and table 6 for more information. Plots show the frequency of (*A*) surface soil texture class (L, loam; LSa, loamy sand; SaL, sandy loam), (*B*) soil depth class, (*C*) soil taxonomy, (*D*) elevation (in meters [m]), (*E*) slope, (*F*) topographic wetness index (TWI), (*G*) observed cow dung, (*H*) log cost-distance to water, and (*I*) surface rock cover. Box and whisker plots are shown for continuous variables, denoting 25th, 50th, and 75th quantiles (boxes); 10th and 90th quantiles (whiskers); and outliers (dots).

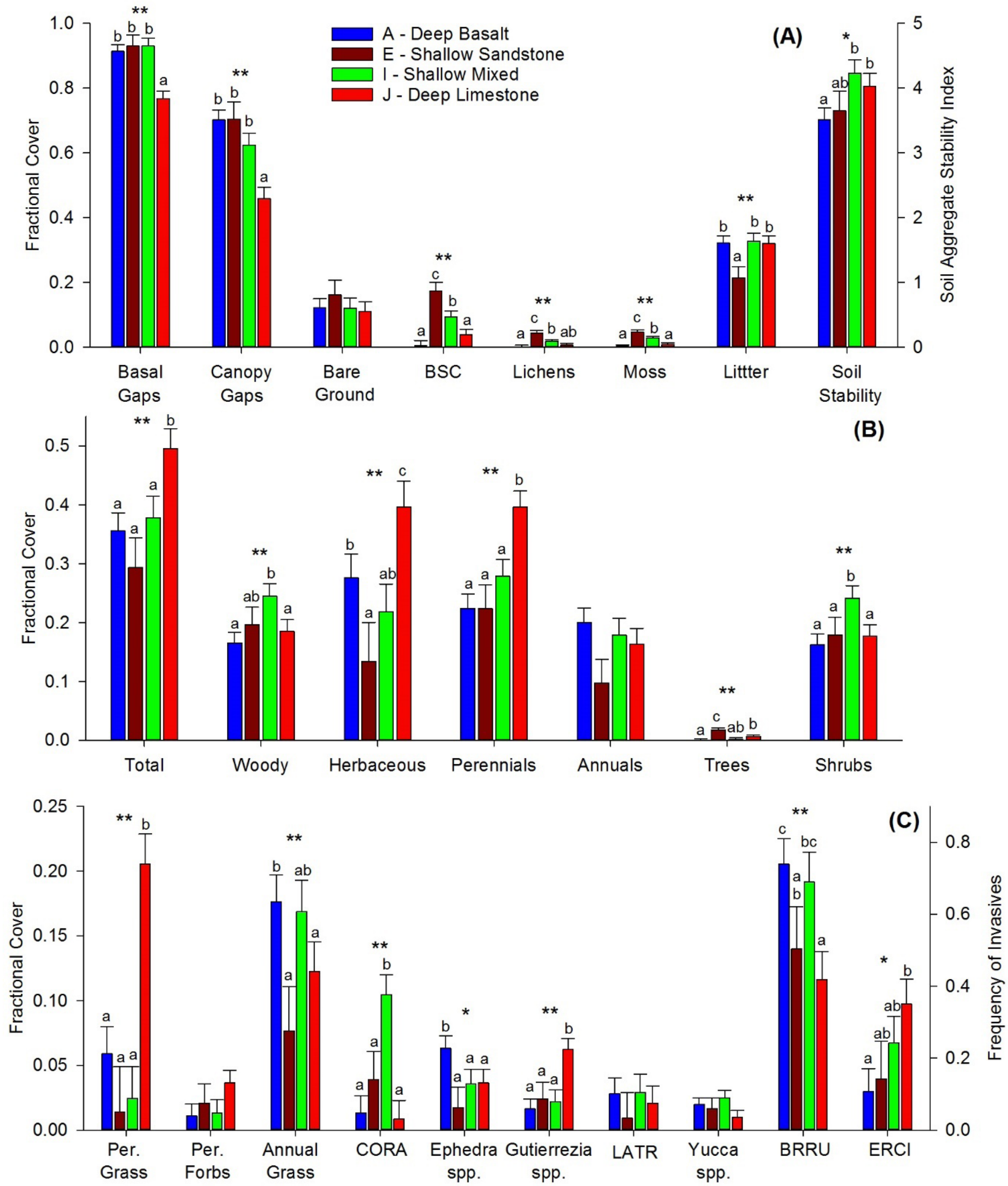

Figure 15. Plots showing fractional cover of the middle desert ecological site groups. See figure 6 and table 6 for more information. *A*, soil and hydrologic function indicators; *B*, plant community functional group cover; and *C*, dominant species cover and invasive species frequency. * indicates $p<0.10$; ** indicates $p<0.05$ for ecological site group differences from mixed model analysis of variance. Where analysis of variance detected differences among ecological site groups, bars with the same letter (a, b, or c) do not differ. BSC, biological soil crust; per., perennial; CORA, *Coleogyne ramosissima*; LATR, *Larrea tridentata*, BRRU, *Bromus rubens*, ERCI, *Eragrostis cilianensis*.

	Landscape setting						Soil surface properties										Cattle			Soil Classes		
Indicators	Elev.	TWI	Flow Acc.	Slop e	Curv- ature	Solar Insol.	Bed- rock	Cob- ble	Gra- vel	All Rock	A-Hor. Frag.	Sand	Clay	Sat. Con	AWC	Field Cap	Cow Dung	Dist. Water	Cattle Index	Dep- th	Tex- ture	Soil Tax.
Soil and site stability and hyrdologic function																						
Basal Gaps	-0.21	-0.02	-0.10	0.00	0.02	-0.13	0.20	-0.09	-0.22	-0.12	-0.17	0.03	-0.04	0.04	-0.02	-0.03	-0.07	0.15	**-0.30**	0.11	0.93	**0.00**
Canopy Gaps	-0.23	0.02	-0.04	-0.02	0.15	-0.03	0.24	-0.14	**-0.29**	-0.18	**-0.25**	-0.03	0.01	0.04	0.03	0.02	0.08	0.07	-0.22	0.29	0.37	**0.00**
Bare Ground	-0.12	0.23	0.04	**-0.34**	-0.17	0.16	-0.13	**-0.33**	**-0.54**	**-0.68**	**-0.39**	0.04	-0.08	0.17	-0.03	-0.06	**0.50**	**-0.28**	**0.30**	0.83	**0.02**	0.75
Ground Cover	0.19	**-0.30**	-0.08	**0.44**	0.20	-0.18	**0.25**	**0.43**	**0.52**	**0.79**	**0.41**	0.17	-0.06	-0.01	-0.19	-0.13	**-0.64**	**0.40**	**-0.49**	0.23	**0.01**	0.16
BSC	**-0.31**	0.15	-0.04	-0.18	-0.09	-0.13	**0.40**	**-0.40**	**-0.48**	**-0.36**	**-0.36**	**0.34**	**-0.33**	**0.42**	**-0.34**	**-0.35**	-0.12	-0.01	0.17	0.06	**0.00**	**0.00**
Lichens	-0.19	0.22	0.00	**-0.27**	-0.08	0.02	**0.40**	**-0.35**	**-0.37**	-0.24	-0.25	0.18	-0.17	0.19	-0.18	-0.18	-0.15	0.04	0.11	0.16	0.32	0.08
Moss	-0.17	-0.14	-0.24	0.01	-0.07	**-0.27**	**0.37**	**-0.25**	**-0.35**	-0.16	-0.15	**0.31**	**-0.29**	**0.31**	**-0.30**	**-0.31**	-0.23	0.12	-0.02	**0.01**	**0.04**	**0.00**
Litter	0.25	0.14	**0.29**	0.09	-0.19	0.03	**-0.43**	0.04	0.23	0.01	**0.31**	**-0.28**	**0.36**	**-0.35**	**0.25**	**0.32**	-0.08	**0.34**	-0.20	**0.05**	**0.02**	0.10
Soil Stability	**-0.31**	-0.13	-0.10	0.15	0.05	**-0.38**	-0.05	0.19	-0.04	0.07	0.20	0.12	-0.11	0.08	-0.11	-0.11	-0.13	0.12	-0.08	0.42	0.51	0.19
Plant diversity and functional groups																						
Diversity	0.00	-0.07	0.01	0.04	-0.07	-0.06	0.12	0.08	-0.14	0.01	0.13	-0.05	0.02	-0.04	0.06	0.04	0.11	-0.05	0.16	0.64	0.94	0.10
Total	0.18	0.05	0.14	0.07	-0.10	0.01	**-0.32**	0.13	0.20	0.09	0.23	-0.18	0.10	-0.17	0.20	0.16	-0.10	0.05	0.12	0.12	0.32	0.14
Woody	0.19	-0.08	-0.06	0.09	-0.18	-0.09	-0.17	0.03	0.14	0.07	0.13	0.17	-0.13	0.08	-0.17	-0.16	-0.24	0.11	-0.10	0.39	0.12	0.06
Herbaceous	0.15	0.09	0.17	0.02	0.01	0.09	-0.24	0.12	0.14	0.07	0.20	**-0.28**	0.20	**-0.25**	**0.30**	**0.26**	-0.04	0.08	0.09	0.14	0.14	0.11
Perennial	0.20	-0.06	0.00	0.09	-0.13	-0.04	**-0.26**	0.17	0.15	0.08	0.14	-0.05	-0.02	-0.04	0.08	0.03	-0.10	-0.03	0.19	0.25	0.80	**0.02**
Annual	0.13	0.20	**0.25**	-0.04	-0.01	0.13	**-0.25**	-0.02	0.14	0.01	0.23	**-0.34**	**0.28**	**-0.35**	**0.35**	**0.33**	-0.08	0.22	-0.11	0.38	**0.02**	0.28
Tree	**-0.30**	0.07	0.00	-0.12	-0.17	-0.20	0.11	-0.04	-0.24	-0.07	-0.02	0.19	-0.19	0.16	-0.18	-0.19	0.19	-0.22	**0.28**	0.91	0.26	0.10
Shrub	0.22	-0.08	-0.05	0.10	-0.17	-0.07	-0.20	0.03	0.18	0.07	0.14	0.15	-0.11	0.06	-0.15	-0.13	**-0.27**	0.14	-0.13	0.36	0.18	0.07
Per. Grass	0.16	0.00	0.08	0.05	-0.03	0.05	-0.17	0.18	0.12	0.10	0.10	-0.11	0.06	-0.08	0.13	0.10	0.02	-0.07	0.24	0.07	0.80	**0.01**
Per. Forbs	-0.11	-0.11	-0.15	0.02	0.08	-0.05	0.02	0.01	-0.19	-0.14	-0.10	**-0.28**	0.05	-0.09	**0.34**	0.20	0.10	-0.13	0.19	0.54	0.23	0.05
Ann. Grass	0.21	0.15	0.24	0.04	0.00	0.12	-0.20	0.06	0.21	0.14	**0.34**	-0.23	0.24	**-0.28**	0.22	0.24	-0.22	**0.28**	-0.21	0.35	0.06	0.27
Dominant species and species of concern																						
CORA	0.16	0.00	-0.12	-0.07	-0.07	0.09	-0.15	-0.12	0.06	-0.08	0.17	0.04	0.00	0.01	-0.05	-0.03	-0.21	**0.28**	-0.15	0.66	0.97	0.24
Ephedra Spp	**0.60**	**-0.26**	-0.05	**0.30**	0.11	0.23	-0.14	0.15	**0.32**	**0.26**	0.14	-0.22	0.19	**-0.26**	0.23	0.22	-0.24	0.18	**-0.34**	**0.03**	0.06	0.07
Gutierrezia Spp	-0.08	0.06	0.05	-0.11	-0.16	-0.03	-0.09	0.01	-0.02	-0.07	0.02	0.02	0.02	-0.02	-0.04	-0.01	**0.29**	**-0.31**	**0.35**	0.42	0.93	0.06
LATR	**-0.39**	0.08	0.01	-0.07	0.05	-0.23	-0.09	0.08	0.07	0.02	-0.10	0.22	-0.23	0.19	-0.21	-0.23	0.02	-0.15	0.06	0.86	0.16	0.43
Yucca Spp	0.19	0.12	0.17	-0.02	0.00	0.18	-0.23	-0.22	0.19	-0.04	0.22	-0.10	0.14	-0.18	0.08	0.12	0.01	0.10	-0.11	0.86	0.25	0.54
BRRU	0.22	0.06	0.19	0.10	0.12	0.14	-0.09	0.22	0.19	**0.28**	**0.54**	-0.25	**0.36**	**-0.41**	0.21	**0.30**	-0.17	0.24	**-0.31**	0.69	**0.00**	0.30
ERCI	0.05	0.17	0.08	-0.24	-0.13	0.19	-0.22	-0.19	0.11	-0.14	-0.09	-0.11	0.06	-0.15	0.13	0.10	0.17	-0.08	0.24	0.63	0.15	0.09
NMS Axis Scores																						
Axis-1	0.15	0.20	**0.30**	-0.01	-0.05	0.15	**-0.37**	0.08	0.14	-0.01	**0.28**	**-0.33**	**0.31**	**-0.34**	**0.33**	**0.33**	0.15	0.07	0.09	**0.04**	**0.02**	**0.05**
Axis-2	-0.14	-0.01	0.03	0.12	0.14	-0.09	0.16	0.09	-0.11	0.05	0.01	0.10	-0.04	0.16	-0.13	-0.09	-0.08	0.20	-0.25	0.59	0.06	0.16
Axis-3	0.15	**-0.28**	-0.13	**0.30**	0.11	-0.12	**0.27**	0.24	-0.07	0.19	-0.14	0.08	-0.10	0.15	-0.08	-0.09	0.06	-0.14	0.12	0.09	0.24	0.40

Figure 16. Plot showing correlations among rangeland health indicators, ordination axes (nonmetric multidimensional scaling [NMS]), and landscape setting, soil, and cattle factors for middle desert settings. See table 1 for descriptions of rangeland health indicators (left column) and table 5 for descriptions of edaphic factors (top row). Cell values are Pearson correlation coefficients (for continuous variables; bold values indicate *p*-values <0.05) or *p*-values from ANOVA tests (for soil classes). Cell color shading provides further emphasis on correlation strength (dark green, strong positive; yellow, near zero; and dark red, strong negative) or ANOVA *p*-value strength (dark green is strong and white is weak).

available water capacity). There are some significant trends in dominant shrub cover relative to cattle variables. Both *Coleogyne ramosissima* and *Ephedra* appear to have high cover in locations that receive low cattle pressure. Conversely, *Gutierrezia* spp. has high cover in locations with high dung frequency, close water sources, and where the cattle index predicts high use. *B. rubens* frequency is negatively correlated with the cattle index.

Ordinations

The middle desert contains three floristic groups identified in the cluster analysis: one dominated by grasses (desert grassland), one that is largely characterized by *C. ramosissima* and a mix of shrubs (blackbrush shrubland), and one that is characterized by *L. tridentata* (creosote slopes; table 12). The final NMS has three axes, stress of 18.03, and instability of 0.00000.

The desert grasslands have the highest average graminoid cover (0.30) and the highest maximum graminoid cover (0.73) for the study area, whereas woody cover is generally low (0.18; table 12). The species with the highest indicator values are all native perennial grasses, but the composition of those grasses within plots is variable. Simpson's diversity within this group is high (0.81) and average species richness is second highest of the eleven floristic groups (13.2). Many of the species that occur within this group occur in different combinations across the landscape and overlap with either the low desert or the high desert floristic groups. It is a transitional community and has a combination of species that are typically found in the Mojave Desert and on the Colorado Plateau.

Blackbrush shrublands are generally less vegetated than the desert grasslands but are comparable in cover to the creosote slopes (table 12). This group has a mix of woody and graminoid cover, where the woody cover is composed almost entirely of shrubs rather than trees (0.21 versus 0.01).

Table 12. Floristic groups in the middle desert climate zone identified by cluster analysis and indicator species analysis.

[In addition to functional groups, species with statistically significant (p <0.05) indicator values are listed, followed by indicator value in parentheses. SD, standard deviation; N, number]

Indicator	Mean (SD)	Min.	Max.
Desert grassland (N = 32)			
Total foliar cover	0.46 (0.16)	0.07	0.88
Woody cover	0.18 (0.09)	0.00	0.31
Annual cover	0.19 (0.10)	0.03	0.54
Graminoid cover	0.30 (0.14)	0.05	0.73
Avg. soil stability	3.88 (0.92)	2.11	5.67
Hilaria rigida (67)	0.05 (0.06)	0.00	0.24
Muhlenbergia porteri (61)	0.03 (0.03)	0.00	0.10
Bouteloua eriopoda (44)	0.03 (0.04)	0.00	0.18
Sporobolus cryptandrus (39)	0.04 (0.09)	0.00	0.40
Tridens muticus (25)	0.01 (0.01)	0.00	0.03
Blackbrush shrubland (N =26)			
Total foliar cover	0.32 (0.11)	0.15	0.62
Woody cover	0.22 (0.10)	0.05	0.47
Graminoid cover	0.14 (0.11)	0.00	0.38
Annual cover	0.15 (0.11)	0.00	0.35
Avg. soil stability	3.86 (0.90)	2.22	5.29
Coleogyne ramosissima (64)	0.08 (0.10)	0.00	0.35
Biological soil crust (49)	0.01 (0.04)	0.00	0.19
Bare soil (40)	0.16 (0.11)	0.05	0.47
Mortonia utahensis (35)	0.02 (0.03)	0.00	0.11
Creosote slopes (N = 6)			
Total foliar cover	0.34 (0.15)	0.21	0.57
Woody cover	0.19 (0.05)	0.11	0.27
Graminoid cover	0.17 (0.17)	0.02	0.39
Annual cover	0.20 (0.20)	0.02	0.49
Avg. soil stability	3.72 (0.65)	2.44	4.20
Larrea tridentata (83)	0.16 (0.07)	0.08	0.26
Pectis papposa (43)	0.04 (0.06)	0.00	0.15

The species with the highest indicator values, although weak, are both native and uncommon in the study area. *Mortonia utahensis* occurs only in this floristic group, albeit sporadically. *Coleogyne ramosissima* occurs sporadically across the study range, but more consistently in this floristic group. *M. utahensis* is typically found in the Mojave Desert, whereas *C. ramosissima* occurs on the Colorado Plateau and into the Mojave. The low indicator values and somewhat low average richness (9.5) are due to the variable composition of the plots. This variability in composition and the mix of species with Mojave Desert and Colorado Plateau affiliations illustrate that this group is also a transitional community. Like the desert grasslands group, this group shares many species with low desert and high desert floristic groups. Soil stability ranges from instable to stable (2.22–5.29), and the average is moderately stable (3.86).

Creosote slopes have moderate levels of average total foliar cover (0.34), of which the woody component is consistent (0.19) and composed of shrubs (table 12). Graminoid and annual covers are variable, but high annual covers correspond with high graminoid covers, indicating the primary driver of graminoid cover is the annual nonnative species *Bromus rubens*. Since forbs are negligible (0.05), this group is characterized by woody shrubs with little understory or an understory of an annual nonnative grass. *Larrea tridentata* is the primary shrub in this group, which is reflected in a high indicator value (83). This group has the lowest average richness (6.8) and the lowest diversity (0.52).

Soils and plant community data suggest the middle desert climate zone has a higher diversity in soils and landscapes as well as associated plant communities than any other climate zone (four ESGs and three floristic groups; table 8, fig. 16). Desert grassland floristic groups were evenly split between the deep basalt and shallow limestone ESGs. Blackbrush shrublands occur in all ESGs but are most common in the shallow mixed group, and creosote slopes are most common in the deep basalt group. Correlations between axis scores and environmental variables were strongest with axis-1, which is positively correlated with contributing area (flow accumulation; fig. 16); negatively correlated with amount of exposed bedrock; and positively correlated with A-horizon rockiness, surface soil sand content (and associated soil hydrologic properties), and soil depth. Axis-2 shows no trends with landscape and soil variables and axis-3 is correlated with sites that have low TWI, steep slopes, and high exposed bedrock.

High Desert and Forest and Savanna

Landscape Setting, Soils, and Rangeland Indicators

In the results presented here, we lump the high desert and forest and savanna ESGs, because there is only one ESG identified in the forest and savanna zone and there is high overlap in elevations and associated climates between the two zones (table 6; fig. 17*D*). The two high desert ESGs are distinguished by both parent material and soil depth. The deep basalt and shallow limestone groups both have shallow to moderate slopes, however, as the names indicate, they have differing parent materials and dominant depths (fig. 17*B*). The high desert basalt group is also generally deeper and finer textured than the high desert shallow limestone group. The shallow loam group in the forest and savanna has a similar elevation range as the high desert basalt group. The shallow loam group is generally shallower and coarser in texture than

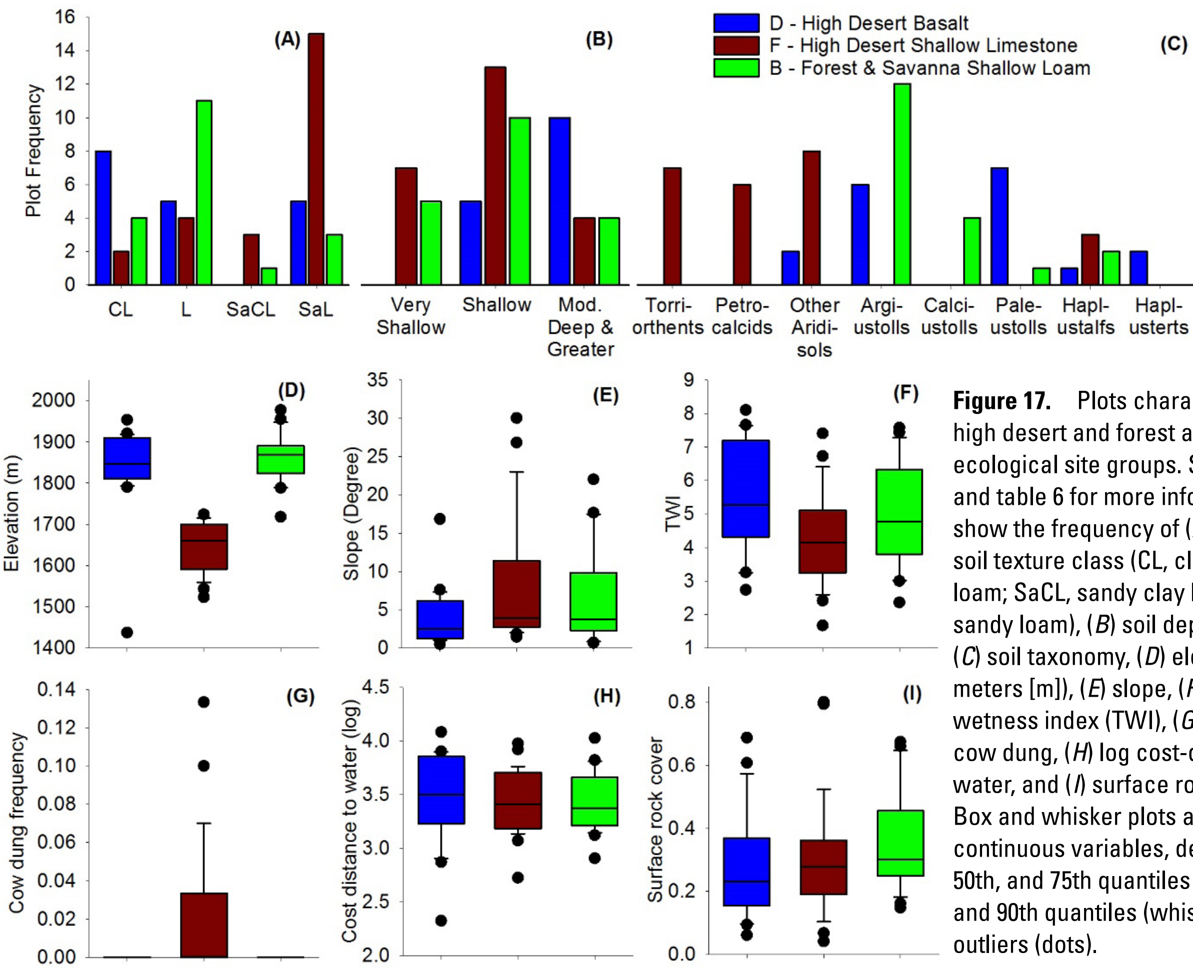

Figure 17. Plots characterizing the high desert and forest and savanna ecological site groups. See figure 6 and table 6 for more information. Plots show the frequency of (*A*) surface soil texture class (CL, clay loam; L, loam; SaCL, sandy clay loam, SaL, sandy loam), (*B*) soil depth class, (*C*) soil taxonomy, (*D*) elevation (in meters [m]), (*E*) slope, (*F*) topographic wetness index (TWI), (*G*) observed cow dung, (*H*) log cost-distance to water, and (*I*) surface rock cover. Box and whisker plots are shown for continuous variables, denoting 25th, 50th, and 75th quantiles (boxes); 10th and 90th quantiles (whiskers); and outliers (dots).

the high desert basalt ESG. Cattle use, as indicated by dung frequency, is absent on the high desert basalt group and forest and savanna shallow loam because these ESGs are restricted to the Home Ranch allotment (fig. 6), which has not been grazed by livestock since 2003. Cattle dung was observed in the high desert shallow limestone group, but frequencies were generally low (fig. 17*G*).

Indicators of soil and site stability, hydrologic function, and plant functional group differed among the three ESGs (fig. 18*A*, *B*). There were no differences in cover of large basal gaps, however, canopy gaps were lower in the forest and savanna shallow loam than the high desert shallow limestone ESG. Bare ground was significantly lower in the forest and savanna ESG than the high desert ESGs. Biological soil crust cover was greatest in the shallow limestone group, potentially because of soil differences and low foliar and litter cover. These trends in gaps, bare ground, and litter are explained in part by trends in vascular plant cover. There were significant differences among all ESGs in indicators of biotic integrity. Total, perennial, and woody cover differed, with cover lowest in the shallow limestone group and highest in the shallow loam group. However, cover of annual grasses, *Artemsia* spp., and *Gutierrezia* spp. were significantly higher in the shallow limestone group than other groups (fig. 18*C*). The two high elevation ESGs had similar high cover of trees (primarily juniper with some pinyon). The two species of the invasive *Bromus* annual grasses (*B. rubens* and *B. tectorum*) were significantly more frequent in the shallow limestone ESG.

Across the high desert and forest and savanna ESGs, there are a number of significant correlations between the soil and site stability and hydrologic function indicators and landscape and soil setting properties (fig. 19). The proportion of canopy gaps is high at low elevations and in landscape settings with high curvatures (more convex). Both ground cover and litter increase with elevation. Unexpectedly, the proportion of bare ground increases with degree of hydrologic enhancement (high TWI, high flow accumulation, and shallow slopes) but also increases in warm aspects (high solar insolation). Rocky areas have low bare ground and high ground cover. Litter cover is also reduced in areas with high bedrock exposure and coarse surface soils. There is no association between cost-distance to cattle water sources and indicators of soil and site stability and hydrologic function.

Indicators of biotic integrity show some association with landscape setting variables and many associations with soil properties (fig. 19). High elevations tend to have high total and

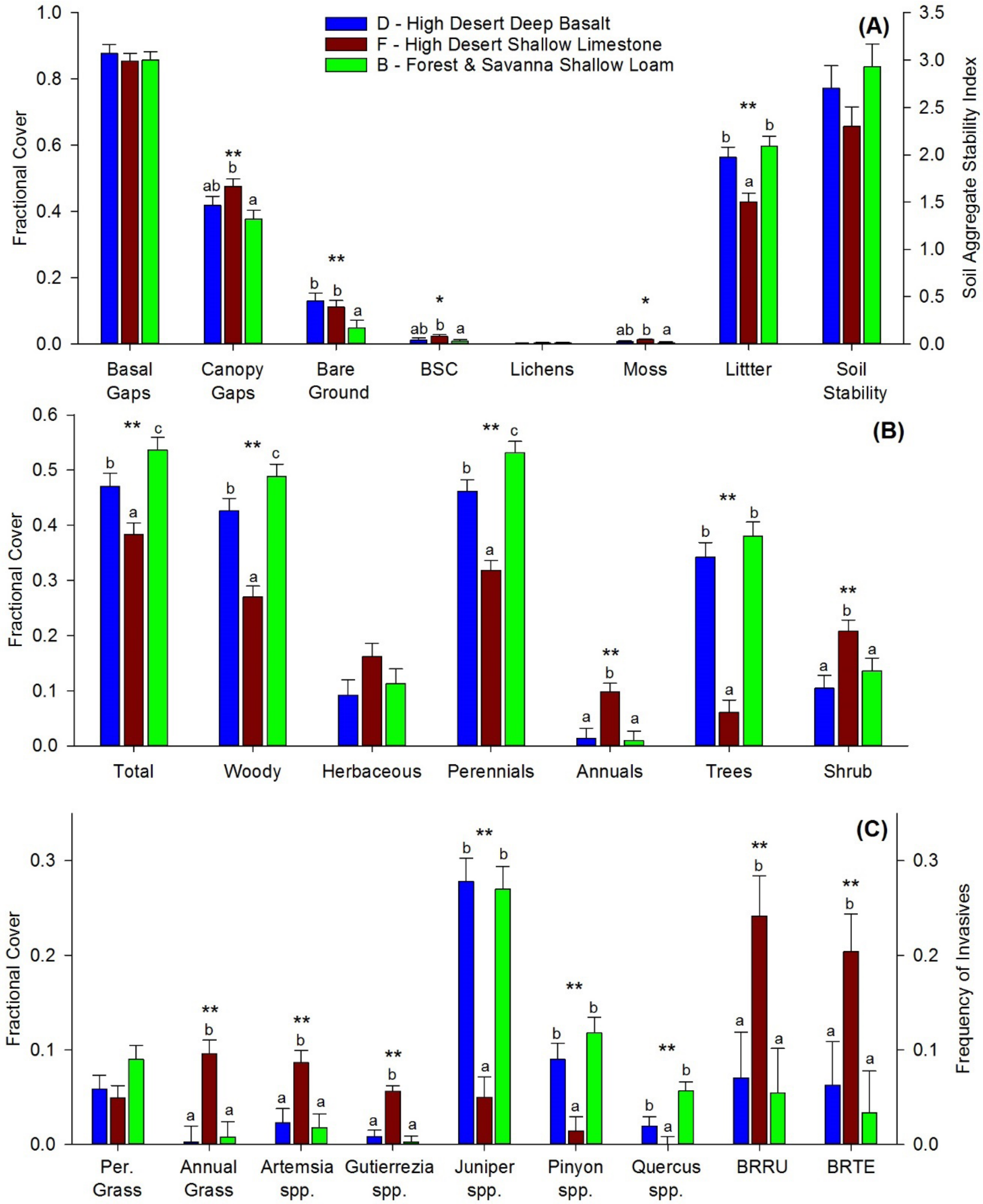

Figure 18. Plots showing fractional cover of the high desert and forest and savanna ecological site groups. See figure 6 and table 6 for more information. *A*, Soil and hydrologic function indicators; *B*, plant community functional group cover; and *C*, dominant species cover and invasive species frequency. * indicates $p<0.10$; ** indicates $p<0.05$ for ecological site group differences from mixed model analysis of variance. Where analysis of variance detected differences among ecological site groups, bars with the same letter (a, b, or c) do not differ. BSC, biological soil crust; per., perennial; BRRU, *Bromus rubens*; BRTE, *Bromus tectorum*.

Indicators	Landscape setting: Elev.	TWI	Flow Acc.	Slope	Curv-ature	Solar Insol	Soil surface properties: Bed-rock	Cob-ble	Gra-vel	All Rock	A-Hor. Frag.	Sand	Clay	Sat. Con	AWC	Field Cap	Cattle: Cow Dung	Dist. Water	Soil Classes: Dep-th	Tex-ture	Soil Tax.
Site stability and hyrdologic function																					
Basal Gaps	-0.05	0.21	0.08	-0.16	0.04	0.11	0.01	0.02	0.06	0.04	0.08	-0.15	0.11	-0.14	0.15	0.13	-0.05	0.05	0.29	0.62	0.87
Canopy Gaps	**-0.33**	0.14	0.01	-0.05	**0.26**	-0.09	0.25	-0.08	0.19	0.14	-0.01	**0.28**	-0.21	0.23	**-0.28**	-0.24	0.18	0.04	0.23	0.31	**0.02**
Bare Ground	0.06	**0.51**	**0.33**	**-0.41**	-0.14	**0.30**	**-0.29**	**-0.27**	**-0.45**	**-0.53**	**-0.34**	0.13	-0.05	0.11	-0.16	-0.09	0.22	-0.18	0.05	0.42	0.57
Ground Cover	**0.31**	-0.22	-0.11	0.22	-0.21	-0.01	-0.01	**0.32**	**0.43**	**0.47**	**0.29**	-0.25	0.11	-0.20	**0.30**	0.18	**-0.32**	0.05	0.84	0.09	0.16
BSC	-0.19	0.12	0.11	-0.07	**0.31**	-0.03	0.03	-0.24	-0.14	-0.24	-0.10	0.08	-0.11	0.06	-0.04	-0.09	0.03	-0.15	0.13	0.78	0.71
Lichens	-0.02	0.11	0.08	-0.14	0.01	0.09	-0.08	-0.22	0.06	-0.11	-0.07	-0.08	-0.02	-0.08	0.16	0.03	-0.04	-0.19	0.26	0.28	1.00
Moss	-0.20	0.13	0.13	-0.06	0.22	-0.06	-0.01	-0.18	-0.22	-0.25	-0.08	0.14	-0.08	0.08	-0.14	-0.10	0.01	-0.17	0.43	0.74	0.48
Litter	**0.48**	0.04	-0.09	-0.24	-0.22	**0.33**	**-0.28**	-0.19	-0.23	**-0.35**	-0.02	**-0.39**	**0.29**	**-0.28**	**0.36**	**0.33**	-0.12	-0.09	0.83	**0.02**	**0.00**
Soil Stability	0.11	-0.14	-0.09	0.08	0.18	0.03	-0.02	**0.32**	-0.03	0.15	-0.17	-0.06	-0.10	-0.10	0.20	-0.01	-0.12	0.03	0.20	**0.00**	0.20
Plant diversity and functional groups																					
Diversity	0.05	**-0.26**	**-0.28**	0.11	0.05	-0.09	0.17	-0.06	-0.19	-0.10	0.22	-0.18	0.19	-0.20	0.14	0.19	0.12	0.01	0.56	0.34	0.29
Total	**0.30**	-0.24	-0.10	0.18	-0.12	0.00	-0.04	0.08	0.02	0.05	0.13	**-0.37**	**0.26**	**-0.32**	**0.36**	**0.31**	-0.14	0.17	0.96	**0.04**	**0.00**
Woody	**0.56**	0.02	0.03	-0.07	**-0.26**	**0.27**	**-0.34**	0.11	-0.11	-0.09	0.02	**-0.43**	**0.35**	**-0.39**	**0.41**	**0.39**	**-0.40**	-0.02	0.23	**0.01**	**0.00**
Herbaceous	**-0.37**	**-0.40**	-0.21	**0.36**	0.19	**-0.40**	**0.37**	-0.08	0.17	0.16	0.10	0.12	-0.15	0.14	-0.08	-0.14	**0.33**	0.25	0.09	0.71	0.12
Perennial	**0.53**	-0.07	-0.01	0.04	-0.25	0.18	**-0.28**	0.13	-0.08	-0.04	0.04	**-0.43**	**0.34**	**-0.39**	**0.41**	**0.39**	**-0.37**	0.01	0.36	**0.01**	**0.00**
Annual	**-0.58**	**-0.32**	-0.20	0.24	**0.32**	**-0.39**	**0.48**	-0.14	0.22	0.18	0.15	0.16	-0.19	0.17	-0.12	-0.19	**0.45**	**0.29**	**0.02**	0.52	**0.00**
Tree	**0.77**	**0.38**	**0.27**	**-0.30**	**-0.35**	**0.54**	**-0.37**	0.15	-0.21	-0.15	-0.10	**-0.47**	**0.43**	**-0.42**	**0.41**	**0.46**	**-0.34**	-0.10	**0.04**	**0.00**	**0.00**
Shrub	**-0.54**	**-0.63**	**-0.41**	**0.45**	0.18	**-0.59**	0.17	-0.12	0.18	0.11	0.23	0.22	**-0.28**	0.18	-0.14	**-0.25**	0.06	0.12	0.17	0.08	**0.00**
Per. Grass	0.06	**-0.36**	-0.18	**0.36**	-0.11	**-0.27**	0.00	0.06	0.08	0.10	0.00	0.05	-0.09	0.06	0.00	-0.07	-0.05	0.04	0.87	0.95	0.12
Ann. Grass	**-0.51**	**-0.33**	-0.22	0.25	**0.33**	**-0.37**	**0.51**	-0.12	0.10	0.11	0.18	0.13	-0.17	0.14	-0.09	-0.16	**0.47**	**0.29**	**0.01**	0.60	**0.00**
Dominant species and species of concern																					
Artemisia	**-0.45**	-0.16	-0.08	0.09	-0.01	**-0.25**	-0.07	0.05	0.00	0.00	-0.06	0.21	-0.23	0.16	-0.14	-0.22	0.08	0.00	0.32	0.23	**0.00**
Gutierrezia	**-0.65**	**-0.35**	**-0.25**	0.24	**0.48**	**-0.43**	**0.42**	-0.20	0.02	0.00	0.18	**0.25**	-0.12	0.09	**-0.26**	-0.16	**0.35**	0.05	0.18	**0.02**	**0.00**
Juniper	**0.74**	**0.51**	**0.35**	**-0.39**	**-0.29**	**0.59**	**-0.37**	-0.01	**-0.32**	**-0.31**	-0.13	**-0.45**	**0.49**	**-0.44**	**0.36**	**0.49**	**-0.29**	-0.13	0.06	**0.00**	**0.00**
Pinyon	**0.43**	0.00	0.00	-0.06	-0.23	0.21	-0.20	**0.26**	0.07	0.13	0.03	**-0.28**	0.15	-0.18	**0.27**	0.20	**-0.26**	0.03	0.17	0.21	**0.02**
Quercus	**0.31**	**-0.28**	-0.21	0.20	-0.14	-0.08	-0.17	-0.07	-0.12	-0.15	0.08	-0.06	-0.05	-0.03	0.12	0.00	-0.18	-0.01	0.98	0.43	**0.00**
BRRU	**-0.48**	**-0.46**	**-0.28**	**0.54**	**0.49**	**-0.55**	**0.59**	-0.05	**0.43**	**0.41**	**0.32**	0.05	-0.04	0.03	-0.04	-0.04	**0.29**	**0.33**	0.10	0.98	**0.00**
BRTE	**-0.38**	-0.20	-0.22	0.01	0.09	-0.20	0.14	-0.19	0.00	-0.08	0.21	0.20	-0.22	0.18	-0.16	-0.22	0.10	0.08	0.12	0.33	0.12
NMS Axis Scores - High Desert																					
Axis-1	**0.77**	**0.62**	**0.41**	**-0.55**	**-0.39**	**0.68**	**-0.54**	-0.02	**-0.49**	**-0.48**	-0.27	-0.29	**0.31**	-0.22	0.23	0.30	-0.25	-0.30	**0.00**	0.14	**0.00**
Axis-2	0.00	0.10	0.04	-0.21	-0.19	0.11	-0.26	-0.03	**-0.37**	**-0.35**	-0.09	0.03	0.01	-0.04	-0.02	0.01	0.05	-0.23	0.23	0.95	**0.00**
Axis-3	**0.34**	0.00	-0.08	-0.22	-0.11	**0.31**	-0.12	-0.12	-0.17	-0.21	0.05	**-0.35**	0.26	-0.23	**0.34**	0.29	-0.05	0.08	0.99	0.18	0.18
NMS Axis Scores - Forest and Savanna																					
Axis-1	-0.07	**-0.56**	-0.41	0.39	-0.11	**-0.54**	-0.33	**-0.49**	-0.19	**-0.57**	0.01	0.18	-0.24	0.27	-0.08	-0.24		0.03	0.97	0.71	0.07
Axis-2	-0.20	**-0.49**	-0.24	0.40	0.03	-0.28	-0.14	0.37	0.20	**0.46**	0.29	0.17	-0.45	0.27	0.10	-0.37		0.12	0.98	0.07	0.37

Figure 19. Plots showing correlations between rangeland health indicators, ordination axes (nonmetric multidimensional scaling [NMS]), and landscape setting, soil, and cattle factors for high desert and forest and savanna settings. See table 1 for descriptions of rangeland health indicators (left column) and table 5 for descriptions of edaphic factors (top row). Cell values are Pearson correlation coefficients (for continuous variables; bold values indicate *p*-values <0.05) or *p*-values from ANOVA tests (for soil classes). Cell color shading provides further emphasis on correlation strength (dark green, strong positive; yellow, near zero; and dark red, strong negative) or ANOVA *p*-value strength (dark green is strong and white is weak).

woody (tree) cover. Low elevations have a large proportion of shrubs and herbaceous species (except perennial grasses). There is also a tendency for high tree cover in hydrologically enhanced areas (high TWI and flow accumulation; more concave), whereas shrubs and herbaceous species occupy less-enhanced, more sloping locations. Woody and tree cover are also positively correlated with high solar gain (high solar insolation) whereas shrubs and herbaceous functional types (annuals, perennial grasses, and so on) tend to occur on cool aspects. The amount of exposed bedrock and soil depth are significantly associated with tree and herbaceous plant cover, but soil rockiness is not. High tree cover is associated with less exposed bedrock and deeper soils, whereas more bedrock and shallow soils favor herbaceous functional groups, including annual forbs and grasses. High surface sand content and associated hydrologic properties favor high tree cover, whereas shrubs show negative correlation with surface clay content and water retention at field capacity.

Dominant species and species of concern also show strong association with landscape position, soil properties, and soil taxonomy (fig. 19). There is high cover of *Artemisia* spp. and *Gutierrezia* spp. and high frequency of *Bromus rubens* and *Bromus tectorum* at low elevations, whereas juniper, pinyon, and *Quercus* spp. have high cover at high elevations. *Gutierrezia* spp. cover and *B. rubens* frequency are associated with landscape settings that shed water (low TWI and flow accumulation; high curvature) whereas juniper species are associated with run-in, shallow slope areas. Both *Artemisia* spp. and *Gutierrezia* spp. have high cover on cool aspects (low solar insolation), as does *B. rubens*. *Gutierrezia* spp. cover is high in locations with more exposed bedrock and sandier soils with low available water holding capacity. *Juniperus* spp. cover is negatively correlated with exposed bedrock and soil rockiness and positively correlated with clay content and associated hydrologic properties. *Pinus* spp. have a similar association with soil texture but are also positively correlated with cobble content. *B. rubens* is more common in sites with high exposed bedrock and high rockiness. The species level of association with soil taxonomy was notably strong in the high desert and forest and savanna climates. *Artemisia* and *Gutierrezia* spp. were most abundant on haploargids and haplocalids, respectively. *Juniperus* and *Pinus* spp. were most abundant on the various taxa characterized by mollic epipedons (argiustolls, calciustolls, and paleustolls) and *Quercus* spp. were most abundant on calcareous soils with a mollic epipedon (calciustolls). *B. rubens* was most frequent on torriorthents.

Ordinations

The cluster analysis identified three floristic groups in the high desert, two of which are characterized by shrubs (mixed shrublands and sagebrush shrublands) and one that is characterized by trees (pinyon-juniper woodlands; table 13). The final NMS has three dimensions, stress of 9.81, and instability of 0.00000.

The mixed shrublands have the highest average richness (15.7) and the highest diversity (Simpson's diversity index of 0.84) of all the floristic groups, despite the small sample size (N = 7). Woody cover is dominant (0.25), but graminoid cover also composes a large portion of the cover in places (as much as 0.29). The woody cover is predominantly composed of shrubs (0.23), rather than trees (0.2). The graminoid cover is due in part to cover of the nonnative annual grasses *Bromus rubens* and *Bromus tectorum*. This group is characterized by *B. rubens*, and the native shrubs *Atriplex canescens*, *Ephedra viridis*, and *Yucca baccata*. Soil stability is generally low (2.12), with only two of the seven plots averaging higher than category 2.

The sagebrush shrublands have a moderate average richness (10.6) and diversity (0.74), and more variability in the amount of total foliar cover (0.19 to 0.58) than the mixed shrublands (table 13). This cover is largely woody cover (0.26) as shrubs (0.23), but graminoid cover in the form of mostly *B. tectorum* and *B. rubens* is also a large component in some areas (ranges from 0.01 to 0.44). *Artemisia tridentata* is the primary shrub and primary indicator for this group. Additionally, *B. tectorum* and *Sphaeralcea grossularifolia* are weak indicators. Average soil stability is low to moderate with an average of 2.47.

Pinyon-juniper woodlands have a moderate average richness (9.7), but low diversity (0.621; table 13). This floristic group has high average total foliar cover (0.46) but is somewhat variable. Most of the total foliar cover is accounted for by woody tree cover (0.37), as shrub (0.09), graminoid (0.04), and forb (0.02) cover are all low. Though low in cover, graminoid cover is composed of perennial grasses rather than annual nonnatives. Tree cover consists of *Juniperus osteosperma* and two species of pinyon (*Pinus monophylla* and *Pinus edulis*), which are also the strongest indicator species. The forb *Eriogonum umbellatum*, though low in cover, was primarily found with this plant assemblage and is therefore a moderate indicator.

In the high desert, we observed strong concordance between ESGs and floristic groups (table 8) and NMS axes

Table 13. Floristic groups in the high desert climate zone identified by cluster analysis and indicator species analysis.

[In addition to functional groups, species with statistically significant (p <0.05) indicator values are listed, followed by indicator value in parentheses. SD, standard deviation; N, number]

Indicator	Mean (SD)	Min.	Max.
Mixed shrublands (N = 7)			
Total foliar cover	0.41 (0.07)	0.31	0.47
Woody cover	0.25 (0.08)	0.15	0.35
Graminoid cover	0.16 (0.08)	0.04	0.29
Annual cover	0.13 (0.09)	0.01	0.25
Avg. soil stability	2.12 (1.24)	1.06	4.28
Bromus rubens (74)	0.08 (0.09)	0.00	0.25
Atriplex canescens (58)	0.02 (0.01)	0.00	0.04
Ephedra viridis (55)	0.03 (0.02)	0.00	0.07
Yucca baccata (53)	0.02 (0.01)	0.00	0.04
Sagebrush shrublands (N = 16)			
Total foliar cover	0.38 (0.13)	0.19	0.58
Woody cover	0.26 (0.08)	0.15	0.41
Graminoid cover	0.16 (0.13)	0.01	0.44
Annual cover	0.11 (0.13)	0.00	0.41
Avg. soil stability	2.47 (0.93)	1.17	4.29
Artemisia tridentata (84)	0.14 (0.08)	0.03	0.34
Bromus tectorum (49)	0.07 (0.08)	0.00	0.24
Sphaeralcea grossularifolia (41)	0.01 (0.02)	0.00	0.05
Pinyon-juniper woodland (N = 19)			
Total foliar cover	0.46 (0.11)	0.25	0.71
Woody cover	0.43 (0.11)	0.25	0.71
Graminoid cover	0.04 (0.05)	0.00	0.17
Annual cover	0.00 (0.00)	0.00	0.01
Avg. soil stability	2.60 (0.96)	1.33	4.94
Juniperus osteosperma (80)	0.30 (0.10)	0.10	0.43
Pinus monophylla (79)	0.06 (0.07)	0.00	0.27
Pinus edulis (63)	0.05 (0.06)	0.00	0.26
Eriogonum umbellatum (53)	0.00 (0.01)	0.00	0.02

(fig. 19). The deep basalt ESG was almost exclusively classified by the cluster analysis as a pinyon-juniper woodland. The shallow limestone ESG has both the mixed shrubland and sagebrush shrubland clusters (table 8). Several landscape and soil factors were strongly correlated with the first NMS axis but fewer significant correlations were found with the second and third axes (fig. 19). Axis-1 is positively correlated with high elevations, run-in topographic settings (high TWI and flow accumulation, shallow slope and curvature), and warm aspects (high solar insolation). Axis-1 is also negatively correlated with soil rockiness (amount of exposed bedrock, gravel cover, and all rock cover) and positively correlated with soil clay content. Axis-2 shows no correlation with landscape metrics but, like axis-1, is negatively correlated with rockiness (gravel cover and all rock cover). Axis-3 is also positively correlated with elevation and solar insolation but negatively correlated with surface sand content and available water capacity.

Three groups were identified within the forest and savanna climate zone (table 14). Two of the groups are typified by different tree species with little understory (pinyon woodlands and juniper woodlands), whereas the third has a dense shrubby understory (forest shrublands). The final NMS has two dimensions, stress of 11.86, and instability of 0.00000.

The pinyon woodlands have low average richness (7.2) and low diversity (0.65), similar to the pinyon-juniper woodlands. The high average total foliar cover (0.50) is composed mostly of woody cover (0.47), especially trees (0.37). This group does have some shrub cover (0.14), particularly *Artemisia tridentata*. Annual cover is negligible (0.01), so most of the graminoid cover (0.04) is attributable to perennial grasses. *Pinus edulis* and *A. tridentata* are strong indicators of this group, but *Juniperus osteosperma* and other shrubs do occur in smaller amounts. Soil stability is moderately stable (3.70).

The juniper woodlands have a moderate average species richness (11.2), but low diversity (0.64), similar to the pinyon-juniper woodlands and the pinyon woodlands. The high average total foliar cover (0.52) is also composed mostly of woody vegetation (0.48), particularly trees (0.40). This group, however, generally has very little shrub understory (0.09) and is characterized by *J. osteosperma*. Although *Pinus monophylla* and *P. edulis* occur, they are in much smaller amounts than in the pinyon-juniper woodlands and in the pinyon woodlands. Graminoid cover (0.07) is predominantly composed of the perennial *Elymus elymoides*. Soil stability is unstable to moderately stable (2.51), and only four of eleven plots have an average soil stability of 3 or more.

The forest shrublands, in contrast to the juniper woodlands and pinyon woodlands, have high average species richness (12.2) and diversity (0.82), despite the small sample size (N = 4). This group also has the highest average and overall total foliar cover of all eleven groups (0.62, ranging from 0.52 to 0.73). Woody cover is the dominant type (0.53), but shrub and tree cover are generally balanced (0.26 and 0.33, respectively). Average graminoid cover is also higher than pinyon woodlands or juniper woodlands (0.22) and is composed mostly of perennial grasses. This group is characterized by the native perennial grass *Poa fendleriana* and the native shrubs *Garrya flavescens*, *Quercus turbinella*, and *Purshia stansburiana*. Soil stability is generally moderately stable (>3), but one plot had very low average stability (1.6).

Fewer landscape and soil factors were correlated with NMS axes in the forest and shrublands than in other climate zones (fig. 19), likely partly because only one ESG is identified in this climate zone (table 8). Axis-1 is negatively correlated with run-in positions (TWI), incoming solar gain (solar insolation), and soil rockiness (cobbles and total rock cover). Axis-2 is negatively correlated with run-in position (TWI) but is positively correlated with soil rockiness (total rock cover).

Across the high desert and forest and savanna field plots, there is no association between plant diversity and soil variables measured and very little association between

Table 14. Floristic groups in the forest and savanna climate zone identified by cluster analysis and indicator species analysis.

[In addition to functional groups, species with statistically significant (p <0.05) indicator values are listed, followed by indicator value in parentheses. SD, standard deviation; N, number]

Indicator	Mean (SD)	Min.	Max.
Pinyon woodlands (N = 4)			
Total foliar cover	0.50 (0.06)	0.44	0.56
Woody cover	0.47 (0.06)	0.43	0.56
Graminoid cover	0.04 (0.07)	0.00	0.15
Annual cover	0.01 (0.02)	0.00	0.03
Avg. soil stability	3.70 (1.17)	2.13	4.61
Pinus edulis (80)	0.24 (0.11)	0.09	0.33
Artemisia tridentata (77)	0.05 (0.05)	0.01	0.11
Juniper woodlands (N = 11)			
Total foliar cover	0.52 (0.08)	0.39	0.67
Woody cover	0.48 (0.09)	0.31	0.63
Graminoid cover	0.07 (0.05)	0.00	0.13
Annual cover	0.01 (0.01)	0.00	0.03
Avg. soil stability	2.51 (0.91)	1.12	4.28
Elymus elymoides (75)	0.02 (0.02)	0.00	0.07
Juniperus osteosperma (52)	0.34 (0.08)	0.19	0.50
Forest shrubland (N = 4)			
Total foliar cover	0.62 (0.09)	0.52	0.73
Woody cover	0.53 (0.10)	0.41	0.65
Graminoid cover	0.22 (0.04)	0.17	0.27
Annual cover	0.00 (0.01)	0.00	0.01
Avg. soil stability	3.33 (1.24)	1.56	4.33
Poa fendleriana (79)	0.19 (0.07)	0.13	0.27
Garrya flavescens (72)	0.04 (0.04)	0.00	0.09
Quercus turbinella (67)	0.13 (0.05)	0.09	0.21
Purshia stansburiana (59)	0.04 (0.02)	0.02	0.07

diversity and landscape factors (fig. 19). The only significant correlation detected suggest locations that are hydrologically enhanced (high TWI and flow accumulation) are characterized by low diversity.

Discussion

Patterns in Rangeland Health Indicators

The results presented here contribute to regional- and national-scale efforts aimed at developing robust conceptual models regarding the role soil, topographic, and climate properties play in controlling ecosystem resilience and vulnerability to land use and climate change (Steele and others, 2012; Bestelmeyer and others, 2016; Williamson and others, 2016). Organizing landscapes based on contextual information that (1) is generally static under management-relevant time frames and (2) groups landscape units based on ecosystem response to management and climate provides a useful framework for management actions, policy decisions, as well as ecological investigations (Duniway, Bestelmeyer, and others, 2010).

In the NPS-managed portions of the Grand Canyon-Parashant National Monument surveyed here (fig. 1), elevation gradients explain much of the broad-scale variation in soil and vegetation indicators, and associated rangeland health interpretations. Broad trends suggest a decrease in erosion risk with increasing elevation because of increasing vegetation cover, including a strong linear decrease in the cover of large canopy gaps and increase in litter cover (fig. 8*A*; Okin, 2008). However, other indicators that are important for soil and site stability and hydrologic function (table 1) either do not have strong elevational trends (for example, bare ground) or have trends that suggest decreasing function with elevation (for example, soil stability; Pellant and others, 2005).

There are few strong associations between plant functional groups and elevation (with trees being the exception; fig. 9*A*), but there are strong species-level climate associations. This suggests that species turnover across elevation zones may represent species differences in adaptation to climates (fig. 9*B*). For example, there is a shift in the dominant shrub from *Ambrosia dumosa* in the low elevations to *Coleogyne ramosissima* in the middle elevations to *Artemisia* spp. in the high elevations. Upper limits for *Larrea tridentata* and *C. ramosissima* are likely attributable to temperature limits and freeze sensitivity (Beatley, 1974; Meyer and Pendleton, 2005), whereas the lower elevation boundaries for both *C. ramosissima* and *Artemisia* spp. likely represent a low aridity tolerance (Meyer and Pendleton, 2005; Schlaepfer and others, 2011). Similarly, the lower limit for *Juniperus* spp. is also likely governed by aridity. The upper limits of *Artemisia* spp. observed here are below known elevation and climate limits of *Artemisia* spp., which can likely be attributed to the increase of *Juniperus* spp. Increases in juniper and pinyon species cover into historic sagebrush shrublands and consequent decrease in other species is a common phenomenon observed across the western United States (McArthur and Plummer, 1978). Several of the plots recorded here, particularly in the pinyon-juniper woodland, pinyon woodland, and juniper woodland floristic groups likely represent some level of tree encroachment (table 7; van Auken, 2000).

Invasive Species

Invasive *Bromus* species are of great management concern in the intermountain west, primarily because of the increase in fire frequency associated with *Bromus* invasions (Beatley, 1966; Balch and others, 2013). However, distributions of these species are likely to shift in response to climate change (Abatzoglou and Kolden, 2011). In particular, *Bromus rubens* is likely to move up-slope, into areas where its distribution has been historically cold limited (Bradley and others, 2016). *B. rubens* is the most frequent invasive species of concern recorded in this study (fig. 9*C*), with a clear upper elevation limit (strong negative correlation with elevation in the high desert and forest and savanna climate zones; fig. 19). Forecasts for increasing temperatures in the southwestern United States (Garfin, 2014) suggest *B. rubens* may move to higher elevations of Grand Canyon-Parashant National Monument in coming decades. Soil associations from the middle desert suggest areas with higher risk of *B. rubens* are rocky soils with fine textures of the nonrock soil fraction (fig. 16).

Schismus arabicus and *Erodium cicutarium* are also nonnative species of concern because of altered fire regimes and competition with native species (Brooks, 1999a, 2000; Steers and Allen, 2010). In this study, *S. arabicus* was more abundant in the low elevations with a strong negative correlation with elevation and an affinity for run-in locations, sites close to livestock water sources, and coarse soils (figs. 9*C*, 16), which agrees with observations in previous studies (Brooks, 1999b). *E. cicutarium* was found in both the low and middle deserts (fig. 9*C*) but showed little association with soil or landscape properties (figs. 16, 19). Similar to concerns regarding *B. rubens*, it is likely that *S. arabicus* will increase in frequency at high elevations as temperatures warm.

Soils, Topography, and Ecosystems

The effect of the combination of climate, topography, and soils on ecosystem properties and processes, including resistance and resilience to drivers of change, is referred to as “ecological potential” or “land potential” (Caudle and others, 2013; Bestelmeyer and others, 2015). The NRCS ecological site system is a land classification system based on concepts of ecological potential. Sites are differentiated primarily by climate, soil depth, soil rockiness, soil texture, soil mineralogy, and site topographic setting (Duniway, Bestelmeyer, and others, 2010). Spatial information on ecological sites is provided through soil survey map units (Duniway, Bestelmeyer, and others, 2010). However, ecological site information is not yet standardized and available for all lands, leading to efforts to standardize methodologies (Caudle and others, 2013). Many ecological site descriptions (ESDs) with associated state-and-transition models are not yet complete for soil units in Grand Canyon-Parashant National Monument (Lindsay and others, 2003; Natural Resources Conservation Service, 2018). A proposed approach to streamline development of robust and data-driven ESDs is to create more generalized groups that fit within hierarchical classes (Bestelmeyer and others, 2016; Duniway and others, 2016; Salley and others, 2016). Indeed, it is fairly common to group ecological sites when using them to understand impacts of management on large heterogeneous landscapes (Duniway and Herrick, 2013; Munson and others, 2016).

Here, we organized the 31 ecological sites we encountered into 10 ecological site groups (ESGs; table 6). These aggregations of ESDs (1–5 ESDs per group) explain important variability in the distribution of plant communities (strong correlation between ESGs and floristic groups; table 8) and many indicators of rangeland health were found to vary systematically among ESGs (figs. 12, 15, 18), although the amount of indicator variation explained by ESGs varies greatly across climate zones. In the low desert, little differentiation in floristic groups was identified between the two non-gypsiferous ESGs (table 8). In the middle and high desert zones, there was generally strong concordance between ESGs and floristic groups. The two shallow ESGs were dominated by blackbrush shrublands floristic groups and the majority of plots in the two deep ESGs were classified as desert grasslands in the ordination. This pattern of shallow soils supporting shrubland communities and deeper soils supporting perennial grasslands follows patterns observed in other areas of the Colorado Plateau (Duniway and others, 2016). We also see a pattern of shrublands (sagebrush and mixed shrubland) in the shallow ESGs in the high desert, however, in contrast to the middle desert, deep soil settings in the high desert support pinyon-juniper woodlands (table 8). In some areas of the Colorado Plateau, sites with deep soil dominated by pinyon-juniper woodlands indicate woody expansion and departure from reference conditions (van Auken, 2000; Duniway and others, 2016).

In addition to concordance of ecosystem condition and ESGs, individual soil and landscape properties were also shown to have a strong control on plant communities and rangeland condition in many instances (McAuliffe, 1994; Duniway, Bestelmeyer, and others, 2010; Munson and others, 2015). The soil and landscape variables found to be important in governing rangeland conditions are consistent with other dryland plant-soil relations frameworks (Duniway, Bestelmeyer, and others, 2010): elevation, topographic setting (run-in/run-off characteristics, slope, aspect), amount of exposed bedrock, soil rockiness, soil texture (and associated hydrologic properties), and soil depth (figs. 13, 16, 19). There is variation in the relative importance of soil and landscape properties among climate zones and attributes of rangeland health. For example, landscape setting variables are less correlated with the ordination axis scores in the middle desert (fig. 16) than any of the other climate zones (figs. 13, 19), suggesting a low importance of topographic setting in the middle desert. Similarly, associations between plant functional group cover and soil and landscape properties varied between climate zones, with woody species showing strong associations in the low desert, high desert, and forest and savanna zones and primarily herbaceous functional groups displaying significant correlations in the middle desert.

Interestingly, cover of woody species displayed essentially opposite associations with soil texture in the lower than higher climate zones, with woody cover greater on well-drained sandy soils in the low desert versus finer textured and higher water-holding-capacity soils in the upper elevations. This inverse association of texture along an aridity gradient has been demonstrated in other studies (Sala and others, 1988) and is thought to be due to the shifting importance of evaporative loss from the soil surface between arid and more mesic climates. Tree species cover, primarily *Juniperus* spp., was also high in run-in locations in the high desert and forest and savanna climate zones (fig. 19). Other work assessing topographic relations and woody encroachment has found that areas with high TWI were more susceptible to woody encroachment (Ben Wu and Archer, 2005). However, more work is needed in the Grand Canyon-Parashant National Monument pinyon-juniper woodlands to establish which woodlands are near reference condition and which represent an alternative state of a shrubland or more open savanna (Archer and others, 2017).

Evidence of Cattle Impacts

Grazing by domestic livestock is one of the most widespread land-use types in the region (Copeland and others, 2017) and has been shown to affect dryland ecosystems both directly, through selective herbivory and hoof impacts, and indirectly via feedbacks with ecosystem processes, such as plant competition and plant-soil feedbacks (Branson and others, 1981; Warren and others, 1986; Fleischner, 1994). Observations from this study support previous work demonstrating that grazing in drylands can lead to increases in bare ground and decreases in ground cover (Turner, 1971; Miller, 2008; Duniway and others, 2018). Here, we observed more bare ground and less ground cover in areas with high evidence of cattle use (figs. 13, 16, 19), suggesting reduced hydrologic function and soil and site stability with increased cattle activity (Pellant and others, 2005), including increased run-off and water erosion (Lusby, 1970; Branson and others, 1981). Of added concern with loss of protective vegetative and ground cover in arid rangeland is risk of accelerated wind erosion and consequent dust emissions, which has been shown to increase in areas with heavy livestock use (Nauman and others, 2018).

In general, improper grazing reduces overall vegetative cover and can alter vegetation composition, favoring unpalatable species and introduction of invasive species (Fleischner, 1994). In the survey results presented here, correlations between biotic integrity indicators and likely cattle use provide some evidence of these negative cattle impacts on Grand Canyon-Parashant National Monument allotments. The biotic integrity indicators that are of concern are *Schismus arabicus* in the low desert (increased frequency close to livestock water sources; fig. 13); decreases in *Coleogyne ramosissima* and *Ephedra* spp. with indicators of cattle use in the middle desert (fig. 16); and increases in *Gutierrezia* spp. (a species that commonly increases with livestock grazing pressure) with cattle indicators in all of the high-elevation areas (figs. 16, 19). Similar to what was observed here, *Schismus arabicus* has been shown to be more abundant in more disturbed areas in the western Mojave Desert (Brooks, 1999b). Evaluation of *C. ramosissima* communities across a grazing gradient east of the study area (in and around Glen Canyon National Recreation Area) also showed decreases in *C. ramosissima* with increased grazing (Jeffries and Klopatek, 1987). However, the correlations between distance to water and *C. ramosissima* cover observed here are potentially confounded by the strong affinity of *C. ramosissima* for the shallow mixed ESG (fig. 14), which tends to occur farther from water (fig. 13). However, reduction of shrubs in winter-use shrub-dominated allotments has been observed in the region (Munson and others, 2016) and livestock are known to browse on shrubs to meet nutrient demands (Cook and others, 1954).

It is noteworthy that we did not find evidence of cattle impacts on perennial grasses, given their importance as livestock forage. We attribute this to (1) generally low cover of perennial grasses in the study area (except for the deep limestone ESG in the middle desert; fig. 15), (2) winter use in many of the allotments where grazing is most prevalent (table 2); and (3) stocking rates well below what is permitted (in most instances; table 2). Indeed, correlations between dung frequency and perennial grass within the deep limestone ESG suggests a negative trend ($r = -0.45$, $p = 0.058$).

The dung frequency and distance from water approach used here to examine cattle impacts on Grand Canyon-Parashant National Monument allotments is essentially evaluating the role livestock distribution within pastures may play in allotment rangeland conditions, and the results described above suggest that cattle distribution in Grand Canyon-Parashant National Monument allotments could be better managed. Careful livestock distribution is one of the primary mechanisms for improving the health of western rangelands (Bailey and Rittenhouse, 1989). Several methods have been suggested for obtaining a more uniform distribution. Creating smaller pastures can help with achieving a more even distribution (Hart and others, 1993), though this may not be feasible given the remote and rugged nature of Grand Canyon-Parashant National Monument and the requirement of frequent movement of herds between pastures. Use of supplements has been shown to be successful to increase use of underutilized areas in large and rugged pastures in Montana (as much as 600 m from supplements; Derek and others, 2001), though other studies using salting stations did not find success in addressing serious livestock distribution problems in large pastures of an arid rangeland (Ganskopp, 2001). A potential long-term solution could be a breed change. Heritage breeds of cattle (for example, Raramuri Criollo cattle; Anderson and others, 2015) have been shown to have better distribution in large arid pastures when compared to the English breeds typically used by ranchers in the United States, with the largest differences observed where green forage is scarce (Peinetti and others, 2011; Spiegal and others, 2019).

Warming and drying predicted for the Desert Southwest will likely further decrease vegetative cover and exacerbate risk to rangeland ecosystems (Seager and others, 2007; Munson and others, 2011; Hoover and others, 2015). Furthermore, increased aridity and severity of drought will heighten risks of improper livestock management, particularly risk to wind erosion (Duniway and others, 2019). The results presented here suggest some improvements to livestock distribution are needed in the Grand Canyon-Parashant National Monument. However, our study did not include evaluation of areas without grazing (long-term exclosures), which can provide a valuable reference for better understanding rangeland condition in the absence of livestock (for example, Duniway and others, 2018). Additionally, our study relied on coarse proxies of cattle use (dung frequency and cost-distance to water). Better understanding of how cattle are distributed and their behaviors in different areas (that is, trailing versus grazing) would greatly increase our understanding of their impacts on Grand Canyon-Parashant National Monument allotments, such as the types of data available from modern GPS tracking collars (Ungar and others, 2005). Finally, these results support rangeland monitoring and assessment programs that collect indicators of soil and site stability (bare ground and ground cover) and do not rely solely on vegetation composition indicators to assess livestock management (Pellant and others, 2005; Toevs and others, 2011).

Conclusion

The Grand Canyon-Parashant National Monument was established on January 11, 2000, to preserve the monument's biologically diversity, "impressive landscape," and an "array of scientific and historic objects." In this survey of 155 plots across the NPS-managed portions of the monument, we document a wide array of soils types, plant species, and communities, including 15 unique soil taxa (to great group level) and 271 plant species. We collected three new plant species for Grand Canyon-Parashant National Monument and 17 new species for the NPS portion of the monument. We also demonstrate strong association between rangeland health indicators and plant community types with elevation, topographic setting, and soils. These results support the management of Grand Canyon-Parashant National Monument lands using land classifications based on concepts of land potential, such as NRCS ecological sites. However, given the tremendous size of Grand Canyon-Parashant National Monument and large number of ESDs present (based on the soil survey), we also suggest using groups of ecological sites for broad management questions, as was done here. There are existing efforts to formalize ecological site groups regionally that may facilitate Grand Canyon-Parashant National Monument management (Bestelmeyer and others, 2016; Duniway and others, 2016). Additionally, recent improvements in digital soil mapping may allow improved maps of ESGs for the monument (Maynard and Karl, 2017; Ramcharan and others, 2018; Maynard and others, 2019).

The large area, rugged terrain, and remote nature of the Grand Canyon-Parashant National Monument makes access for field sampling of rangeland health indicators challenging and costly. Developments in satellite-based remote sensing of indicators may improve the efficiency of monitoring in Grand Canyon-Parashant National Monument (Jones and others, 2018; Poitras and others, 2018), particularly if monitoring methods employed are compatible with other national-level programs (as was done here). Additionally, classification of field plots into ecological sites that are linked to state-and-transition models (Miller and others, 2011) can then be used to train remote-sensing-based classifications of landscapes into putative ecological states (Poitras and others, 2018). Such maps, coupled with ecological site (or group) maps, can then be used for landscape-scale management actions (Steele and others, 2012) or to understand climate sensitivities (Bunting and others, 2017; Thoma and others, 2018).

Based on the above, the next steps for a rangeland health monitoring program for the Grand Canyon-Parashant National Monument are: (1) integrate the ecological site groups developed here with regional grouping efforts and use these as a basis for monitoring; (2) leverage new digital soil mapping workflows and products to create more precise and accurate spatial depiction of ESGs; (3) develop a rangeland health monitoring strategy that leverages field and remote-sensing-based measures; and (4) utilize decision frameworks, such as state-and-transition models, for interpreting monitoring results and guiding management objectives. In this project, developing the ecological site groups for analysis and developing new themes and maps for sample design required significant expertise and resources. Completing steps 1 and 2 above would streamline this for future assessments. Our ability to address study objectives was also limited by the high travel costs and difficult access for field work in Grand Canyon-Parashant National Monument. Incorporating remote sensing indicators (step 3) to expand sampling to remote areas (such as Lone Mountain) in future assessments will represent a substantial improvement. Finally, contextualizing assessments relative to known ecological processes and management goals is necessary for using rangeland assessments in decision-making processes. Development of group-level state-and-transition models (step 4) is one approach for translating assessment results into management decisions. Importantly, the data and interpretations from the 155 plots presented here are a valuable resource for achieving these next steps and will help Grand Canyon-Parashant National Monument staff better address potential threats to monument resources, including invasive species, unsustainable grazing by domestic livestock, and climate change.

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Appendix 1. Identification of Hydrologically Enhanced Areas

The identification of hydrologically enhanced areas was done using the maximum likelihood classification tool in the Spatial Analyst extension of ArcGIS (ver. 10.1). More than 3,000 training polygons were manually digitized through examination of contemporary 1-meter color aerial imagery in the study area. Observers visually inspected aerial photographs with overlaid shaded-relief layers and created circular polygon features that either had (1) evidence of increased productivity or water accumulation (coded as “1”) or (2) were clearly upland areas without significant run-in (coded as “2”). These polygons were then used to create a supervised classification within shallow-slope soil-geologic strata (table 3) and, based on multiple terrain derivatives (table 1.1), signatures extracted and classified. Cells classified as hydrologically enhanced and with slopes less than 8° were then put into the “run-in” strata. This was accomplished using the model builder in ArcCatalog.

Table 1.1. Raster input layers for the supervised classification of hydrologically enhanced areas used in the study sample design.

[Derivatives were calculated using Spatial Analyst (ArcMap ver. 10.1) and a 10-meter digital elevation model (DEM) from the U.S. Geological Survey National Elevation Dataset (https://nationalmap.gov). m, meters]

DEM-derived layer	Description
Relative elevation	Difference in elevation between local mean (0–20 m from cell center) and annular ring at 70 –80 m distance
Flow accumulation	Mean of 1og10-flow accumulation in a 30 m radius around the target pixel
Distance to stream or other drainage	Horizontal distance to stream or other drainage (identified using flow accumulation raster) based on water-flow patterns (using cost distance tool)
Height above stream or other drainage	Elevation (in meters) above closest stream or drainage

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