



Soil Inventory Results and Relationships to Vegetation Monitoring Data at Gila Cliff Dwellings National Monument

Natural Resource Technical Report NPS/SODN/NRTR—2011/479



ON THE COVER

Gila Cliff Dwellings National Monument. NPS photo.

Soil Inventory Results and Relationships to Vegetation Monitoring Data at Gila Cliff Dwellings National Monument

Natural Resource Technical Report NPS/SODN/NRTR—2011/479

Author

Travis Nauman
Nauman GeoSpatial, LLC
Tucson, Arizona
www.naumangeospatial.com

Editing and Design

Alice Wondrak Biel
Sonoran Desert Network
National Park Service
7660 E. Broadway Blvd., #303
Tucson, AZ 85710

August 2011

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service's Natural Resource Stewardship and Science office, in Fort Collins, Colorado, publishes a range of reports that address natural resource topics of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Technical Report Series is used to disseminate results of scientific studies in the physical, biological, and social sciences for both the advancement of science and the achievement of the National Park Service mission. The series provides contributors with a forum for displaying comprehensive data that are often deleted from journals because of page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. Data in this report were collected and analyzed using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

This report is available from the Sonoran Desert Network website, <http://www.nature.nps.gov/im/units/sodn/>, as well as at the Natural Resource Publications Management web site, <http://www.nature.nps.gov/publications/nrpm/>.

Please cite this publication as:

Nauman, T. 2011. Soil inventory results and relationships to vegetation monitoring data at Gila Cliff Dwellings National Monument. Natural Resource Technical Report NPS/SODN/NRTR—2011/479. National Park Service, Fort Collins, Colorado.

Contents

Figures v

Tables v

Abstract vii

Acronyms and Abbreviations ix

1 Introduction 1

2 Methods.....3

 2.1 Sampling 3

 2.2 Analysis 3

3 Results.....7

 3.1 Soil properties 7

 3.2 Other properties in plots 9

 3.3 Plot clustering.....10

 3.4 Soil aggregate stability and erosion 12

4 Discussion 13

5 Literature Cited 15

Appendix A. Supplemental Information 17

Figures

Figure 1-1. Gila Cliff Dwellings National Monument, New Mexico.....	1
Figure 2-1. Soil assessment plot locations, Gila Cliff Dwellings National Monument. Monument boundary lines are in black.....	3
Figure 2-2. Terrestrial vegetation and soils monitoring plot design	6
Figure 3-1. Averages of different soil parameters across plots, Gila Cliff Dwellings NM.....	8
Figure 3-2. Parallel plot showing cluster values relative to dataset average scaled by the standard deviation of each variable	11

Tables

Table 2-1. Variables used for analysis in this report, by parameter type.....	5
Table 3-1. Summary statistics for soil properties, Gila Cliff Dwellings NM.....	7
Table 3-2. Significant pairwise correlations amongst soil properties.	7
Table 3-3. Summary statistics for vegetation, cover, and topography properties, Gila Cliff Dwellings NM.....	9
Table 3-4. Significant correlations in soil plot data, Gila Cliff Dwellings NM.	10
Table 3-5. Erosion area class estimates by soil cluster.	12
Table A1. One-way ANOVA of soil properties by plot.....	17
Table A2. Parameter averages by plot.....	18
Table A3. Soil sample values.....	20
Table A4. Parameter averages by cluster.....	21

Abstract

The Sonoran Desert Network, as part of the National Park Service's Inventory and Monitoring Program, has identified terrestrial vegetation and dynamic soil functional attributes as important ecosystem monitoring parameters, or "vital signs" (NPS 2005) that provide key insights into the integrity of terrestrial ecosystems at Gila Cliff Dwellings National Monument (NM). Soil properties have important consequences for vegetation composition, persistence, and productivity (McAulliffe 1999), yet soil information for Gila Cliff Dwellings NM is scant, as the park has never had a comprehensive soil survey due to a lack of funding. Therefore, the network contracted this complementary assessment to establish a monitoring baseline for vegetation and soil health. In 2009, ten soil and vegetation plots were visited at the park. Surface soil samples collected from each plot indicated the presence of sandy loam and sandy clay loam surface soils, with a wide variety of pH, solute, and organic carbon levels. Variances in texture and chemistry between plots were related to dynamic soil function monitoring parameters, such as rock surface cover and soil aggregate stability. Site topography influenced soil surface cover type and herbaceous production by mediating soil water status (as indicated by Topographical Wetness Index). Moderate sheet and rill erosion were observed on a few plots and were associated with exposed bedrock (indicating shallow soils) and areas with relatively high upper canopy cover.

Acronyms and Abbreviations

ANOVA	analysis of variance
CaCl ₂	calcium chloride
cm	centimeters
EC	electrical conductivity
H ⁺	positively charged hydrogen ion
M	molar
m	meters
MANOVA	multiple analysis of variance
mm	millimeters
mS	millisiemens
NM	national monument
Pr(> t)	probability value associated with correlation statistic
SD	standard deviation
SODN	Sonoran Desert Network
TOC	total organic carbon
TWI	topographic wetness index

1 Introduction

The Sonoran Desert Network (SODN), as part of the National Park Service's Inventory and Monitoring Program, has identified terrestrial vegetation and dynamic soil functional attributes as important ecosystem monitoring parameters, or "vital signs" (NPS 2005) that provide key insights into the integrity of terrestrial ecosystems at Gila Cliff Dwellings National Monument (NM) (Figure 1-1). Soil properties have important consequences for vegetation composition, persistence, and productivity (McAulliffe 1999), yet soil information for Gila Cliff Dwellings NM is scant, as the park has never had a comprehensive soil survey due to a lack of funding. Therefore, the network contracted this complementary assessment to establish a monitoring baseline for vegetation and soil health, improve understanding of data related to vegetation and dynamic soil function, and evaluate the efficacy of sampling strata used for SODN uplands monitoring. This report summarizes the soils data; examines trends between soil parameters, vegetation cover parameters, and soil aggregate stability; and notes the types and extent of erosion observed.

Located in southwestern New Mexico, Gila Cliff Dwellings National Monument (NM) is surrounded by the Mogollon Mountains and Aldo Leopold Wilderness. The monument lies at mid-elevations within this mountain basin, and contains riparian, forest, woodland, savanna, and grassland systems. Areas sampled in this study were non-riparian, at elevations ranging from 5,700 to 6,300 feet.

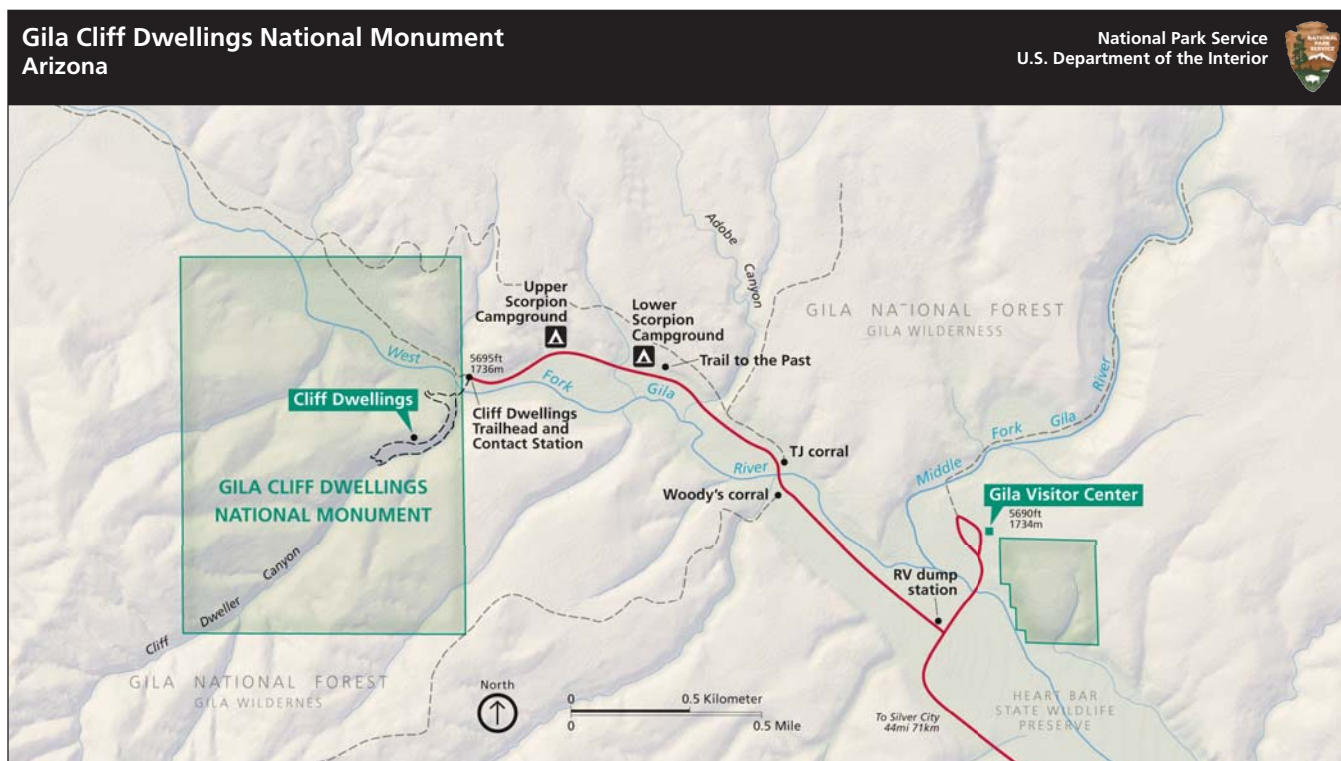


Figure 1-1. Gila Cliff Dwellings National Monument, New Mexico.

2 Methods

2.1 Sampling

At each of the 10 vegetation monitoring plots established by SODN in 2009 (Figure 2-1; Hubbard and Studd 2010), three soil cores (0–10 cm depth) were collected from random locations within the center and two outer subplot areas (subplots C, A, and E; Figure 2-2). These samples were used to estimate total organic carbon, pH, reserve acidity, sample bulk density, electrical conductivity, and soil texture via sand and clay content. Table 2-1 outlines the variables used for analysis in this report.

Vegetation canopy and ground cover were measured by line-point intercept along each of the six 20-meter transects. Vegetation (to species) and cover data were collected every 0.5 meters along each transect (n=240) for ground cover, herbaceous cover (0.025–0.5 m), subcanopy (0.5–2.0 m), and canopy (>2.0 m). Soil aggregate stability samples (n=48) were collected along transects and tested in groups of 16 via a wet aggregate stability method (Herrick et. al. 2001).

Within GIS, topographical analysis was used to calculate a Topographic Wetness Index (TWI; Yang et al. 2007), to investigate the potential influence of topographical context on the plot data collected. This index integrates the site steepness and potential upslope runoff onto a site into a

score that represents a site’s likelihood of being more moist relative to surrounding areas. Calculations for this index were completed using the System for Automated Geoscientific Analyses (<http://www.saga-gis.org/en/index.html>), an open-source GIS software package, using the D-infinity flow-routing algorithm (Tarboton 1997) and one arc-second elevation values from the National Elevation Data set (<http://seamless.usgs.gov/index.php>). Plots were attributed with a 3 × 3-pixel average TWI value. Values usually range from 1 or 2 to 20, with 20 representing extremely high potential for wetness relative to local conditions.

2.2 Analysis

A combination of correlation, ANOVA, multiple regression, and hierarchical clustering was used to examine plot heterogeneity, associative relationships, and groupings. Basic statistics, One-Way ANOVA, and MANOVA were used to examine variability in the properties of soil samples within and between plots, and to determine whether plots showed significant differences in soil properties. Correlation analysis was applied to pairs of variables to search for soil sample trends. Then, plot summaries (averages) of soil samples were created for comparison with vegetation structure data derived from point-line-intercept transects. Correlations between soil sample averages and vegetation/cover parameters from plot transects were examined for relationships.

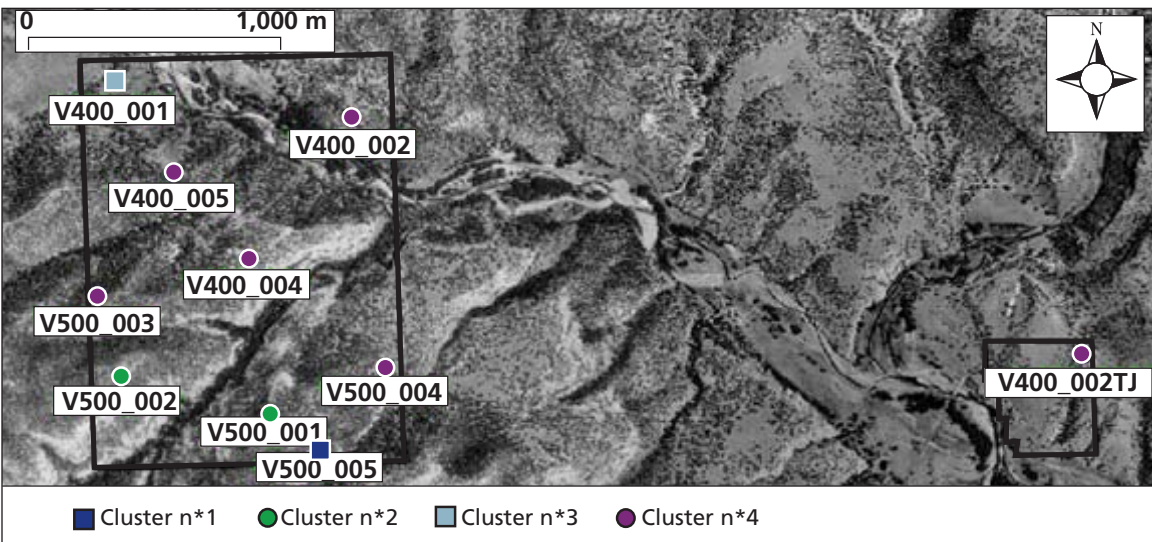


Figure 2-1. Soil assessment plot locations, Gila Cliff Dwellings National Monument. Monument boundary lines are in black. There is one plot in the TJ unit about 2 km east of the main unit. The main drainage is the Gila River.

Ward's hierarchical clustering was used to group plots by soil properties (contingent on plots' showing statistical differences in soil properties) to examine whether vegetation/cover properties differed by soil groupings. Soil stability and erosion observations were also examined using correlation, multiple regression, and linear discriminant analysis for associations with any soil, vegetation, or topographical parameter. All statistical analysis was performed within the TAN-AGRA open-source statistical analysis program (Rakotomalala 2005).

Erosion features were described using a semi-quantitative scheme to estimate approximate

extent (%) of affected areas. Estimated erosion classes were as follows: 0%, 1–5%, 6–25%, 26–50%, 51–75%, and >75%. Recorded features included tunneling, sheeting, rilling, gully, pedestal development, terracette occurrence, and burrowing activity. Sheet, rill, and gully features are direct indicators of erosion, while the other features are precursors to water erosion or signs of susceptibility. Erosion observations were used to indicate site stability and help identify any other measured features that might be associated with increased erosion.

Table 2-1. Variables used for analysis in this report, by parameter type.

Name	Explanation
Soil	
Bulk density	Density in grams/cm ³ of in situ soil samples (including any rock fragments in the sample)
Rock fragments	Fraction of soil >2 mm in diameter by mass
Sand	Fraction of soil particles (excludes rock fraction) 0.005–2 mm in diameter
Clay	Fraction of soil particles (excludes rock fraction) <0.0002 mm in diameter
Total organic carbon (TOC)	Fraction of soil composed of organic carbon determined using an N-C-S combustion analyzer
1:1 pH	pH measured in a solution of one part soil to one part water
1:2 pH	pH measure in soil of one part soil to two parts 0.01 M CaCl ₂ solution, used to estimate reserve acidity
Reserve acidity	Difference in pH of 1:1 pH and 1:2 pH 0.01 M CaCl ₂ , giving a measure of H ⁺ on soil exchange sites
Electrical conductivity (EC)	EC, measured in mS/cm, provides a surrogate measure of soil salinity or dissolvable solids in the soil.
Cover	
Bare ground	Fraction of ground surface with bare ground exposed
Bedrock	Fraction of ground surface with bedrock exposed
Duff	Fraction of ground surface covered with partially decomposed organic materials
Gravel cover	Fraction of ground surface covered with rock 2–75 mm in diameter
Litter	Fraction of ground surface covered by plant materials
Lichen on rock	Fraction of ground surface covered by lichen on rock
Moss	Fraction of ground surface covered by moss
Plant basal	Fraction of ground surface covered by the base of plants
Rock cover	Fraction of ground surface covered by rocks 76–600 mm in diameter
Canopy	
Herbaceous	Fraction of vegetation coverage 0.025–0.5 m in height
Subcanopy	Fraction of vegetation coverage 0.5–2.0 m in height
Canopy	Fraction of vegetation coverage >2.0 m in height
No cover	Fraction of surface with no vegetation coverage
Canopy and cover	
NC bare	Surface is bare ground with no canopy cover
Topography	
Mean slope	Average of ground slope measures taken at plots
Soil dynamics	
Soil stability	Soil macro-aggregate stability in water (Herrick et al. 2001)

Cover, canopy and soils parameters are documented in Hubbard and others (in review).

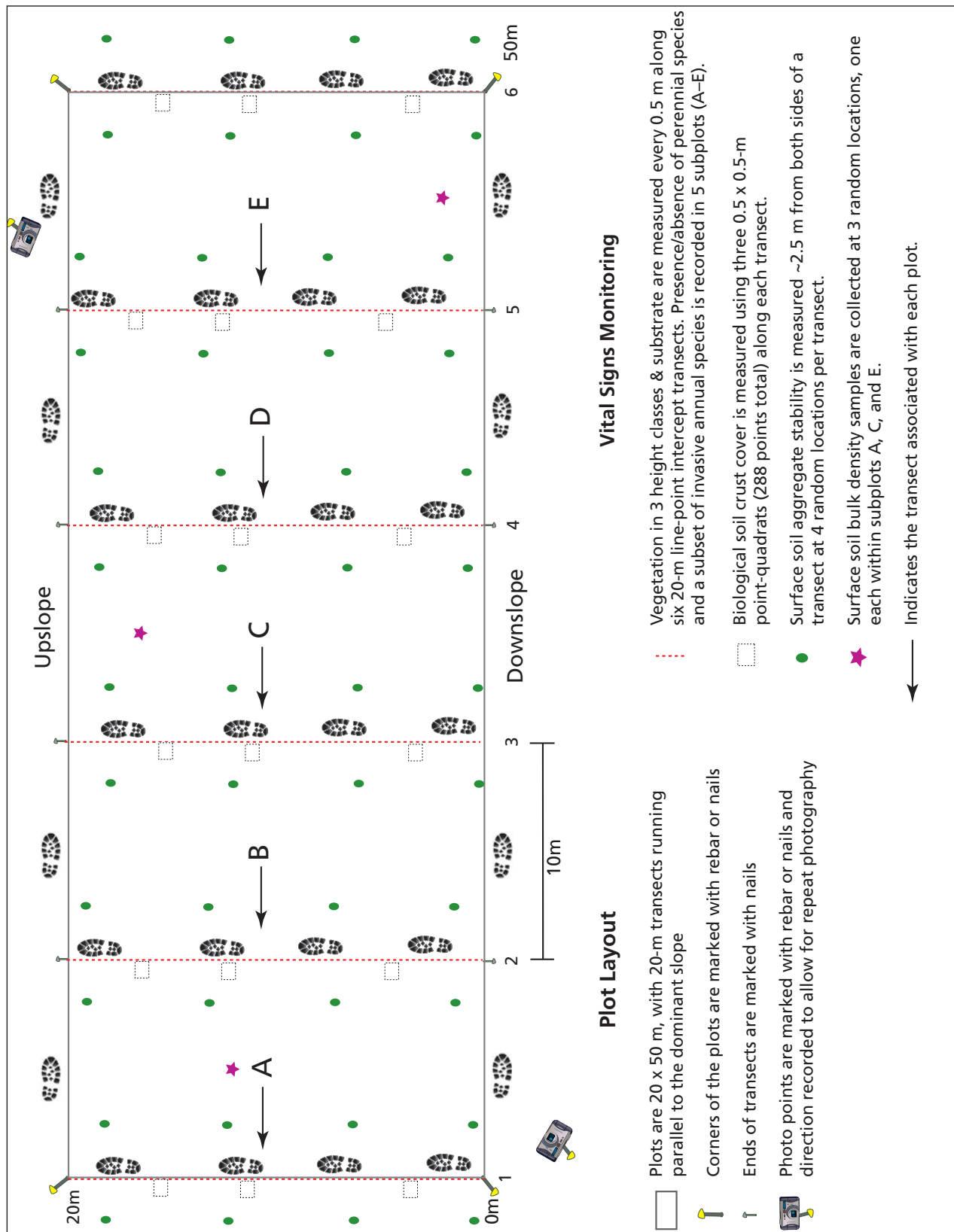


Figure 2-2. Terrestrial vegetation and soils monitoring plot design. See Hubbard and others (in review) for additional details on design and data collection.

3 Results

3.1 Soil properties

3.1.1 Summary of soil properties

Soil textures at Gila Cliff Dwellings NM varied from gravelly to extremely gravelly sandy loam to sandy clay loam, ranging from 8 to 25% clay, 58–81% sand, and 18–87% rock fragments. These relatively coarse soils were often covered with litter or, occasionally, partially decomposed duff. Total organic carbon (TOC) values were relatively high for the American Southwest and quite variable, ranging from 0.65 to 6.63%, with an average of 2.3%. TOC is generally doubled to estimate the percent organic matter in the soil. Soil pH and EC were somewhat variable between plots: one-to-one pH values ranged from 5.62 to 8.01, and EC ranged from 0.07 to 0.83 mS/cm. Reserve acidity ranged from 0.06 to 1.00 pH units, indicating considerable variance in soil-buffering capacities. Sample bulk densities were similarly variable (0.59–1.94 g/cm³). See Table 3-1 for summary.

3.1.2 Relationships among soil properties

3.1.2.1 Differences among plots

Most soil properties differed among plots, as was evident when averages of various soil properties were compared (see Appendix A). MANOVA analysis also indicated strong differences between plots based on all measured parameters (Wilks Lambda = 0.0013; Bartlett's Chi²₍₇₂₎ = 132.74, p-value = 0.0000). The sharpest individual parameter differences were seen in 1:2 pH, 1:1 pH, and clay content ($F_{9,20}$ and p-values of 6.24, 5.04, 4.59 and 0.0003, 0.0013, and 0.0022, respectively). Differences in pH levels (range 5–8) seemed to indicate a variety of soil ages, biota, and/or mineralogy. Clay differences (range 8–25%) were not as wide in a functional context, but still differed enough to affect water movement and other physical interactions in soil.

Weaker, but measurable differences ($\alpha = 0.05$) were seen in reserve acidity, TOC, and bulk density ($F_{9,20}$ and p-values of 2.44, 2.61, 2.76 and 0.0462, 0.0354, 0.0281, respectively). Although differences in these properties were less detectable statistically, the range of values indicated important differences in chemical, physical, and biological interactions. The ranges of both TOC and bulk density—closely related parameters—indicated a variety of biological and physical en-

Table 3-1. Summary statistics for soil properties, Gila Cliff Dwellings NM.

Attribute	Min	Max	Average	SD	SD/avg
Rock fragments	18.08%	87.36%	55.15%	18.67%	0.34
Bulk density (g/cm ³)	0.59	1.94	1.30	0.35	0.27
TOC	0.66%	6.63%	2.30%	1.42%	0.62
1:1 pH	5.62	8.01	6.77	0.67	0.10
1:2 pH	5.05	7.63	6.18	0.77	0.12
Reserve acidity	0.06	1.00	0.60	0.22	0.36
EC (mS/cm)	0.07	0.83	0.21	0.15	0.73
Clay	8.2%	24.8%	15.8%	4.9%	0.31
Sand	58.3%	81.3%	69.0%	6.2%	0.09

A total of 30 samples were taken from 10 plots throughout the park (see Figure 2-1).

Table 3-2. Significant pairwise correlations amongst soil properties.

Variable 1	Variable 2	r	r ²	t	Pr(> t)
Bulk density	TOC	-0.78	0.61	-6.60	0.0000
1:2 pH	EC	0.71	0.50	5.27	0.0000
TOC	EC	0.56	0.32	3.60	0.0012
1:2 pH	Reserve pH	-0.56	0.31	-3.53	0.0015
Reserve acidity	EC	-0.47	0.22	-2.84	0.0083
1:1 pH	Sand	0.47	0.22	2.79	0.0093
1:2 pH	Sand	0.45	0.20	2.67	0.0125
Bulk density	Reserve pH	0.40	0.16	2.31	0.0285
1:1 pH	Clay	-0.40	0.16	-2.28	0.0306
Bulk density	EC	-0.38	0.14	-2.15	0.0400
TOC	1:2 pH	0.36	0.13	2.07	0.0480
TOC	Reserve pH	-0.35	0.12	-1.99	0.0566

vironments in the soil. Reserve acidity differences (range 0.06–1.00) suggested a range of chemical buffering capacity, with higher reserves indicating that those soils were holding a much larger amount of acid and, possibly, had higher cation-exchange capacities (Figure 3-1).

3.1.2.2 Similarities among plots

Correlations among bulk density and chemical parameters (TOC, EC and reserve acidity) showed strong trends (Table 3-2). Bulk density and TOC showed a strong negative relationship ($r = -0.78$), as is typical of soils in which organic materials strongly influence the soil environment. Increased amounts of organic matter generally

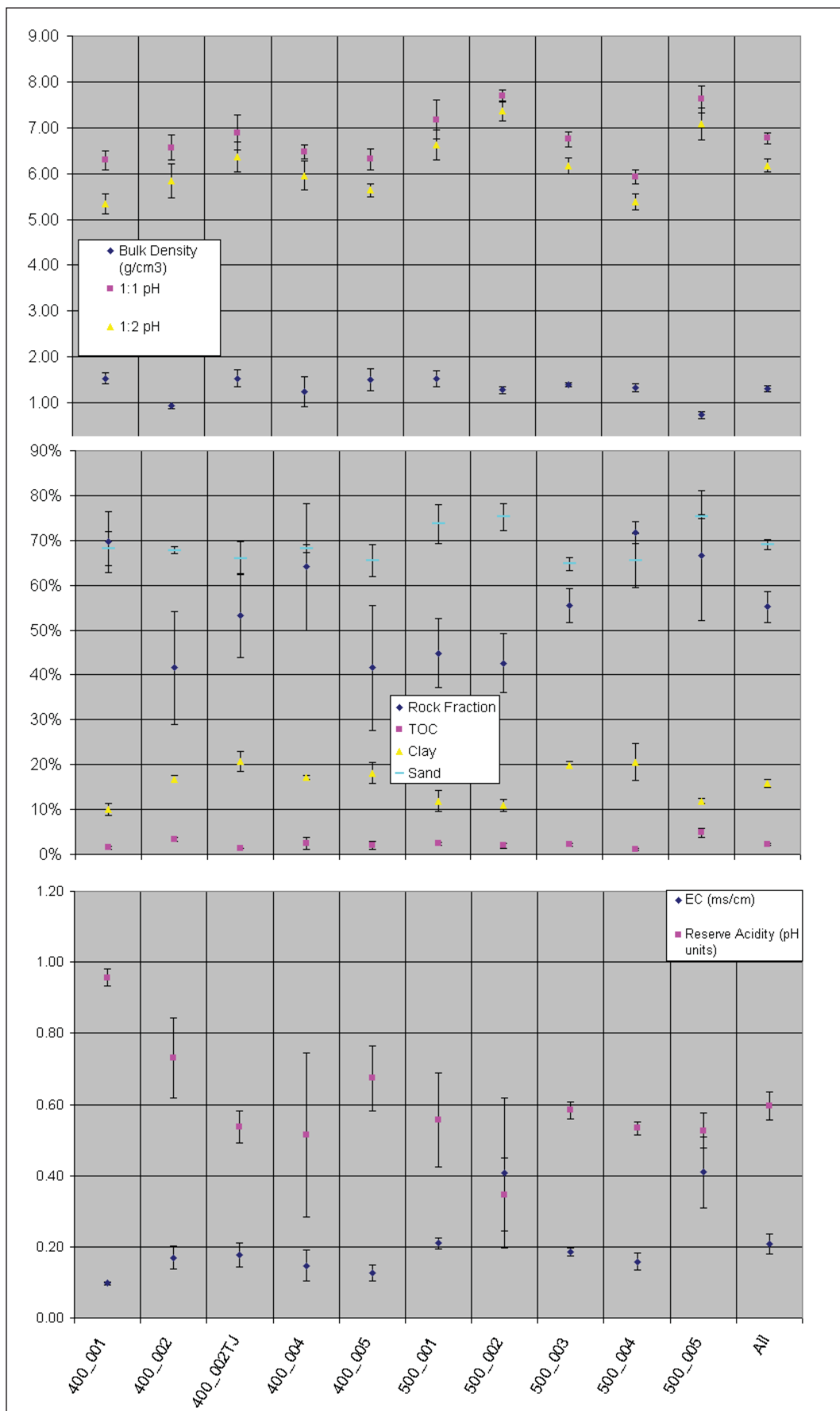


Figure 3-1. Averages of different soil parameters across plots, Gila Cliff Dwellings NM. Black brackets show standard error for each parameter at each plot (IDs at bottom).

help to aggregate soils and lower bulk density, which may have been the case here. TOC showed a strong relationship with EC ($r = 0.56$), which may suggest that either ions were adsorbed to organic matter or charged organic materials had dissolved in soil solution, contributing to solute activity. pH parameters also trended with EC, texture (sand and clay), and bulk density. There were many possible co-correlations in the data, suggesting the presence of more complicated interactions beyond pairwise trending. Higher pH values generally correlated with higher EC and sandier soils.

In summary, soils with higher amounts of organic carbon (i.e., more vegetative input) were less acidic, less dense, and tended to have less acidic buffering. More acidic soils tended to have less sand (and more clay), less solutes (EC), and less organic matter. They also tended to have much more acidic buffering. The finer texture of the acidic soils might indicate slightly older soils or more weatherable mineralogy, as acidity and clays tend to accumulate in more weathered soils. Based on these results, park soils can be split into two main conceptual groups: (1) a more highly vegetated group (higher organics) with less dense

soils and substantial nutrient cycling, and (2) a more barren, older group, with a lower pH and finer soil fraction (i.e., more clays and less sands).

3.2 Other properties in plots

3.2.1 Summary of other properties

Plots displayed a wide variety of values for ground cover, vegetation structure, topography, and soil stability (Table 3-3), and exhibited universally high rock content. The range of TWI (an index of potential soil–water relations) was constrained despite wide variance in plot slope steepness. Soil stability values (1–6 scale) showed only mediocre surface aggregation, with a poor minimum average, across plots, of 1.8. However, the domination of the soil surface by litter, duff, and gravel, as was the case here, can sometimes limit soil aggregation (depending on the type of litter) to the subsurface level, leading to low stability values but actually still providing a degree of protection from erosion for mineral soil.

Table 3-3. Summary statistics for vegetation, cover, and topography properties, Gila Cliff Dwellings NM.

Attribute	Min	Max	Average	SD	SD/avg
TWI	5.21	6.86	5.86	0.50	0.0856
No cover	11.7%	33.3%	23.0%	6.0%	0.2588
No cover (bare)	0.4%	7.1%	2.5%	2.0%	0.7707
Bare ground	0.4%	35.4%	8.2%	10.1%	1.2358
Bedrock	0.0%	4.6%	1.1%	1.8%	1.6538
Duff	0.0%	32.9%	12.9%	11.9%	0.9206
Gravel	1.3%	37.9%	20.9%	10.5%	0.503
Litter	9.6%	69.6%	44.5%	14.8%	0.3314
Cyano (dark)	0.0%	1.7%	0.2%	0.5%	3.1623
Moss	0.0%	2.5%	0.5%	0.8%	1.4068
Lichen on rock	0.0%	13.3%	2.5%	4.0%	1.5618
Plant basal	0.0%	18.8%	5.5%	6.2%	1.1343
Rock cover	0.0%	15.8%	3.7%	4.8%	1.2947
Herbaceous	23.3%	70.0%	44.1%	18.7%	0.4233
Subcanopy	9.6%	43.3%	24.3%	11.1%	0.4548
Canopy	10.4%	55.4%	30.8%	15.7%	0.5076
Mean slope	1.0%	58.5%	23.5%	18.4%	0.7831
Soil stability	1.8	4.5	2.9	0.8	0.2788

3.2.2 Relationships among other properties and soils in plots

Correlation analysis showed several trends between different cover types and the topographical parameters of slope and TWI (Table 3-4). TWI showed positive trends with plant basal cover, herbaceous vegetation, and bare ground. Co-correlations and interactions also occurred, for instance, between plant basal cover and herbaceous vegetation. Overall, areas with higher potential for wetness (higher TWI) had lower vegetation cover and less surface rock. Higher TWI values also seemed to be associated with lower pH values and more clay. Another topographical association occurred between lower rock fractions in soil samples in sites with steeper slopes.

Some trends were also seen between vegetation structure, soil cover, and soil sample parameters

in the correlation data. Vegetation-structure variables (canopy and subcanopy) showed positive trends between higher levels of duff cover and higher soil pH. Areas with more canopy also generally had more surface cover. Reserve acidity showed a negative relationship with gravel cover. Plots of higher pH, EC, and sand tended to have higher surface rock cover.

3.3 Plot clustering

Using Ward's hierarchical clustering, plots were grouped by soil properties (averaged by plot) to determine whether vegetation, topography, and cover parameters were associated with generalized soil types. Four clusters were separated using the Best Cluster Selection tool in TANAGRA (which uses in-cluster variance minimization to determine which step of clustering creates the largest drop in overall clustering variance while

Table 3-4. Significant correlations in soil plot data, Gila Cliff Dwellings NM.

Variable 1	Variable 2	r	r ²	t	Pr(> t)
<i>Bare ground</i>	<i>Moss</i>	0.8732	0.7625	5.0685	0.001
TWI	Plant basal	0.8449	0.7138	4.467	0.0021
TWI	Herbaceous vegetation	0.8441	0.7126	4.4532	0.0021
Plant basal	Herbaceous vegetation	0.8061	0.6498	3.8532	0.0049
<i>Bare ground</i>	<i>Plant basal</i>	0.7632	0.5824	3.3403	0.0102
pH1:2	Rock cover	0.7595	0.5768	3.3022	0.0108
Duff	Soil stability	-0.7379	0.5445	-3.0926	0.0148
EC	Rock cover	0.7313	0.5348	3.0326	0.0162
Herbaceous vegetation	Mean slope	-0.7078	0.501	-2.8343	0.022
TWI	Bare ground	0.7006	0.4908	2.7768	0.024
Duff	Canopy	0.695	0.483	2.734	0.0257
Sand	Rock cover	0.6894	0.4753	2.692	0.0274
Reserve acidity	Gravel cover	-0.679	0.4611	-2.6162	0.0308
No cover (bare)	Subcanopy	-0.6714	0.4507	-2.5621	0.0335
TWI	Rock cover	-0.6576	0.4324	-2.4689	0.0388
Herbaceous vegetation	Canopy	-0.6443	0.4152	-2.3831	0.0443
pH1:1	Subcanopy	0.6403	0.4099	2.3575	0.0461
<i>Moss</i>	<i>Plant basal</i>	0.6347	0.4028	2.3228	0.0487
pH1:1	TWI	-0.6303	0.3973	-2.2965	0.0508
Clay	TWI	0.6296	0.3964	2.2922	0.0511
% rock fraction	Mean slope	-0.6289	0.3956	-2.2881	0.0514

Italicized text indicates data parameters that were collected in mutually exclusive point-line-intercept surveys but still showed correlations. For example, because bare ground and moss were collected in the same data type, a hit for one would exclude a hit for the other, so a negative correlation would be expected. However, in highlighted cases, the correlation was the opposite of what would be expected, indicating that the trend was stronger than indicated.

Bolded text indicates possible strong co-correlation.

Boxed variables are from soil sample data; others are from plot-intercept or topographical data.

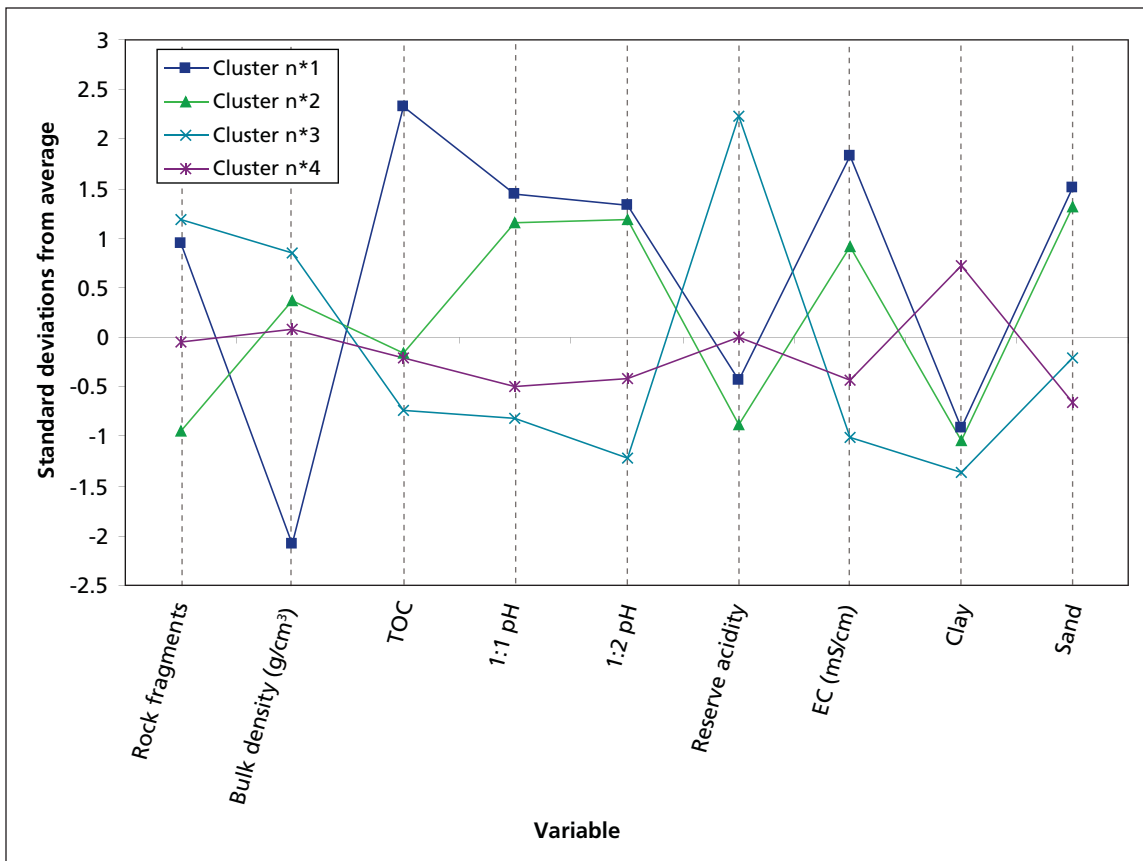


Figure 3-2. Parallel plot showing cluster values relative to dataset average scaled by the standard deviation of each variable. Clusters 1 and 3 are single plots, while clusters 2 and 4 included two and six plots, respectively. Because of the small sample size, outliers are placed into their own classes.

maximizing fit of data), including one cluster of six plots (n*4), one cluster of two plots (n*2), and two outlier plots (n*1 and n*3). Clustering was done at the plot level using averages of samples in each plot as data points.

Cluster groupings in Figure 3-2 highlight some associations between multiple soil parameters, as well as some of the correlation trends from Table 3-4. Plot clusters with higher pH also had higher TOC, sandier textures, higher EC's, and lower reserve acidities. Cluster groupings also highlighted some of the correlation trends seen in Table 3-4. Cluster n*4 had finer textures, higher TWI values, and lower pH values than the others. Cluster n*3 (plot 400_001), one of the outlier plots, had a substantially higher stability average than the other plots. This cluster also had a siltier texture, lower pH and TOC, and higher rock fragment content than the other plots, as well as mostly herbaceous cover and a ground surface primarily covered by litter (see Appendix Table A4 for data).

Of the vegetation, topography, and cover parameters, only rock cover showed a moderately detectable possible difference among soil cluster classes (F-test, $F_{3,6} = 4.56$, $p = 0.0544$). Cluster class n*2 showed the highest rock cover (11%) followed by n*1 (4.6%), n*4 (1.7%), and n*3 (0.4%). Cluster n*2, located at the highest elevation and on relatively steep terrain, also showed the highest incidence in rill and sheet erosion features (see Table 3-5), suggesting that the two plots in n*2 (500_001 and 500_002) may be subject to a slightly different set of environmental conditions than the others. Oddly, cluster n*2 (plots 500_001 and 500_002) also had the lowest percentage of rock fragments in the soil samples, yet the highest percentage of exposed surface rock cover (see Appendix A, Table A4 for data). In light of the erosion features observed, this result may be due to overland water flow eroding away the smaller surface soil particles, leaving more exposed rocks at the surface.

3.4 Soil aggregate stability and erosion

Soil stability averages increased in areas with less duff and canopy ($r^2 = 0.54$ and 0.34 ; p-values = 0.015 and 0.077 , respectively; see Appendix A, Table A2). Multiple regression of soil types (clusters) and duff created a strong model relative to soil stability ($r^2 = 0.88$; $F_{2,7} = 26.2597$; p-value = 0.00056). In this model, duff showed a strong negative effect on soil stability, while soil cluster n*3 (rocky, finer textured and acidic soils) showed a sizably higher soil stability than other plot soils (Appendix Table A4).

Minor disturbances (burrowing) were seen in limited areas of most plots in the park. Rill and sheet erosion were seen in sizable areas in a couple

of plots (Table 3-5). Almost all erosion was found in soil clusters n*4 and n*2, with n*2 showing a large concentration in Plot 500_001. Estimated areal erosion effects were seen in areas with more canopy, more observed lichens on rocks, less soil rock content, more bedrock cover, and less gravel cover, from interpretation of moderate to weak pairwise correlations observed in the data (p-values = 0.044 , 0.076 , 0.0873 , 0.10 , and 0.12 , respectively). When all these parameters were incorporated into a regression model (simple, forward, stepwise, multiple linear regression with no interactions) to decipher more dominant factors, higher levels of canopy and bedrock cover both showed moderately detectable associations with eroded areas (F-test, $F_{2,7} = 7.0328$, p-value = 0.0212).

Table 3-5. Erosion area class estimates by soil cluster.

Soil cluster	Plot	Percent class							Est. degraded area (avg %)
		Tunneling	Pedestals	Terracettes	Burrowing	Sheet	Rill	Gully	
n*1	500_005	0	0	0	1-5	0	1-5	0	3
n*2	500_001	0	0	0	0	26-50	6-25	0	51
	500_002	0	0	0	1-5	1-5	1-5	0	6
n*3	400_001	0	0	0	1-5	0	0	0	0
n*4	400_002	0	0	0	0	26-50	0	0	38
	400_002TJ	0	0	0	1-5	1-5	0	0	3
	400_004	0	0	0	0	0	0	0	0
	400_005	0	0	0	1-5	0	1-5	0	3
	500_003	0	0	0	1-5	0	1-5	0	3
	500_004	0	0	0	1-5	0	0	0	0

The estimated degraded area can be created by summing the middle values of sheet, rill, and gully erosion. This estimate was used in basic modeling to look for associations with other parameters.

4 Discussion

Data from the large number of integrated variables collected from plots at Gila Cliff Dwellings NM revealed some interesting relationships. All of the soils sampled were relatively rocky, but showed considerable variation in other properties. In some soils, higher levels of organic matter, pH, EC, and sand, along with lower bulk densities, were associated. In others, higher levels of reserve acidity were associated with finer textures. The finer, more acidic soils seemed to produce and incorporate less organic matter, have higher clay content and lower pH values, and lack solutes typically seen in younger soil, possibly indicating that they may be older surfaces.

The erosion observed at plots 400_002 and 500_001 may be cause for some concern. The primary factors separating these plots from the others were their higher levels of exposed bedrock and canopy. The exposed bedrock may be one cause of increased erosion on these plots, as it may be a sign of shallower soils that are less able to infiltrate water, thus causing accelerated flow. The soil samples at these plots also had lower levels of rock fragments, which also leave soils more vulnerable to water erosion than those in rockier areas.

Plot 400_001 turned out to be an outlier to most of the relationships observed in the data, and was clustered uniquely by soil properties ($n=3$). It had a combination of the rockiest and siltiest particle-size distribution (although not much silt), a lower than average pH, and the highest reserve acidity of any plot. Plot 400_001 also had the highest soil aggregate stability values by a wide range (4.5 versus an average of 2.9 for all plots). It had the highest litter cover of all plots, with very little duff, and was dominated almost entirely by herbaceous vegetation, in contrast to most of the other plots. The plot also had no active erosion features. The lack of erosion and high soil stability values of the plot suggest that its soils and vegetation were in a state of equilibrium not observed in the other plots. More investigation might be interesting at this plot, as the results are not all intuitive. Soil stability values would usually be lower at sites with lower levels of organic carbon, as at 400_001. However, the plot's high reserve acidity may suggest that the clays and mineralogy present have high partial ionic charges that could promote cohesion and, thus, aggregate stability.

5 Literature Cited

- Herrick, J. E., W. G. Whitford, A. G. de Soyza, J. W. Van Zee, K. M. Havstad, C. A. Seybold, and M. Walton. 2001. Field soil aggregate stability kit for soil quality and rangeland health evaluations. *Catena* 44:27–35.
- Hubbard, J. A., and S. E. Studd. 2010. Terrestrial vegetation and soils monitoring at Gila Cliff Dwellings National Monument: 2009 status report. Natural Resource Technical Report NPS/SODN/NRTR—2010/375. National Park Service, Fort Collins, Colorado.
- Hubbard, J. A., C. L. McIntyre, S. E. Studd, T. W. Nauman, D. Angell, M. K. Connor, and K. Beaupre. In review. Terrestrial vegetation and soils monitoring protocol and standard operating procedures for the Sonoran Desert Network.
- McAuliffe, J. R. 1999. The Sonoran Desert: Landscape complexity and ecological diversity. Pages 68–114 *in* R. H. Robichaux, ed., *Ecology of Sonoran Desert plants and plant communities*. Tucson: University of Arizona Press.
- National Park Service (NPS). 2005. Sonoran Desert Network vital signs monitoring plan. Technical Report NPS/IMR/SODN-003. National Park Service, Denver, Co.
- Rakotomalala, R. 2005. TANAGRA: A free software for research and academic purposes. Pages 697–702 *in* Proceedings of EGC'2005, RNTI-E-3, vol. 2. <http://eric.univ-lyon2.fr/~ricco/tanagra/en/tanagra.html>.
- Tarboton, D. 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. *Water Resources Research* 33(2):309–319.
- Yang, X., G. A. Chapman, J. M. Gray, and M. A. Young. 2007. Delineating soil landscape facets from digital elevation models using compound topographic index in a geographic information system. *Australian Journal of Soil Research* 45(8):569–576.

Appendix A. Supplemental Information

Table A1. One-way ANOVA of soil properties by plot.

Location	1:2 pH			Reserve Acidity			Final EC (ms/cm)			Clay			% Sand		
Plot ID	n	Average	Std-dev	n	Average	Std-dev	n	Average	Std-dev	n	Average	Std-dev	n	Average	Std-dev
400_001	3	5.34	0.39	3	0.96	0.04	3	0.10	0.01	3	10.0%	2.2%	3	68.1%	6.6%
400_002	3	5.84	0.65	3	0.73	0.20	3	0.17	0.06	3	16.7%	1.4%	3	67.8%	1.4%
400_002TJ	3	6.36	0.57	3	0.54	0.08	3	0.18	0.06	3	20.6%	3.9%	3	66.1%	6.3%
400_004	3	5.95	0.54	3	0.51	0.40	3	0.15	0.08	3	17.1%	0.9%	3	68.1%	1.6%
400_005	3	5.64	0.25	3	0.67	0.16	3	0.13	0.04	3	18.2%	3.9%	3	65.4%	6.1%
500_001	3	6.62	0.56	3	0.56	0.23	3	0.21	0.03	3	11.9%	4.2%	3	73.7%	7.7%
500_002	3	7.36	0.37	3	0.35	0.18	3	0.41	0.36	3	10.9%	2.4%	3	75.3%	5.2%
500_003	3	6.16	0.31	3	0.58	0.04	3	0.19	0.02	3	19.9%	1.5%	3	64.8%	2.6%
500_004	3	5.39	0.31	3	0.53	0.03	3	0.16	0.04	3	20.6%	7.2%	3	65.6%	10.5%
500_005	3	7.09	0.61	3	0.53	0.09	3	0.41	0.17	3	11.9%	0.8%	3	75.2%	0.8%
All	30	6.18	0.77	30	0.60	0.22	30	0.21	0.15	30	15.8%	4.9%	30	69.0%	6.2%
ANOVA Variance Decomp	Variance decomposition			Variance decomposition			Variance decomposition			Variance decomposition			Variance decomposition		
	Source	Sum of square	d.f.	Source	Sum of square	d.f.	Source	Sum of square	d.f.	Source	Sum of square	d.f.	Source	Sum of square	d.f.
	BSS	12.6977	9	BSS	0.7109	9	BSS	0.3241	9	BSS	0.0478	9	BSS	0.0462	9
	WSS	4.5189	20	WSS	0.647	20	WSS	0.3591	20	WSS	0.0231	20	WSS	0.0659	20
	TSS	17.2165	29	TSS	1.3579	29	TSS	0.6832	29	TSS	0.0709	29	TSS	0.1121	29
	Significance level			Significance level			Significance level			Significance level			Significance level		
	Statistics	Value	Proba	Statistics	Value	Proba	Statistics	Value	Proba	Statistics	Value	Proba	Statistics	Value	Proba
	Fisher's F	6.24428	0.000328	Fisher's F	2.441823	0.046249	Fisher's F	2.005928	0.093491	Fisher's F	4.5923	0.002188	Fisher's F	1.559896	0.194734

Location	frac rock by oven-dry mass			Total Sample oven dry density			TOC			1:1 pH		
Plot ID	n	Average	Std-dev	n	Average	Std-dev	n	Average	Std-dev	n	Average	Std-dev
400_001	3	69.63%	11.86%	3	1.53	0.21	3	1.50%	0.56%	3	6.29	0.35
400_002	3	41.60%	21.87%	3	0.94	0.11	3	3.32%	0.76%	3	6.57	0.49
400_002TJ	3	53.22%	16.29%	3	1.54	0.31	3	1.33%	0.18%	3	6.90	0.64
400_004	3	64.07%	24.60%	3	1.25	0.57	3	2.46%	2.31%	3	6.47	0.27
400_005	3	41.65%	24.11%	3	1.50	0.41	3	1.98%	1.64%	3	6.31	0.39
500_001	3	44.82%	13.27%	3	1.52	0.31	3	2.35%	0.67%	3	7.18	0.74
500_002	3	42.64%	11.26%	3	1.28	0.13	3	1.92%	1.02%	3	7.70	0.20
500_003	3	55.49%	6.59%	3	1.39	0.09	3	2.14%	0.47%	3	6.75	0.29
500_004	3	71.75%	4.14%	3	1.33	0.14	3	1.18%	0.36%	3	5.92	0.27
500_005	3	66.65%	25.05%	3	0.73	0.13	3	4.81%	1.61%	3	7.62	0.53
All	30	55.15%	18.67%	30	1.30	0.35	30	2.30%	1.42%	30	6.77	0.67
ANOVA Variance Decomp	Variance decomposition			Variance decomposition			Variance decomposition			Variance decomposition		
	Source	Sum of square	d.f.	Source	Sum of square	d.f.	Source	Sum of square	d.f.	Source	Sum of square	d.f.
	BSS	0.399	9	BSS	1.9782	9	BSS	0.0031	9	BSS	9.1636	9
	WSS	0.6123	20	WSS	1.5923	20	WSS	0.0027	20	WSS	4.0428	20
	TSS	1.0113	29	TSS	3.5706	29	TSS	0.0058	29	TSS	13.2064	29
	Significance level			Significance level			Significance level			Significance level		
	Statistics	Value	Proba	Statistics	Value	Proba	Statistics	Value	Proba	Statistics	Value	Proba
	Fisher's F	1.448097	0.233799	Fisher's F	2.76083	0.028079	Fisher's F	2.610367	0.035463	Fisher's F	5.036985	0.00127

Table A2. Parameter averages by plot.

Parameter	Cluster									
	n*1	n*2		n*3	n*4					
	500_005	500_001	500_002	400_001	400_002	400_002TJ	400_004	400_005	500_003	500_004
Rock fragments	0.667	0.448	0.426	0.696	0.416	0.532	0.641	0.416	0.555	0.717
Bulk density	0.73	1.52	1.28	1.53	0.94	1.54	1.25	1.5	1.39	1.33
Total organic carbon	0.0481	0.0235	0.0192	0.015	0.0332	0.0133	0.0246	0.0198	0.0214	0.0118
pH1_1	7.62	7.18	7.7	6.29	6.57	6.9	6.47	6.31	6.75	5.92
pH1_2	7.09	6.62	7.36	5.34	5.84	6.36	5.95	5.64	6.16	5.39
Reserve acidity	0.53	0.56	0.35	0.96	0.73	0.54	0.51	0.67	0.58	0.53
Electrical conductivity	0.41	0.21	0.41	0.1	0.17	0.18	0.15	0.13	0.19	0.16
Clay	0.119	0.119	0.109	0.1	0.167	0.206	0.171	0.181	0.199	0.206
Sand	0.752	0.736	0.753	0.681	0.678	0.661	0.681	0.654	0.648	0.655
TWI	5.521	5.598	5.207	5.978	5.47	6.518	5.945	5.622	5.845	6.855
Tunneling	0	0	0	0	0	0	0	0	0	0
Sheet	0	26–50	1–5	0	26–50	1–5	0	0	0	0
Rill		6–25	1–5	0	0	0	0	1–5	1–5	0
Gully	0	0	0	0	0	0	0	0	0	0
Pedestals	0	0	0	0	0	0	0	0	0	0
Terracettes	0	0	0	0	0	0	0	0	0	0
Burrowing	1–5	0	1–5	1–5	0	1–5	0	1–5	1–5	1–5
Erosion	low	high	low	none	medium	low	none	low	low	none
Erosion issues	3	51	6	0	38	3	0	3	3	0
No cover	0.2708	0.1917	0.2833	0.2125	0.2125	0.1167	0.2042	0.3333	0.2625	0.2167
No cover (bare)	0.025	0.0292	0.0042	0.0208	0.0042	0.0083	0.0292	0.0375	0.025	0.0708
Bare ground	0.0583	0.0917	0.0042	0.0333	0.0083	0.0375	0.1	0.0917	0.0417	0.3542
Bedrock	0.0083	0.0417	0	0	0.0125	0	0	0.0458	0	0
Duff	0.1083	0.1375	0	0.0417	0.3292	0.175	0.0083	0.1125	0.325	0.05
Gravel cover	0.2667	0.1625	0.3792	0.1667	0.0125	0.2625	0.3	0.1458	0.1292	0.2625
Litter	0.4958	0.4375	0.4417	0.6958	0.4708	0.4208	0.4208	0.525	0.4458	0.0958
Cyanobacteria (light)	0	0	0	0	0	0	0	0	0	0
Cyanobacteria (dark)	0	0	0	0	0	0	0	0	0	0.0167
Lichen	0	0	0	0	0	0	0	0	0	0
Moss	0.0042	0.0083	0	0	0.0083	0	0.0042	0	0.0042	0.025
Lichen on rock	0.0042	0.025	0	0	0.1333	0.0042	0.0292	0.0292	0.0208	0.0083
Plant basal	0.0083	0.0333	0.0167	0.0583	0.0208	0.0958	0.125	0.0042	0	0.1875
Rock cover	0.0458	0.0625	0.1583	0.0042	0.0042	0.0042	0.0125	0.0458	0.0333	0
Herbaceous	0.2917	0.4625	0.2417	0.6333	0.2625	0.7	0.5167	0.3792	0.2333	0.6917
Subcanopy	0.35	0.2792	0.2833	0.1333	0.3417	0.4333	0.1583	0.2	0.1583	0.0958
Canopy	0.3667	0.45	0.2917	0.1167	0.5542	0.2625	0.3208	0.1417	0.475	0.1042
Mean slope	0.125	0.27	0.475	0.01	0.255	0.17	0.055	0.3	0.585	0.1

Table A2. Parameter averages by plot, cont.

Parameter	Cluster									
	n*1	n*2		n*3	n*4					
	500_005	500_001	500_002	400_001	400_002	400_002TJ	400_004	400_005	500_003	500_004
Soil stability	2.25	2.89	3.76	4.49	2.14	3.24	3.39	2.52	1.78	2.87
Elevation	6,145	6,163	6,249	5,782	5,867	5,847	6,051	5,861	6,117	6,074

Table A3. Soil sample values.

Plot ID	Parameter								
	Rock fragments	Bulk density	TOC	1:1 pH	1:2 pH	Reserve acidity	Final EC (mS/cm)	Clay	Sand
400_001	0.5716	1.31	0.0171	6.07	5.07	1.00	0.09	0.090	0.719
400_001	0.7094	1.71	0.0194	6.11	5.16	0.95	0.11	0.085	0.720
400_001	0.8078	1.57	0.0087	6.70	5.78	0.92	0.10	0.126	0.605
400_002	0.4539	1.06	0.0335	7.13	6.59	0.54	0.23	0.152	0.686
400_002	0.1808	0.89	0.0255	6.25	5.53	0.72	0.12	0.173	0.686
400_002	0.6133	0.85	0.0408	6.33	5.40	0.93	0.15	0.176	0.662
400_002TJ	0.3579	1.25	0.0117	6.18	5.73	0.45	0.11	0.229	0.618
400_002TJ	0.6807	1.50	0.0153	7.08	6.52	0.56	0.21	0.229	0.631
400_002TJ	0.5580	1.86	0.0128	7.43	6.83	0.60	0.21	0.162	0.733
400_004	0.8019	1.58	0.0066	6.18	5.37	0.81	0.07	0.181	0.672
400_004	0.3576	1.56	0.0166	6.72	6.05	0.67	0.14	0.168	0.699
400_004	0.7625	0.59	0.0507	6.50	6.44	0.06	0.23	0.164	0.672
400_005	0.6945	1.12	0.0386	5.87	5.37	0.50	0.17	0.144	0.695
400_005	0.2905	1.94	0.0120	6.50	5.69	0.81	0.11	0.177	0.685
400_005	0.2644	1.44	0.0088	6.57	5.86	0.71	0.10	0.223	0.584
500_001	0.4570	1.87	0.0165	8.01	7.27	0.74	0.24	0.082	0.813
500_001	0.3114	1.34	0.0241	6.92	6.29	0.63	0.19	0.164	0.659
500_001	0.5763	1.35	0.0298	6.60	6.30	0.30	0.20	0.110	0.737
500_002	0.4268	1.40	0.0114	7.49	6.94	0.55	0.21	0.127	0.724
500_002	0.5387	1.32	0.0156	7.74	7.50	0.24	0.19	0.082	0.813
500_002	0.3136	1.14	0.0307	7.88	7.63	0.25	0.83	0.118	0.721
500_003	0.5589	1.46	0.0236	7.08	6.51	0.57	0.20	0.191	0.646
500_003	0.6188	1.42	0.0159	6.61	6.06	0.55	0.17	0.216	0.623
500_003	0.4871	1.29	0.0246	6.55	5.92	0.63	0.19	0.191	0.674
500_004	0.6699	1.44	0.0089	5.62	5.05	0.57	0.14	0.123	0.776
500_004	0.7455	1.17	0.0159	6.00	5.48	0.52	0.21	0.248	0.583
500_004	0.7371	1.37	0.0105	6.15	5.64	0.51	0.13	0.248	0.608
500_005	0.7379	0.62	0.0361	7.01	6.39	0.62	0.25	0.129	0.761
500_005	0.3882	0.88	0.0417	7.88	7.43	0.45	0.38	0.114	0.748
500_005	0.8736	0.70	0.0663	7.96	7.45	0.51	0.60	0.114	0.747

Table A4. Parameter averages by cluster.

Parameters	Cluster IDs			
	n*1	n*2 (2 plots)	n*3	n*4 (6 plots)
Rock fragments	0.667	0.437	0.696	0.546
Bulk density	0.73	1.40	1.53	1.32
Total organic carbon	0.0481	0.0213	0.0150	0.0207
pH1_1	7.62	7.44	6.29	6.49
pH1_2	7.09	6.99	5.34	5.89
Reserve acidity	0.53	0.45	0.96	0.59
Electrical conductivity	0.41	0.31	0.10	0.16
Clay	0.119	0.114	0.100	0.189
Sand	0.752	0.745	0.681	0.663
TWI	5.521	5.403	5.978	6.043
Erosion issues (%)	3	29	0	8
No cover	0.2708	0.2375	0.2125	0.2243
No cover (bare)	0.0250	0.0167	0.0208	0.0292
Bare ground	0.0583	0.0479	0.0333	0.1056
Bedrock	0.0083	0.0208	0.0000	0.0097
Duff	0.1083	0.0688	0.0417	0.1667
Gravel cover	0.2667	0.2708	0.1667	0.1854
Litter	0.4958	0.4396	0.6958	0.3965
Cyanobacteria (light)	0.0000	0.0000	0.0000	0.0000
Cyanobacteria (dark)	0.0000	0.0000	0.0000	0.0028
Lichen	0.0000	0.0000	0.0000	0.0000
Moss	0.0042	0.0042	0.0000	0.0069
Lichen on rock	0.0042	0.0125	0.0000	0.0375
Plant basal	0.0083	0.0250	0.0583	0.0722
Rock cover	0.0458	0.1104	0.0042	0.0167
Herbaceous	0.2917	0.3521	0.6333	0.4639
Subcanopy	0.3500	0.2813	0.1333	0.2312
Canopy	0.3667	0.3708	0.1167	0.3097
Mean slope	0.13	0.37	0.01	0.24
Soil stability	2.25	3.33	4.49	2.65
Elevation	6,145	6,206	5,782	5,970

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 349/109189, August 2011

National Park Service
U.S. Department of the Interior



Natural Resource Stewardship and Science

1201 Oak Ridge Drive, Suite 150
Fort Collins, Colorado 80525

www.nature.nps.gov

EXPERIENCE YOUR AMERICA™