



Status and Trends of Terrestrial Vegetation and Soils at Casa Grande Ruins National Monument, 2008–2016

Natural Resource Report NPS/SODN/NRR—2018/1800



ON THE COVER

Biologists sample terrestrial vegetation and soils at Casa Grande Ruins National Monument.
NPS photo.

Status and Trends of Terrestrial Vegetation and Soils at Casa Grande Ruins National Monument, 2008–2016

Natural Resource Report NPS/SODN/NRR—2018/1800

Prepared by

J. A. Hubbard¹, Cheryl McIntyre², and Sarah E. Studd¹

¹Sonoran Desert Network
National Park Service
12661 E. Broadway Blvd.
Tucson, AZ 85748

²Chihuahuan Desert Network
National Park Service
12661 E. Broadway Blvd.
Tucson, AZ 85748

Editing and Design

Alice Wondrak Biel
Sonoran Desert Network
National Park Service
12661 E. Broadway Blvd.
Tucson, AZ 85748

November 2018

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

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are 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 Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with 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. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

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, as well as at the Natural Resource Publications Management website. If you have difficulty accessing information in this publication, particularly if using assistive technology, please email irma@nps.gov.

Please cite this publication as:

McIntyre, C., J. A. Hubbard, and S. E. Studd. 2018. Status and trends of terrestrial vegetation and soils at Casa Grande Ruins National Monument, 2008–2016. Natural Resource Report NPS/SODN/NRR—2018/1800. National Park Service, Fort Collins, Colorado.

Contents

Figures v

Tables v

Executive Summary vii

Acknowledgements ix

1 Introduction 1

 1.1 Background 1

 1.2 Goals and objectives 1

 1.3 How to use this report 2

 1.4 Study area 2

 1.5 Assessment points and natural resource management issues 5

2 Methods 11

 2.1 Response design 11

 2.2 Sampling design 13

 2.3 Analyses 15

3 Results 17

 3.1 Site characterization 17

 3.2 Vegetation formations, lifeforms, and perennial plant diversity 17

 3.3 Cover and extent of perennial plant species 17

 3.4 Frequency and extent of uncommon plant species 17

 3.5 Cover and frequency of exotic species 17

 3.6 Soil cover 17

 3.7 Biological soil crusts 19

 3.8 Soil stability 19

 3.9 Management assessment points 19

4 Discussion 23

 4.1 Groundwater depletion and vegetation change 23

 4.2 Surprisingly low perennial plant diversity (and almost no saguaros) 24

 4.3 Biological soil crusts and erosion hazards 25

 4.4 Stabilization plots vs. monitoring plots 25

 4.5 Exotic plants, fire, and community resilience/resistance 27

 4.6 Are terrestrial vegetation and soils within the range of natural variability? 27

 4.7 Recommendations for additional research 27

5 Literature Cited 29

Figures

Figure 1-1. Field staff recording terrestrial vegetation at Casa Grande Ruins National Monument.	1
Figure 1-2. Soil map units (NRCS n.d.) and vegetation and soils plots at Casa Grande Ruins National Monument, 2008–2016.....	3
Figure 1-3. Monthly 30-year normal climate data, 1981–2010, based on National Oceanic and Atmospheric Administration Cooperative Observer station at Casa Grande Ruins National Monument (WRCC n.d.).	4
Figure 1-4. Vegetation and land cover types (from Buckley et al. 2009), and vegetation and soils plots, Casa Grande Ruins National Monument, 2008–2016.	4
Figure 2-1. Terrestrial vegetation and soils monitoring plot design	12
Figure 2-2. Sampling frame, strata, and plot locations for terrestrial vegetation and soils monitoring at Casa Grande Ruins National Monument.	14
Figure 2-3. Schematic of key to vegetation formations in Sonoran Desert Network parks	16
Figure 3-1. Lifeform cover in field (<0.5 m height) and subcanopy (0.5–2 m) layers of terrestrial vegetation monitoring plots at Casa Grande Ruins National Monument, 2008–2016.....	18
Figure 3-2. Soil substrate cover for (A) monitoring plots (2013), and (B) stabilization plots (2016), Casa Grande Ruins National Monument.....	20
Figure 3-3. Biological soil crust cover, by morphological group and lichen growth form, within available habitat on (A) monitoring plots (2013) and (B) stabilization plots (2016), Casa Grande Ruins National Monument.	20
Figure 4-1. Typical current vegetation at Casa Grande Ruins National Monument. Annual forbs are common during the winter rainy season.....	23
Figure 4-2. Mean annual rainfall (1981–2010; blue circles) and within-plot perennial species richness (" S_{plot} "; mean $\pm$ SE, 2008–2016) for non-rocky valley bottom (<2,500' elevation <35% surface soil rock fragments) plots on four Sonoran Desert parks and refuges that contain extensive areas of valley bottom	24
Figure 4-3. Estimated annual precipitation ("") for Casa Grande Ruins National Monument, 2008–2016.....	25
Figure 4-4. Terrestrial vegetation and soils summary for monitoring plots and stabilization plots in the context of management assessment points, Casa Grande Ruins National Monument, 2008–2016.....	26

Tables

Table 1-1. Non-native invasive plants detected at Casa Grande Ruins National Monument, 1999–2015.....	7
Table 2-1. Height categories for vegetation measurement.	11
Table 2-2. Categories for aggregate stability of surface soils.....	13
Table 3-1. Terrestrial vegetation and soils data for non-rocky valley bottom monitoring plots and stabilization plots in the context of management assessment points, Casa Grande Ruins National Monument, 2008–2016.....	21

Executive Summary

This report summarizes results of the Sonoran Desert Network's second round of terrestrial vegetation and soils monitoring in upland areas of Casa Grande Ruins National Monument (NM), in Arizona. We resampled six permanent field-monitoring sites (3 originally established in 2008 and 3 established in 2011) from 2013 to 2016. Our objectives were to determine status and detect trends in cover of vegetation, soil, and biological soil crusts; stability of surface soils; and frequency of vegetation. We also assessed the degree of ecological impact from ongoing stabilization efforts on key archeological sites within the monument.

Groundwater depletion has led to tremendous change in the monument flora over the past century. However, terrestrial vegetation, biological soil crusts, and other dynamic soil-function parameters have remained consistent since monitoring efforts began in 2008. The sparse native shrublands of the monument are very stable and appear to be highly resistant to drought, frost, and other perturbations.

Perennial plant diversity is remarkably low at the monument—a near monoculture of creosotebush (*Larrea tridentata*), perhaps due to extensive soil modification during the period of intensive occupation of the Casa Grande complex (AD 950–1450). We suggest additional research to evaluate these conditions and the potential for recruitment of other native plants—including saguaro cacti, the iconic Sonoran Desert plant that is common on similar sites elsewhere.

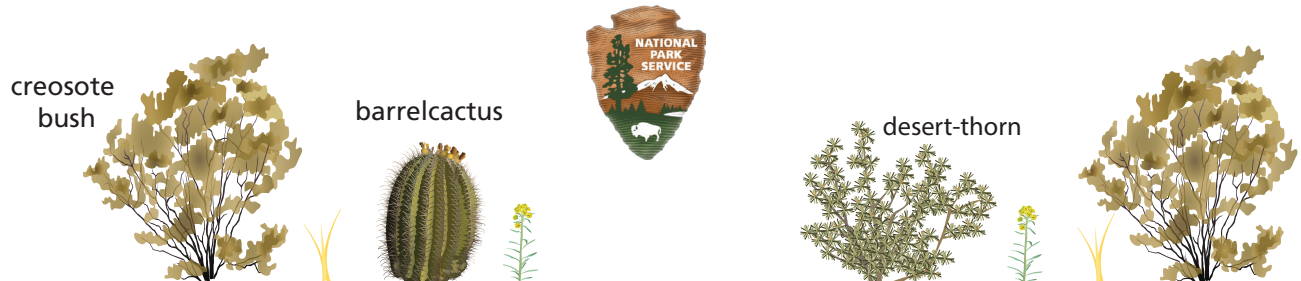
In contrast to the low plant diversity, biological soil crusts are an extensive and important component of terrestrial ecosystems at Casa Grande Ruins NM. During the most recent sampling, biological soil crusts, primarily light cyanobacteria, occupied more than half of the available habitat on the monument. Surface soil aggregate stability was similarly high, while the cover of exposed bare soil was relatively low. In combination, soil conditions throughout most of the monument should limit the degree of soil erosion. This is particularly important because nearly the entire unit contains near-surface archeological resources. Surface soil aggregate stability and cover of vegetation and biological crusts were substantially lower—and bare soil was markedly higher—on plots where recent archeological stabilization efforts have occurred. We recommend continued observation of these sites to detect and address wind and water erosion of soils.

Although we have observed 35 exotic plant species at Casa Grande Ruins NM, they appear to be largely restricted to roadsides and other high-disturbance areas. None has been detected on monitoring or stabilization sites since monitoring began in 2008. Likely due to the paucity of exotic and native grasses and forbs, the potential for altered fire regimes (i.e., wildfire in low-elevation desert ecosystems, driven by fine fuels) is currently low at Casa Grande Ruins NM. As with localized erosion potential, we will continue to monitor exotic-plant occurrence and fine-fuel accumulation, and recommend vigilance in the face of these potentially system-changing management issues.

At Casa Grande Ruins National Monument, a suite of management assessment points have been proposed relative to issues of vegetation management concern. Management assessment points are intended to serve as a potential early warning system, giving scientists and managers the opportunity to pause, review the available information in detail, and consider options. Management assessment points for monitoring described in this report identified several issues of potential concern (see figure, next page). Erosion hazard due to the prevalence of exposed bare soil was identified as a potential issue of management concern on the recently manipulated stabilization plots. The cover of mature biological soil crusts could not be differentiated from the assessment point on either monitoring or stabilization plots. Saguaro cacti recruitment was also of potential concern on both monitoring and stabilization plots.

Management Assessment Points Summary

Sonoran Desert Network Terrestrial Vegetation and Soils Monitoring Casa Grande Ruins National Monument, 2008–2016



Monitoring plots

Sparse Shrublands
(Perennial species: $1.3 \pm 0.3/\text{plot}$)

Stabilization plots

Sparse Shrublands
(Perennial species: $1.5 \pm 0.3/\text{plot}$)

Erosion Potential		
15% (+/- 3%)	Exposed bare soil >20%	50% (+/- 11%)
4.9 (+/- 0.2)	Soil stability <Class 3	4.0 (+/- 0.1)
Biological Soil Crusts		
15% (+/- 10%)	Mature biocrust <10%	14% (+/- 7%)
Exotic Plant Dispersal		
None	New species detections	None
None	Species new to a plot	None
Exotic Plant Invasion		
0%	Exotic plant cover >5%	0%
0%	Buffelgrass cover >1%	0%
0%	Red brome cover >1%	0%
Plant Community Resilience		
0.1% (+/- 0.1%)	Dead plant cover (<0.5 m) >15%	0.3% (+/- 0.3%)
0.1% (+/- 0.1%)	Dead plant cover (0.5–2 m) >5%	0%
Saguaro Cacti Occupancy		
0%	Nurse plant cover <10%	0%
Altered Fire Regimes		
10% (+/- 5)	Herbaceous cover >35%	4% (+/- 2%)
Within normal range ~ Nearing potential concern ~ Potential concern		

Terrestrial vegetation and soils summary for monitoring plots and stabilization plots in the context of management assessment points, Casa Grande Ruins National Monument, 2008–2016. Red results are of potential concern. Orange results cannot be differentiated from the assessment point. Plant symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/). Data provided in this graphic can also be found in Table 3-1.

Acknowledgements

We thank Superintendent Karl Pierce, Chief of Resources Alycia Hayes, and the rest of the staff of Casa Grande Ruins National Monument for their on-site support of the field effort and the Sonoran Desert Network. Ed Kuklinski, Greg Goodrum, Elisa Neves, Hannah Andrascik, Jeff Galvin, Shannon Henke, Fraser Watson, and Jesper Devantier conducted the field-data collection. Greg Goodrum and staff from Brigham Young University's Environmental Analytical Laboratory processed the soil samples. Steve Buckley provided expert botanical expertise for crew training and identification of unknown samples while in the field. Data processing and management support was provided by Kristen Bonebrake. Don Swann, Dana Backer, Natasha Kline, Perry Grissom, and Scott Stonum (all of Saguaro National Park) assisted in the determination of appropriate management assessment point thresholds. Lastly, many thanks to the Student Conservation Association and the National Park Service International Volunteers in Parks Program, which provided several of the field personnel throughout this and many ongoing projects. Their technical and administrative support has proved invaluable during the course of this collaboration.

1 Introduction

1.1 Background

Generating more than 99.9% of Earth's biomass (Whittaker 1975), plants are the primary producers of life on Earth. Vegetation represents much of the biological foundation of terrestrial ecosystems, and it comprises or interacts with all primary structural and functional components of these systems. Vegetation dynamics can indicate the integrity of ecological processes, productivity trends, and ecosystem interactions that can otherwise be difficult to monitor. Land-management actions often focus on manipulating vegetation to achieve management objectives, with defined conditions based on community structure or lifeform composition.

In the deserts of the American Southwest, vegetation composition, distribution, and production are highly influenced by edaphic factors, such as soil texture, mineralogy depth, and landform type (McAuliffe 1999). Especially as they relate to water, these influences are magnified at local scales, as described by pioneering desert ecologist Forrest Shreve:

“The profound influence of soil upon desert vegetation is to be attributed to its strong control of the amount, availability and continuity of water supply. This fundamental requisite in plants is the most effective single factor in the differentiation of desert communities” (Shreve 1951).

As such, a fundamental understanding of soils and landforms is essential for evaluating vegetation patterns and processes (McAuliffe 1999).

The Sonoran Desert Network part of the National Park Service (NPS) Inventory and Monitoring (I&M) Division, identified terrestrial vegetation and dynamic soil functional attributes as important ecosystem monitoring parameters, or “vital signs” (SODN 2005) that provide key insights into the integrity of terrestrial ecosystems at Casa Grande Ruins National Monument (NM; Figure 1-1). Indicators of terrestrial vegetation integrity include vegetation community structure, lifeform abundance, status and



Figure 1-1. Field staff recording terrestrial vegetation at Casa Grande Ruins National Monument.

trends of established exotic plants, and early detection of previously undetected exotic plants. Indicators of soil dynamic function and erosion resistance include the cover of mineral soil (including bare ground), biological soil crusts, and the stability of surface soil aggregates.

1.2 Goals and objectives

The overall goal of the Sonoran Desert Network's terrestrial vegetation and soils monitoring program is to ascertain broad-scale changes in vegetation and dynamic soil properties in the context of changes in other ecological drivers, stressors, ecological processes, and focal resources of interest (Hubbard et al. 2012). This integrated approach explores patterns and identifies candidate explanations to support effective management and protection of natural resources in a cumulative fashion, such that the results of each successive round of monitoring build upon knowledge gained from previous efforts and related research and monitoring activities.

Objectives for terrestrial vegetation and soils monitoring at Casa Grande Ruins NM are to determine status and trends in (over five-year intervals):

1. Terrestrial *vegetation cover* for common perennial species, including non-native plants, and all plant lifeforms.

2. Terrestrial *vegetation frequency* of uncommon perennial species including non-native plants.
3. Terrestrial *vegetation density* of columnar cacti and ocotillo (*Fouquieria splendens*).
4. Terrestrial *soil cover* by substrate classes (bare soil, litter, fuel/woody debris, vegetation, biological soil crust, rock fragments of several size classes) that influence resistance to erosion.
5. Terrestrial *soil stability* of surface aggregates by stability class (1–6).
6. Cover and frequency of *biological soil crusts* by lichen growth form and morphological group.

1.3 How to use this report

This is a large report. Readers with specific interests can focus on particular sections.

Just the highlights, please:

- Executive Summary
- Chapter 4

Add detail on management implications:

- Sections 1.5, 3.9
- Table 3-1, Figure 4-4

Add detail on field methods and sampling design:

- Chapter 2
- Figures 2-1, 2-2

1.4 Study area

1.4.1 Park establishment and purpose

Located approximately 70 miles northwest of Tucson and 60 miles southeast of Phoenix, Casa Grande Ruins NM is the fifth-oldest unit in the National Park Service and was the first prehistoric and cultural preserve established in the United States (NPS 2011). The monument was authorized in 1889. A June 22, 1892 proclamation by President Benjamin Harrison created Casa Grande Ruin Reservation to protect the Casa Grande, a four-story adobe structure that was built by the Hohokam between AD 1200 and 1450

(Clemensen 1992). On August 3, 1918, President Woodrow Wilson proclaimed Casa Grande a national monument to ensure the “protection, preservation and care of the ancient buildings and other objects of prehistoric interest thereon” (Wilson 1918). The 472.5-acre monument contains dozens of prehistoric archeological sites, most of which are closed to the public and managed as backcountry sites, and 15 historic structures eligible for listing on the National Register of Historic Places (NPS 2011). From 2008 to 2016, the monument averaged around 70,000 visitors annually (NPS 2018a).

1.4.2 Natural resources overview

Casa Grande Ruins NM is located in the Basin and Range physiographic province, characterized by nearly level valley floors surrounded by mountain ranges (Clemensen 1992). The monument lies within the Sonoran Desert ecoregion, spanning 55 million acres in Arizona, California, Baja California, and Sonora (Marshall et al. 2000). A late Pleistocene-aged alluvial deposit of gravel underlies the monument (NPS 2018b). The alluvium at the monument is approximately 800–1,200 feet thick (Cooley 1973).

1.4.2.1 Soils

As described by the Pinal County Soil Survey (SCS 1991), Coolidge sandy loam is the dominant soil type within the current monument boundary, comprising over 80% of the soil, with the remainder being the Laveen loam soil type (Figure 1-2; NRCS n.d.). However, the Natural Resources Conservation Service warns that the 1:24,000 mapping scale used in the Pinal County Soil Survey may not be valid or appropriate at the scale of the monument. At the monument scale, the placement of the lines between soil map units may not be accurate, and the map does not show small soil inclusions (NRCS n.d.).

Both soil map units have surface soils with less than 15% rock fragments by volume, are considered well-drained, and have a slight risk of water erosion. Coolidge sandy loams typically have a calcic horizon at depths between 14 and 40 inches (NRCS n.d.). Soil factors mediate water relations for plants in semi-arid environments (McAuliffe 1999),

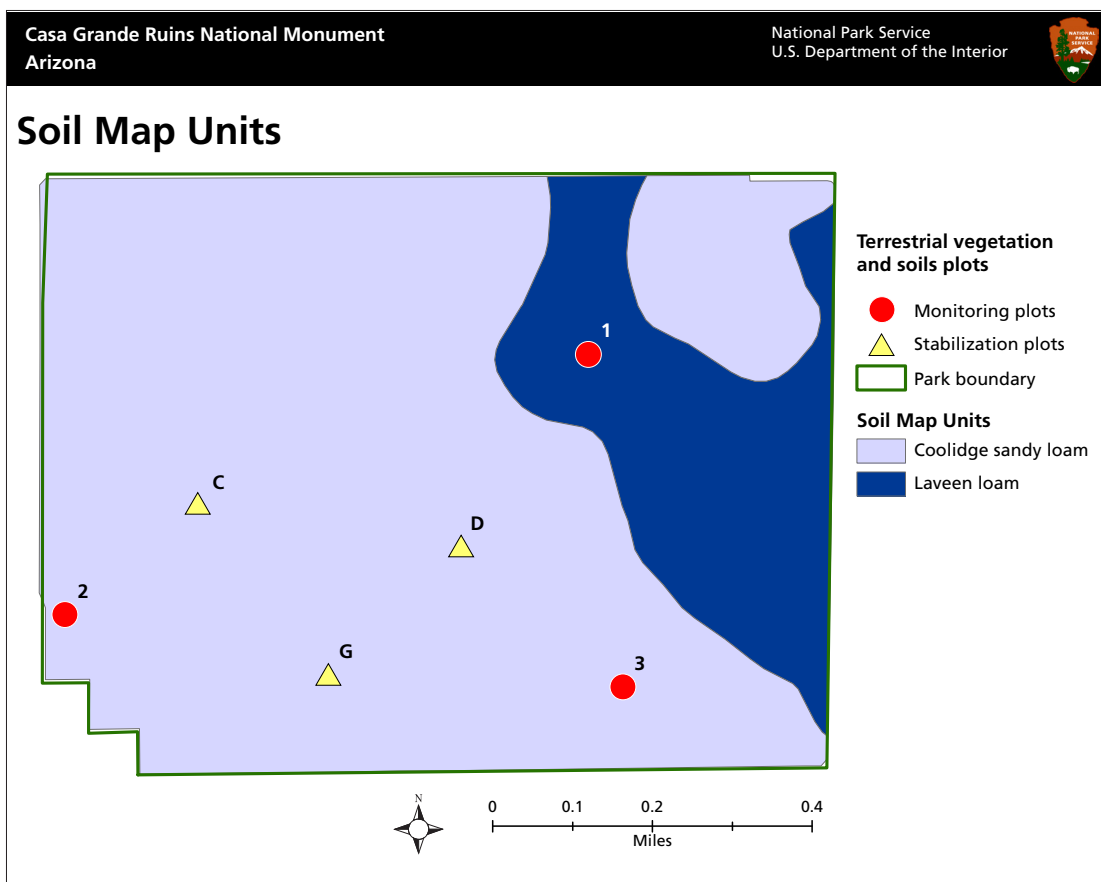


Figure 1-2. Soil map units (NRCS n.d.) and vegetation and soils plots at Casa Grande Ruins National Monument, 2008–2016. Note that the Natural Resources Conservation Service warns that the map may not be valid at this scale.

thereby controlling patch-scale ecological composition and net primary productivity (Herrick et al. 2005b).

1.4.2.2 Climate

Casa Grande Ruins NM experiences climate typical of the Sonoran Desert ecoregion (Figure 1-3): highly variable, bimodal precipitation with a considerable range in daily and seasonal air temperature and relatively high potential evapotranspiration rates (Ingram 2000). Approximately one-third of the annual total of 9.18" of precipitation falls during summer thunderstorms from July through September (WRCC 2018), when maximum air temperatures can exceed 104°F and lead to violent (and often localized) storms (Shepard et al. 2002). The bulk of the remaining annual precipitation falls in relatively gentle events of broad extent from November through March (Ingram 2000).

1.4.2.3 Vegetation

With elevations ranging from 1,414 to 1,427 feet (Clemensen 1992), the monument falls

within the Arizona Upland subdivision of the Sonoran Desert, a biome that is perhaps better described as “thornscrub” than “desert” due to climate, plant productivity, and biodiversity (Dimmit 2000). Vegetation characterization and mapping efforts at the monument in 2007–2008 revealed eight distinct types in and around the main unit, with a total of 20 species recorded during sampling efforts (Figure 1-4) (Buckley et al. 2009). The creosotebush (*Larrea tridentata*) shrubland alliance dominated the monument’s main unit. The monument falls within the Limey Fan 7–10" precipitation zone (p.z.) ecological site (NRCS n.d.), typically shrublands that occur on deep soils. The historic climax vegetation community of the ecological site is dominated by creosotebush with subdominants of bursage (*Ambrosia* spp.) and ratany (*Krameria* spp.) shrubs and a scattering of grasses and forbs (Robinett et al. n.d.).

In the mid-to-late 1800s, the desert plants at Casa Grande Ruins NM, particularly the tall mesquite (*Prosopis* sp.), impressed travelers.

Figure 1-3. Monthly 30-year normal climate data, 1981–2010, based on National Oceanic and Atmospheric Administration Cooperative Observer station at Casa Grande Ruins National Monument (WRCC n.d.).

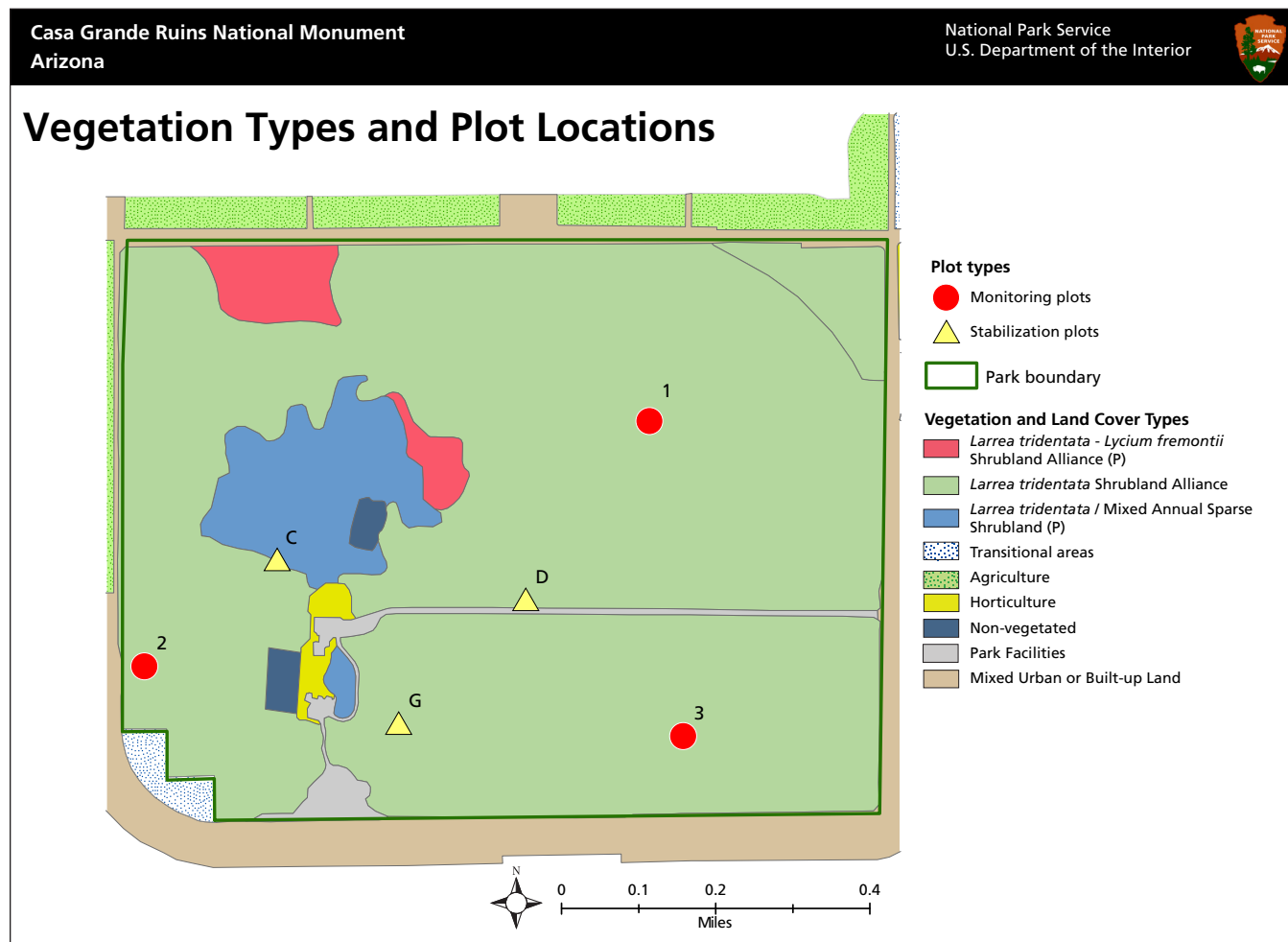
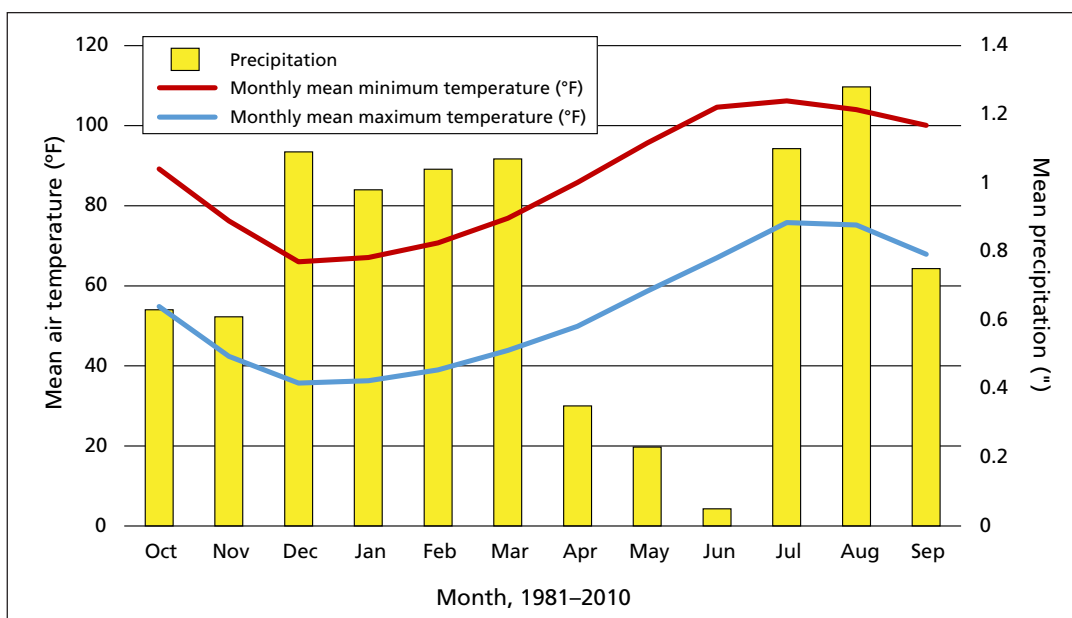


Figure 1-4. Vegetation and land cover types (from Buckley et al. 2009), and vegetation and soils plots, Casa Grande Ruins National Monument, 2008–2016.

One account from 1879 described mesquite hiding the Great House from view until one was nearly upon it (distance unspecified; Clemensen 1992). An 1869 survey noted the presence of mesquite, greasewood, and grass; the latter had attracted ranchers to the area by the early 1870s, and cattle ranching prospered for roughly 50 years. The cattle grazed vegetation around the ruins and trampled plants and soils. In 1902, monument custodian Frank Pinkley reported that cattle had consumed all forage within 100 yards of the Great House. The monument was grazed until 1934, when a fence enclosed the monument and prevented large animals from entering (Clemensen 1992). Today, the monument is surrounded by agricultural, commercial, and residential development.

Limiting soil erosion on and around high-priority cultural sites is a major focus of resource management for Casa Grande Ruins NM. Particularly fragile sites, such as Compound B and the areas around the original entrance road, receive regular maintenance to stabilize the original soils and structures. This includes the widespread addition of archaeological fill soil atop key existing surfaces to minimize surface erosion. Imported from offsite, this fill material can be readily distinguished from the in-situ soils, so archeologists of the future can differentiate this protective layer from the original materials.

1.5 Assessment points and natural resource management issues

To achieve the National Park Service mission of resource protection, resource management and monitoring must be explicitly linked (Bingham et al. 2007). Management assessment points can act as a bridge between science and management. Management assessment points are "... pre-selected points along a continuum of resource-indicator values where scientists and managers have agreed to stop and assess the status or trend of a resource relative to program goals, natural variation, or potential concerns" (Bennetts et al. 2007).

Management assessment points aid interpretation of ecological information in a management context. They do not define strict management or ecological thresholds, inevitably

result in management actions, or reflect any legal or regulatory standard. They are only intended to serve as a potential early warning system, giving scientists and managers the opportunity to pause, review the available information in detail, and consider options (Bennetts et al. 2007). Bennetts and others (2007) provide a detailed explanation of this concept and its application to monitoring and management of protected areas.

Below, we describe natural resource management issues at Casa Grande Ruins NM and propose a suite of management assessment points related to those issues. The issues, measures, and assessment-point values are based on the ecological literature and our collective knowledge of these ecosystems and park management goals. They are not enshrined in law, policy, or formal planning. Rather, they serve to provide context for resource condition and management discussions with park leadership.

1.5.1 Site stability and erosion potential

Site stability is the resistance of a site to localized wind and water erosion of soils (Herrick et al. 2005b)—with tremendous consequences for ecosystems and the protection of finite aboveground and subsurface cultural resources. Potential soil erosion is of particular concern at Casa Grande Ruins NM, as the monument contains extensive areas of near-surface cultural resources (Clemensen 1992). As recovery of disturbed soils is particularly slow in dry and seasonally dry environments (Aber and Melillo 1991), avoiding erosion is of paramount importance for effective natural resource management in the Desert Southwest.

Static and dynamic factors determine the vulnerability of a site to water erosion (Herrick et al. 2005b). Dynamic factors affecting water erosion include soil disturbance, soil structure, total cover, and plant basal cover. The amount of total cover (soil cover and vegetation cover) is the single most-important dynamic factor affecting water erosion (Herrick et al. 2005b). Most soil loss occurs in "unprotected" areas with uncovered, bare soils (Davenport et al. 1998), whereas rock,

gravel, vegetation, biological soil crusts, and even plant debris (litter and duff) can “armor” the soil, slowing the flow of water and permitting increased infiltration of water into the soil profile (Belnap et al. 2007).

*Management assessment point:
Site stability and erosion potential*

- Cover (%) of exposed bare soil is >20%
Value is based on professional judgment of authors and Saguaro National Park (NP) resource management staff (see Acknowledgements); modified from Las Cienegas National Conservation Area Management Plan (2003, as cited in Gori and Schussman 2005).
- Surface soil aggregate stability is <Class 3 (moderately stable)
Value is based on professional judgment of authors; issue is described in Herrick and others (2005b).

1.5.2 Biological soil crusts

Open spaces on the soils in arid and semi-arid regions are often covered by biological soil crusts, which are communities of cyanobacteria, algae, lichens, and bryophytes. Biological soil crusts (biocrusts) provide key ecosystem functions, such as increasing resistance to water and wind erosion, contributing organic matter, and fixing atmospheric nitrogen (Belnap 2003a). The distribution and species composition of biological soil crusts is influenced by soil chemistry and disturbance (Belnap et al. 2001).

The recovery of biological soil crusts from disturbance depends on factors such as the climatic regime and type of disturbance. Generally, crusts recover slowly in areas with high annual temperature and low annual precipitation (Belnap and Eldridge 2003), such as Casa Grande Ruins NM. Biological soil crusts follow a recovery sequence in which, typically, cyanobacteria first colonize a site, followed by cyanolichens, other lichens, and then moss (Belnap et al. 2001). Within the climax community of the Limey Fan 7–10" p.z. ecological site, biological soil crusts (or possibly just the lichen component of the community) cover 10–15% of the soil surface (Robinnett et al. n.d.).

We refer to more developed biological soil crusts as “mature” biological soil crusts, which include dark cyanobacteria crusts, lichens, and bryophytes (after Bowker and Belnap 2008).

*Management assessment point:
Biological soil crusts*

- Mature biological soil crust cover is <10% of available habitat
 - *Value is based on Limey Fan 7–10" p.z. ecological site description (Robinnett et al. n.d.) and modified from Bowker and Belnap (2008) surveys of biological soil crusts at Montezuma Castle NM.*

1.5.3 Invasive exotic plants

Biological invasions into new regions, whether accidental or deliberate, have increased at unprecedented rates in the past few hundred years (D’Antonio and Vitousek 1992). Once established, non-native plant species often lead to changes in ecosystem processes that are self-maintaining and evolving, leading to functional as well as compositional change. Several studies have implicated environmental and climatic variables as potential drivers for sustaining or accelerating non-native plant dominance in semi-arid ecosystems (Shinneman and Baker 2009).

In the American Southwest, historic and current land-use practices, such as livestock grazing and fire suppression, are thought to have contributed to the susceptibility of arid lands to invasion and subsequent loss of native species, as well as decreased biodiversity (Brown and Archer 1999). Over the past 20 years, several efforts have focused on invasive exotic plant presence, abundance, and distribution at Casa Grande Ruins NM (Table 1-1). (Note that although all efforts were looking for all species, study designs varied among the efforts. Blanks in Table 1-1 can indicate unobserved or non-target species.)

Exotic plant encroachment typically occurs in two phases (D’Antonio and Vitousek 1992): (1) colonization, the process by which a problematic species gradually disperses into suitable habitats, recruits into the system, and competes for resources with other members

Table 1-1. Non-native invasive plants detected at Casa Grande Ruins National Monument, 1999–2015.

Species	Common name	1999–2001 ^a	2002–2003 ^b	2006 ^c	2008 ^d	2012 ^e	2013 ^f	2015 ^g
<i>Avena fatua</i>	wild oats	present	–	not present	–	–	–	–
<i>Boerhavia coccinea</i>	scarlet spiderling	present	–	non-target	–	–	–	–
<i>Brassica tournefortii</i>	Sahara mustard	present	present	present	–	present	present	–
<i>Bromus carinatus</i>	California brome	present	–	non-target	–	–	–	–
<i>Bromus rubens</i>	red brome	present	present	present	–	present	present	–
<i>Centaurea melitensis</i>	Malta starthistle	present	–	present	–	–	–	–
<i>Chenopodium murale</i>	nettleleaf goosefoot	present	present	non-target	–	–	–	–
<i>Conyza</i> sp.	horseweed	present	–	non-target	–	–	–	–
<i>Cynodon dactylon</i>	Bermuda grass	present	–	present	–	–	present	–
<i>Descurania sophia</i>	flixweed	present	–	non-target	–	–	–	–
<i>Dimorphotheca sinuata</i>	African daisy	present	–	non-target	–	–	–	–
<i>Echinochloa crus-galli</i>	barnyard grass	not present	–	present	–	–	–	–
<i>Eragrostis lehmanniana</i>	Lehmann lovegrass	present	–	not present	–	–	–	–
<i>Erodium cicutarium</i>	redstem filaree	present	present	present	–	present	present	–
<i>Hordeum leporinum</i>	wild barley	present	present	non-target	–	–	–	–
<i>Hordeum murinum</i>	mouse barley	–	–	–	–	present	present	–
<i>Hordeum vulgare</i>	common barley	present	–	present	–	present	–	–
<i>Lactuca serriola</i>	prickly lettuce	present	–	non-target	–	present	present	–
<i>Matthiola longipetala</i>	none	–	–	–	–	–	–	present
<i>Malva parviflora</i>	little mallow	present	present	non-target	–	present	present	present
<i>Medicago polymorpha</i>	burclover	–	–	–	–	–	present	–
<i>Melilotus</i> spp.	sweetclovers	present	present	present	–	present	–	–
<i>Nicotiana glauca</i>	tree tobacco	present	present	present	–	–	–	–
<i>Oncosiphon piluliferum</i>	stinknet	–	–	–	–	present	–	present
<i>Pennisetum ciliare</i>	buffelgrass	present	–	not present	–	–	–	–
<i>Phalaris minor</i>	little seed	present	present	present	–	–	–	–
<i>Polygonum aviculare</i>	prostrate knotweed	present	–	non-target	–	–	–	–
<i>Salsola</i> sp.	Russian thistle	present	–	present	–	present	present	–
<i>Schismus arabicus</i>	Arabian schismus	present	present	present	–	–	–	–
<i>Schismus barbatus</i>	Mediterranean grass	present	–	present	–	present	present	–
<i>Sisymbrium irio</i>	London rocket	present	present	present	–	present	present	–
<i>Sonchus asper</i>	spiny sowthistle	present	present	present	–	present	–	–
<i>Sorghum halepense</i>	Johnsongrass	present	–	present	–	–	–	–
<i>Tamarix</i> sp.	saltcedar	not present	–	present	–	–	–	–
<i>Tribulus terrestris</i>	puncturevine	present	–	not present	–	–	–	–

^aHalvorson and Guertin (2003); ^bPowell and others (2006); ^cStudd and McIntyre (2007); ^dMcIntyre and others (2011); ^eNational Park Service (2012); ^fNational Park Service (2013); ^gNational Park Service (2015)

of the plant community; and (2) domination, the process by which, via asymmetrical competition (often mediated through disturbance), the new species becomes common or even dominant in the plant community, often with negative consequences for ecosystem structure and function. It is important to note that the second phase often requires a specific set of ecological triggers or conditions that may in fact never occur (this is why many exotic species are relatively innocuous under some environmental conditions). Determining if either phase has occurred is crucial to developing successful management strategies.

*Management assessment points:
Exotic plant dispersal*

- Any new species of exotic plant detected on any plot
- Existing exotic plants detected in any additional plots

Values are based on professional judgment of authors and Saguaro NP Resource Management staff (see Acknowledgements).

*Management assessment points:
Exotic plant invasion*

- Exotic plant cover is >5%
- Buffelgrass cover is >1%
- Red brome cover is >1%

Values are based on professional judgment of authors and Saguaro NP Resource Management staff (see Acknowledgements).

1.5.4 Plant community resistance and resilience

Resistance is the ability of an existing plant community to survive and persist following disturbance or acute stress, whereas *resilience* is the ability to recover through recruitment after the event has occurred (Enright et al. 2014). In combination, resistance and resilience provide insights into plant community stability—the degree to which species composition and biomass following perturbation will reflect prior conditions (Grime et al. 2000). We apply this concept to altered

disturbance regimes (e.g., fire outside historic regimes, see 1.5.6) and environmental stress (such as extreme weather events and drought) as they influence terrestrial vegetation, with a particular focus on the potential consequences of climate change.

Whereas there is a near consensus amongst scientists as to the occurrence, causes, mechanisms, and broad-scale ecological consequences of global climate change, rates and patterns at finer spatial and temporal scales can be challenging to predict at present (IPCC 2007). The Assessment of Climate Change in the Southwest United States (Overpeck et al. 2013) predicted with high or medium-high confidence that the southwestern United States (including Casa Grande Ruins NM) will sustain increased drought and heat extremes and decreased available water resources due to climate change. Positive feedback cycles with drought, fire, and insect outbreaks are forecast, as are increased occurrence of extreme weather events (Overpeck et al. 2013).

*Management assessment points:
Plant community resistance and resilience*

- Dead plant cover in field layer (<0.5 m height) is >15%
- Dead plant cover in subcanopy layer (>0.5 m height) is >5%

Values are professional judgement of authors and Saguaro NP Resource Management staff (see Acknowledgements).

1.5.5 Saguaro cacti occurrence and potential

The saguaro cactus (*Carnegie gigantea*) is the iconic plant species of the northern Sonoran Desert, which includes Casa Grande Ruins NM. Recruitment of this long-lived columnar cactus generally requires the occurrence of “nurse plants”—small trees and shrubs that facilitate saguaro recruitment during the critical early stages of development of this long-lived species. The canopies of nurse plants provide protection from climate extremes for young saguaros, particularly extended freezing events (Steenbergh and Lowe 1977).

Terrestrial vegetation and soils data provide information on saguaro occurrence and density, and also address the question of whether nurse-plant conditions are sufficient to support new cohorts of saguaros. This is achieved by monitoring the foliar cover of nurse plants.

*Management assessment points:
Saguaro cacti occurrence and potential*

- Nurse plant cover is <10% (trees and shrubs above 2.0 m height)
Values are professional judgement of authors and Saguaro NP Resource Management staff (see Acknowledgements).

1.5.6 Altered fire regimes

Recent invasions of non-native exotic grasses, such as buffelgrass (*Cenchrus ciliaris*) and, to a lesser extent, the annual, red brome (*Bromus rubens*), into low and mid-elevation plant communities within the Sonoran Des-

ert ecoregion has dramatically increased the frequency, extent, and severity of wildfire by creating contiguous fuel loads in the generally bare patches between native plants (Olsson et al. 2012). Whereas buffelgrass is generally promoted by fire (Miller et al. 2010), most desert trees, shrubs, and, particularly, cacti, are poorly adapted to survive wildfire (McLaughlin and Bowers 1982). The result can be a type shift from native Sonoran Desert shrubland toward non-native grassland (Burgess et al. 1991; McDonald and McPherson 2013), with high mortality of saguaros (Rogers 1986), the Sonoran Desert's flagship species.

*Management assessment points:
Altered fire regimes*

- Herbaceous cover is >35%
Values are professional judgement of authors and Saguaro NP Resource Management staff (see Acknowledgements).

2 Methods

2.1 Response design

The response design for this protocol employs permanent, 20 × 50-meter sampling plots (Figure 2-1). The 50-meter edges of the plot run parallel with the contours of the site. Vegetation sampling is done in conjunction with soil cover and stability measures along six transects within the plot. In the spaces between transects (subplots), within-plot frequency is estimated by noting the occurrence of any perennial or non-native annual plant species or lifeform not observed on the adjacent transects. See Hubbard and others (2012) for details on plot configuration and data collection.

2.1.1 Soil and site characterization

Proximate soil and landform factors are known to influence vegetation and dynamic soil function at local scales (McAuliffe 1999). To characterize the soil and landscape attributes of each plot, a suite of topodaphic variables was collected through site diagrams, repeat photo points, and collection of a soil core (only during plot establishment). Landform and slope position, type, and inclination (%) were recorded at each plot. Erosion features were described by estimating broad areal percentage classes of areas affected by tunneling, sheets, rills, gullies, pedestals, terracettes, and burrowing. Permanent photo points were established at each plot corner to characterize general site physiognomy and as an aid to interpreting quantitative trend data in successive sampling periods. In addition, general site descriptions (including observed disturbances, such as fire) were collected for each plot.

At the time of plot establishment, three soil cores were collected at a pre-determined random location within the plot, with alternate random locations sampled if pre-determined locations were not suitable. The soil-core collection followed the compliant cavity method (Blake and Hartge 1986). Cores were approximately 10 centimeters deep and 10 centimeters in diameter. These soil samples

were returned to a lab, where they were processed to determine bulk density, rock-fragment content, soil texture, total organic content, electrical conductivity (EC), and pH (Hubbard et al. 2012).

2.1.2 Vegetation and soil cover: Line-point intercept

Line-point intercept is a common and efficient technique for measuring the vegetation cover of plants. Line-point intercept measures the number of “hits” of a given species out of the total number of points measured (Elzinga et al. 1998; Bonham 1989). Vegetation was recorded within three height categories along each of the six transects using the line-point intercept method, with points spaced every 0.5 meters (240 points total). The three height categories were field (0.025–0.5 m), subcanopy (>0.5–2.0 m), and canopy (>2.0 m) (Table 2-1). Perennial vegetation was recorded to species. Annual vegetation was recorded to lifeform, with the exception of annual non-native plants, which were recorded to the species level.

Table 2-1. Height categories for vegetation measurement.

Category	Height
Field	0.025–0.5 m
Subcanopy	>0.5–2.0 m
Canopy	>2.0 m

Soil cover was recorded by substrate class (e.g., rock, gravel, litter, woody debris; see SOP #5, Hubbard et al. 2012). Litter and woody debris were recorded to fuel type (fine fuels [litter], 1-hour fuels, 10-hour fuels, 100-hour fuels, 1,000-hour fuels; Deeming et al. 1977). Biological soil crust cover was recorded to morphological group (light cyanobacteria, dark cyanobacteria, lichen, moss/bryophyte).

Vegetation and soil cover are reported as percent cover (points hit/points sampled, i.e., 240), with standard error and the minimum detectable change (MDC) given the estimated statistical power of the study design.

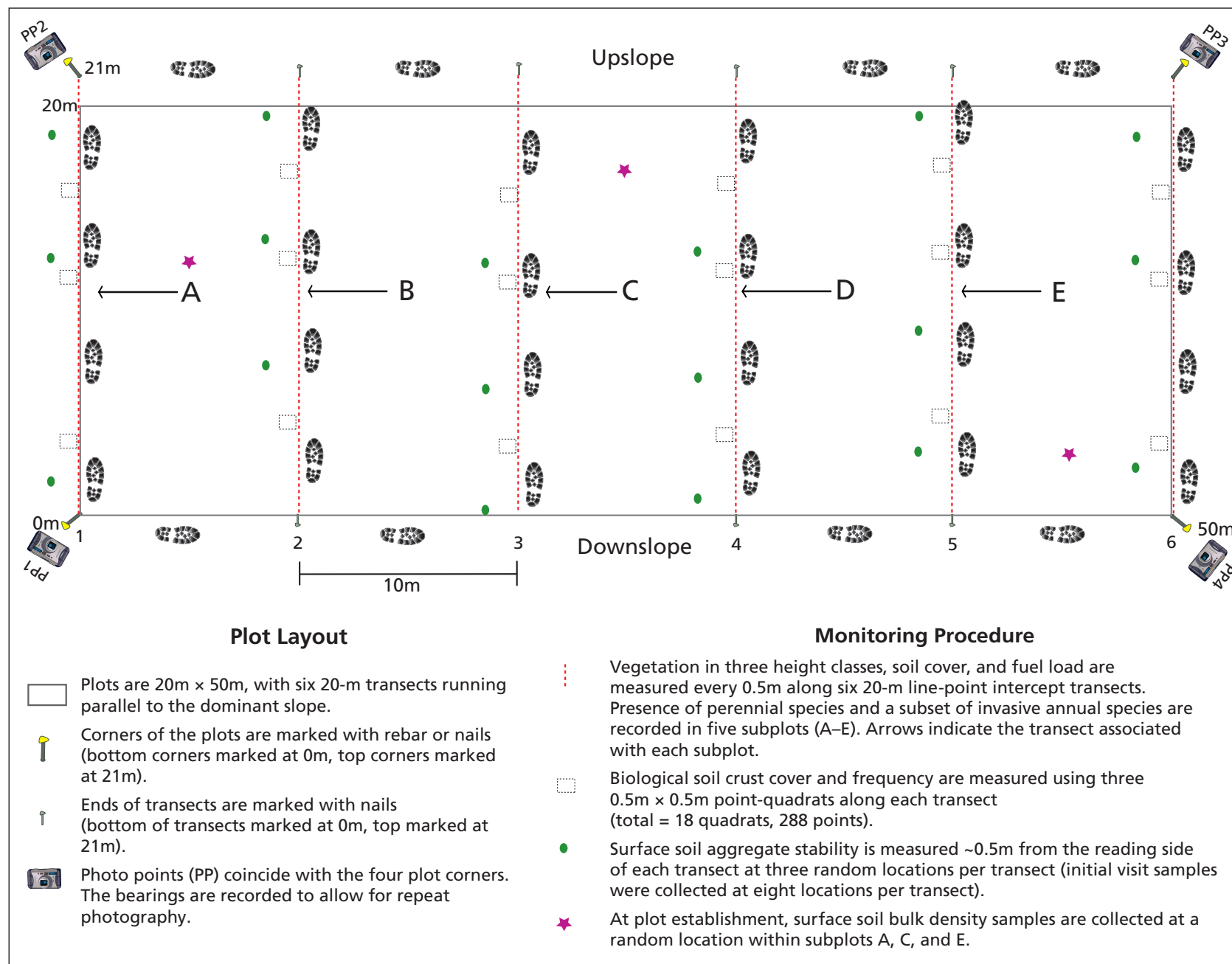


Figure 2-1. Terrestrial vegetation and soils monitoring plot design. See Hubbard and others (2012) for additional details on design and data collection.

2.1.3 Vegetation frequency and density: Subplots

The area between any two adjacent transects formed the boundary of 10 × 20-meter subplots used to estimate within-plot frequency of perennial plant species and annual non-native plant species. The occurrence of any species that was not measured on the adjacent line-point transect was recorded to determine a within-plot frequency based on number of subplots occupied relative to the total number of subplots (i.e., 5). In addition, within each subplot, individual columnar cacti and ocotillo (*Fouquieria splendens*) were counted by height class to estimate density for these select species.

2.1.4 Soil aggregate stability

Surface soil aggregate stability was measured using a modified wet aggregate stability method (Herrick et al. 2005a). Within each plot, samples were collected at a total of 48 (first visit) or 18 (second visit) pre-determined points along the line-point intercept transects (see Figure 2-1). The dominant vegetation canopy cover and substrate cover at each point were determined. A uniformly sized (approximately 2–3 mm thick and 6–8 mm on each side) soil sample was collected at each pre-determined point. Each sample was placed on a screen and soaked in water for five minutes. After five minutes, the samples were slowly dipped up and down in the water, with the remaining amount of soil recorded as an index of the wet aggregate stability of the sample. Samples were scored from 1 to 6, with 6 being the most stable

(Herrick et al. 2005a; Table 2-2).

2.1.5 Biological soil crust cover and frequency: Point-quadrats

In addition to line-point intercept measurements, biological soil crust cover was measured using 0.25-m² quadrats. Three quadrats were measured per transect using the point-quadrat method (similar in concept to line-point intercept), with 16 intercept measurements per quadrat, resulting in 18 quadrats and 288 measurements per plot. At each intercept, biological soil crusts were recorded as light cyanobacteria, dark cyanobacteria, bryophytes (moss or liverwort), and lichens by growth form (crustose, gelatinous, foliose, fruticose, and squamulose). The observer then visually surveyed the quadrat for all morphological groups or lichen growth forms that were present. Biological soil crust frequency by lichen growth form and morphological group was determined by the number of quadrats occupied relative to the total number of quadrats (i.e., 18). Biological soil crust cover are reported at the plot-scale as percent cover (# points hit/# points sampled [i.e., 288]).

2.2 Sampling design

In 2008, we allocated six monitoring plots to Casa Grande Ruins NM and the proposed Adamsville unit on nearby state land (3 each), based on a priori expectations of required sample size to meet our criteria for statistical power and detectability. Results from that initial effort are given in McIntyre

Table 2-2. Categories for aggregate stability of surface soils.

Class	Category	Criteria
1	Very unstable	50% of structural integrity lost (melts) within 5 seconds of immersion in water AND <10% of soil remains on sieve after 5 dipping cycles, OR soil too unstable to sample (falls through sieve)
2	Unstable	50% of structural integrity lost (melts) within 5–30 seconds of immersion in water AND <10% of soil remains on sieve after 5 dipping cycles
3	Somewhat unstable	50% of structural integrity lost (melts) within 30–300 seconds of immersion in water OR <10% of soil remains after 5 dipping cycles
4	Moderately stable	10–25% of soil remains on sieve after 5 dipping cycles
5	Stable	25–75% of soil remains on sieve after 5 dipping cycles
6	Very stable	75–100% of soil remains on sieve after 5 dipping cycles

Modified from Herrick and others (2005a).

and others (2011). The Adamsville unit plots were dropped in 2011, at the behest of park management, and three new monitoring locations were randomly located on areas of the park that are subject to continuing disturbance related to stabilization efforts on various archeological sites (see Section 1.4.2.3). Therefore, a total of six permanent sampling plots comprise the long-term monitoring design for the park. Hereafter, the original three plots (1, 2, 3) are referred to as “monitoring plots.” The three additional plots (C, D, G) are referred to as “stabilization plots” (Figure 2-2).

The permanent sampling plots are revisited on five-year intervals for both monitoring plots (e.g., 2008–2013) and stabilization plots (e.g., 2011–2016). If a major disturbance (e.g., fire, extended periods of temperature extremes, mass soil movement) occurs in the intervening years, we may collect additional plot data to characterize and account for the potential effects of these important stochastic events.

2.2.1 Sampling frame for monitoring plots

The sampling frame for monitoring plots at Casa Grande Ruins NM includes all terrestrial areas within park boundaries, except for the following (see Figure 2-2):

- Roads, buildings, parking areas, and the visitor picnic area (including 100-m buffer)
- Selected cultural features (e.g., Compounds A and B, Great House).

The total area excluded under these criteria was 36% of the total park area.

Because they were selected intentionally instead of randomly, the stabilization plots did not utilize this design.

2.2.2 Stratification

SODN terrestrial vegetation and soils monitoring plots are allocated using a combination of elevation intervals and soil rock-fragment

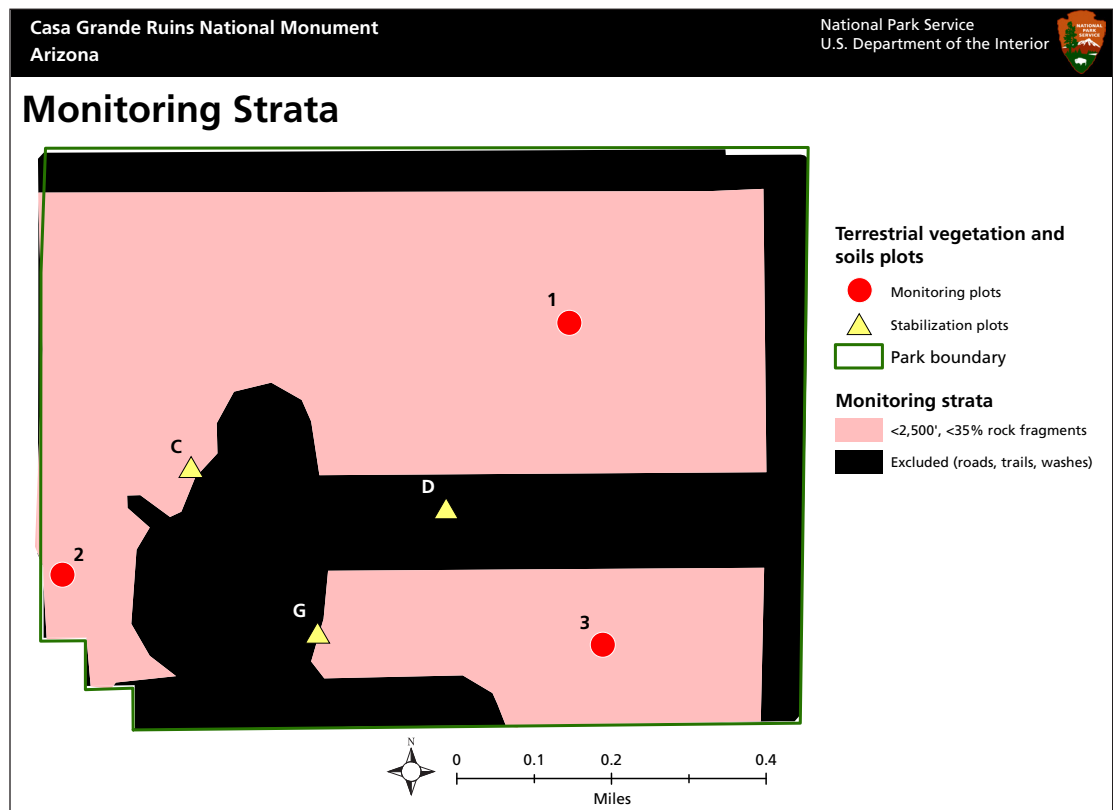


Figure 2-2. Sampling frame, strata, and plot locations for terrestrial vegetation and soils monitoring at Casa Grande Ruins National Monument.

classes (Hubbard et al. 2012). All areas within Casa Grande Ruins NM occur within one stratum: non-rocky valley-bottom (<2,500' elevation, <35% surface soil rock fragments. This is known as stratum 101.

Inference from the monitoring plots at Casa Grande Ruins NM is to all terrestrial areas of the monument, except the excluded areas discussed in Section 2.2.1. Inference for the stabilization plots is limited to the specific sites where the plots occur.

2.2.3 Spatial balance

The spatial sampling design for this protocol employs permanent plots, allocated through a Reversed Randomized Quadrant-Recursive Raster (RRQRR) spatially balanced design (Theobald et al. 2007), using the “spatially balanced sample” function in the STARMAP Spatial Sampling Toolbox in ArcGIS 9.0 (<http://www.spatialecology.com/htools/index.php>). This tool produces a design that is spatially well-balanced, probability-based, flexible, and simple (Theobald et al. 2007). Because it tries to maximize the spatial independence between plots, the spatially balanced sampling design should provide more information per plot, thus increasing efficiency (Theobald et al. 2007).

2.3 Analyses

2.3.1 Statistical power to distinguish status from management assessment points

Estimating our statistical power to distinguish current conditions (status) from management assessment points (see Section 1.5) is important for both protocol design (especially for determining adequate sample sizes) and data interpretation. Adequate sample size (number of plots) is estimated by (Herrick et al. 2005b):

$$n = \frac{(S)^2 (Z_{\alpha} + Z_{\beta})^2}{(MDC)^2}$$

Where:

S= Standard deviation of the sample

Z_{α} = Z-coefficient for false-change (Type I) error (we set at 90%)

Z_{β} = Z-coefficient for missed-change (Type II) error (we set at 10%)

MDC = minimum detectable change from the assessment point (set at 5–20%).

Bonham (1989), Elzinga and others (1998), and Herrick and others (2005b) provide detailed discussions of statistical power to detect differences from a standard.

2.3.2 Statistical power to detect trends

Statistical power is also important for evaluating trends (change over time) in monitoring parameters. Adequate sample size (number of plots) for detecting a trend of a given size across a landscape with permanent plots is estimated from (Herrick et al. 2005b):

$$n = \frac{(S_{diff})^2 (Z_{\alpha} + Z_{\beta})^2}{(MDC)^2}$$

Where:

S_{diff} = Standard deviation of the differences between paired samples

Z_{α} = Z-coefficient for false-change (Type I) error (we set at 90%)

Z_{β} = Z-coefficient for missed-change (Type II) error (we set at 10%)

MDC = minimum detectable change size between time 1 and time 2 (set at 5–20%).

Bonham (1989), Elzinga and others (1998), and Herrick and others (2005b) provide detailed discussions of statistical power to detect trend.

2.3.3 Diversity of perennial plants

Biodiversity is a primary focus of ecological research, and maintaining native biodiversity is a central tenet of natural resource conservation (Keddy 2007). Diversity indices can provide an indicator of the ecological well-being of an ecosystem, and are well-established measures in ecology. See Izsák and Papp (2000) and Warwick and Clarke (1995) for two of many published overviews of traditional indices, their assumptions, and their limitations.

There are three major limitations for utilizing traditional diversity indices in an ecological monitoring context:

1. Sampling effort has a large influence on diversity measures, restricting valid comparisons to sites with consistent methods and effort.
2. Phylogenetic diversity is not reflected in the measure (i.e., two species in the same genera count as being equally “diverse” as two species from different orders).
3. There are no statistical approaches for testing departure from expected diversity and potential effects of human perturbation (Warwick and Clarke 1995).

We standardize sampling effort by using average within-plot species richness (S_{plot}) as a proxy for perennial plant species diversity. Because it is dependent on sample effort (which is constant between plots but will vary by the number of plots per stratum and park), the within-plot species richness, (S_{plot}) is an index of diversity rather than “true” species richness.

2.3.4 Vegetation formations

Vegetation formations (Keddy 2007) describe the overall structure of a plant community

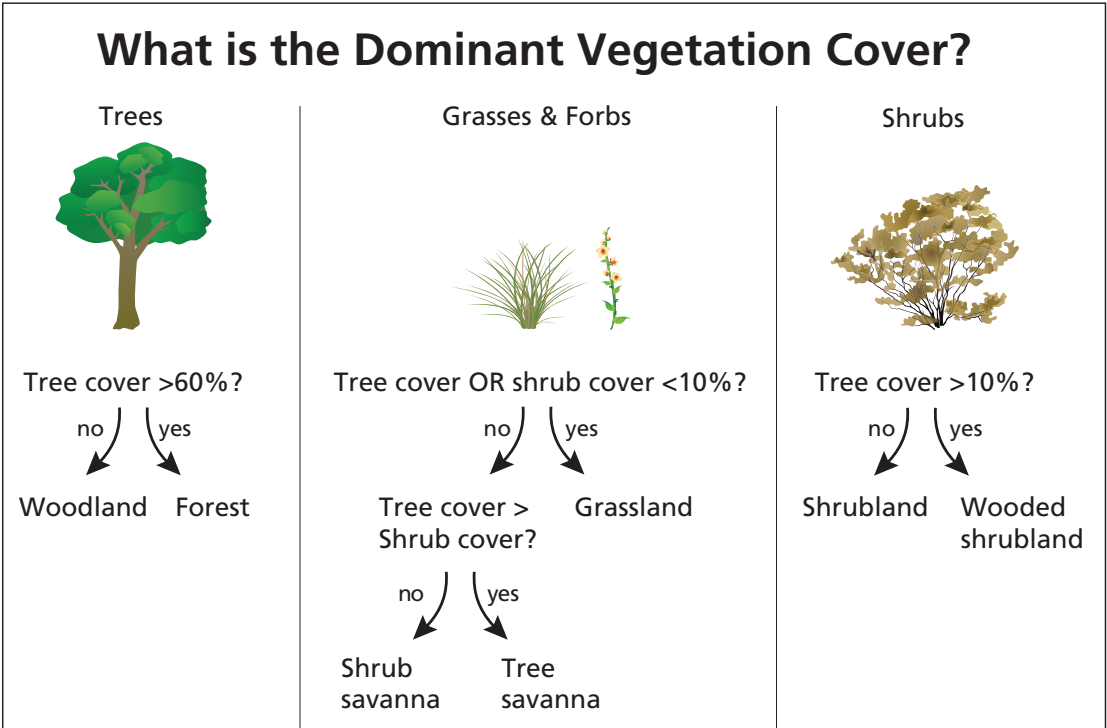
from the perspective of lifeforms rather than species (e.g., “perennial bunchgrasses” vs. *Bouteloua curtipendula*). We use formations to provide additional detail and context for understanding the conditions of monitoring sites and as a linkage to vegetation mapping and other landscape-scale research and monitoring applications. A key for determining vegetation formations is provided in Figure 2-3.

2.3.5 Change detection

Potential changes in vegetation similarity over time were evaluated using permutational multivariate analysis of variance on similarity matrices (PERMANOVA+) in the PRIMER (v.7) analysis package. This non-parametric multivariate community analytical approach makes few assumptions about the data, yielding a simple yet powerful analysis tool (Clarke and Warwick 2001).

We tested for potential changes in univariate data (e.g., cover of individual species, lifeforms, soil substrate types, and biological soil crust morphological groups) between time 1 and time 2 using paired t-tests (Zar 1999). In the future, we will develop and apply general linear models and regression tools to evaluate potential trends beyond two sampling periods (Crawley 2013).

Figure 2-3. Schematic of key to vegetation formations in Sonoran Desert Network parks (follows Studd et al. 2013). Symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).



3 Results

3.1 Site characterization

At establishment, surface soil texture for five plots was sandy loams. Stabilization plot D was sandy clay loam (higher clay content compared to other plots). pH of the surface soils was 8.2–8.3 for monitoring plots and 7.9–8.0 for stabilization plots. Bulk density of surface soils was 1.2–1.6 g/cm³ on monitoring plots and 1.4–1.5 g/cm³ on stabilization plots. At establishment, all plots had evidence of burrowing (<5% of plot affected). On revisit, burrowing was observed at the same level for all plots except stabilization plot C.

3.2 Vegetation formations, lifeforms, and perennial plant diversity

Monitoring plots and stabilization plots both contained sparse shrublands (Figure 3-1) composed of shrubs in a very sparse and highly variable mix of annual forbs and grasses, which coincided with the vegetation types mapped during the characterization effort (see Figure 1-4). Although annual forb cover decreased by nearly 9% (absolute) and annual grass cover decreased by roughly 8% on monitoring plots, these changes were not significant ($P > 0.20$), perhaps due to a near absence of annuals on monitoring plot 2. Although our initial goal was to detect a 10% change, we estimate we can only detect a 15–16% absolute change in annuals with our three monitoring plots.

Annual plants were absent on the stabilization-plot transects in 2011, but annual grasses were encountered on two stabilization plots in 2016. All other lifeforms were absent, with the exception of a trace amount (<1%) of tree cover on stabilization plot G.

No vegetation over two meters in height was detected on monitoring or stabilization plots; the majority of foliar cover was below 0.5 meters (Figure 3-1). No cover of any vegetation lifeform changed over time on monitoring ($P \geq 0.20$) or stabilization ($P \geq 0.15$) plots. Average within-plot perennial species richness (S_{plot}) was 1.3 ± 0.3 for monitoring plots in 2013 and 1.5 ± 0.3 for stabilization plots in 2016. S_{plot} did not change over time ($P =$ un-

defined and $P = 0.42$, respectively).

3.3 Cover and extent of perennial plant species

Common perennial species on monitoring plots were limited to the shrub, creosotebush (*Larrea tridentata*; see Figure 3-1), which was found on all three plots in both 2008 and 2013. Cover of this species was fairly evenly split between field ($8.2\% \pm 1.8$) and subcanopy (7.5 ± 1.5) layers. Stabilization plots had similar creosotebush cover across all three plots in 2011 and 2016 (Figure 3-1; $6.5\% \pm 3.7$ in field and $8.1\% \pm 5.1$ in subcanopy), with the additional subdominant Fremont's desert-thorn (*Lycium fremontii*) found on plot D only. No other perennial plant species were detected along line-point transects of any plot during any sampling period. Mesquite (*Prosopis velutina*) was detected on one point of plot D in 2011, but was not detected on any line-intercept points in 2016. Vegetation cover did not change over time for any species on monitoring ($P \geq 0.29$) or stabilization ($P \geq 0.25$) plots.

3.4 Frequency and extent of uncommon plant species

One uncommon perennial plant species—the succulent, candy barrelcactus (*Ferocactus wislizeni*)—was detected on two subplots of monitoring plot 2 in both 2008 and 2013, resulting in an average within-plot frequency of $13\% \pm 13$ across the monitoring plots. The shrub, cattle saltbush (*Atriplex polycarpa*), occurred on all five subplots of stabilization plot C in 2011 ($33\% \pm 33$), and 4 of 5 subplots in 2016 ($27\% \pm 27$). No other perennial plant species were detected in any subplots on any monitoring sites over all sampling periods.

3.5 Cover and frequency of exotic species

No exotic species were detected along line-point transects or within subplots on any plot during any sampling event.

3.6 Soil cover

Within the monitoring plots, soil substrate cover along the line-point intercept transects was dominated by biological soil crusts, with

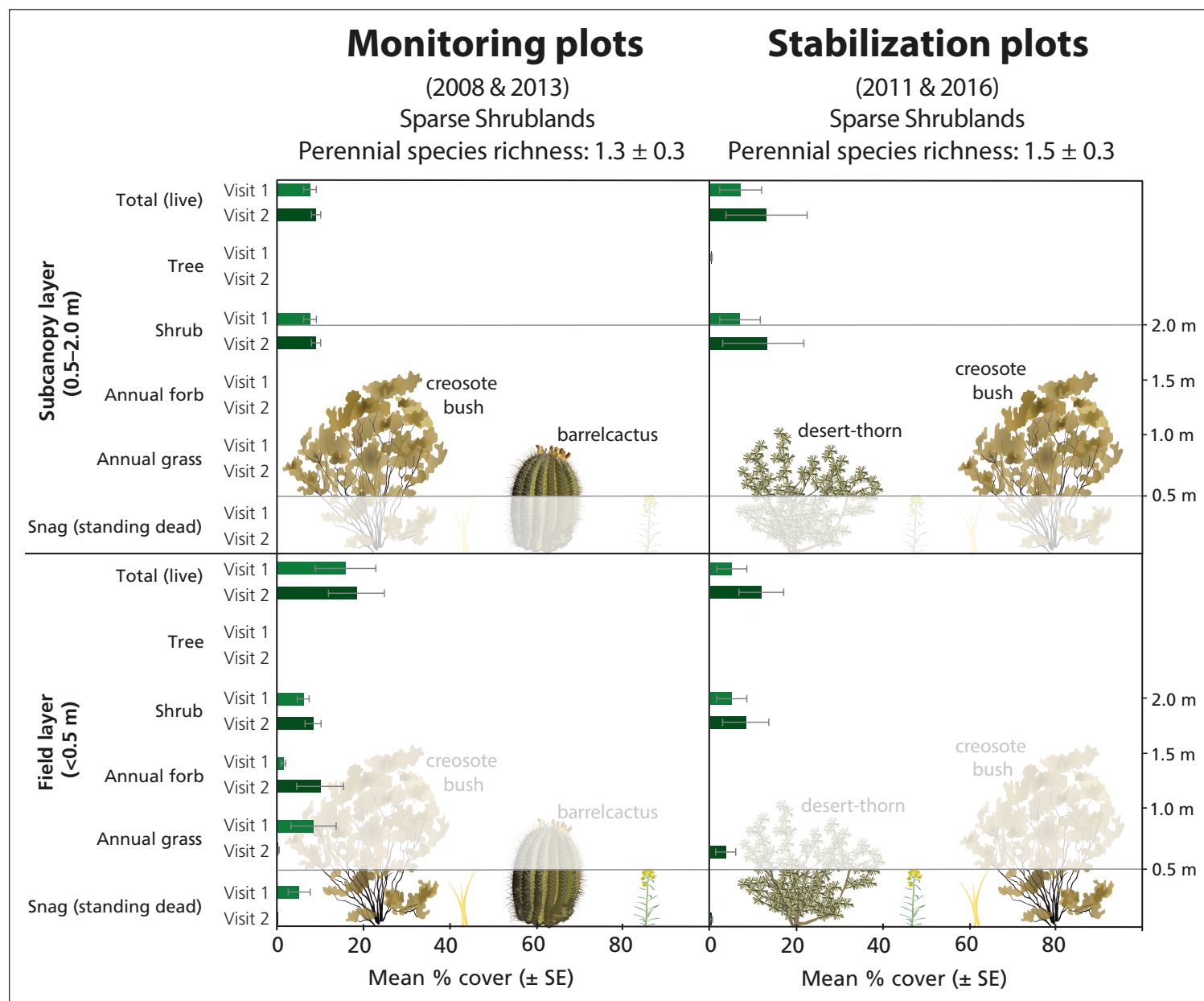


Figure 3-1. Lifeform cover in field (<0.5 m height) and subcanopy (0.5–2 m) layers of terrestrial vegetation monitoring plots at Casa Grande Ruins National Monument, 2008–2016. There was no cover above two meters in height. Lifeform cover ($P \geq 0.15$) did not change over time. Plant symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

light cyanobacteria biocrusts dominant. Exposed soil without overhead vegetation and gravel (2–75 mm diameter) were also common, whereas rocks (>75 mm diameter), plant bases, and medium-to-heavy fuels were absent or nearly so (Figure 3-2a). By contrast, exposed bare soil (without overhead vegetative cover) was much higher on stabilization plots, comprising half of the cover on these locations (Figure 3-2b). Soil substrate cover did not change over time for monitoring plots ($P \geq 0.09$) or stabilization plots ($P \geq 0.08$).

3.7 Biological soil crusts

Biological soil crusts were measured using two methods: line-point intercept transects and point-quadrats (see Sections 2.1.2, 2.1.5). Within the point-quadrats, light cyanobacteria dominated the biological crust community across the monitoring and stabilization plots, with dark cyanobacteria and lichens as important subdominants (Figure 3-3). Although the monitoring plots had more light cyanobacteria, the cover of mature biological soil crusts (dark cyanobacteria, lichens, and bryophytes) in available habitat was similar between the monitoring (Figure 3-3a; 15%) and stabilization (Figure 3-3b; 14%) plots. Notably, the cover of gelatinous lichens was higher on the monitoring plots ($5\% \pm 4$) compared to the stabilization plots ($0.2\% \pm 0.2$), but the difference was not significant ($P = 0.3$). Biological soil crust cover was highly variable within the plot types and did not change over time for either monitoring ($P \geq 0.29$) or stabilization ($P \geq 0.16$) plots.

3.8 Soil stability

Mean surface soil aggregate stability on monitoring plots was moderately stable to stable (4.9 ± 0.2) and did not change ($P = 0.37$) since the original sampling in 2008. Surface aggregate stability on stabilization plots was somewhat unstable to moderately stable (4.0 ± 0.1), and also did not change over time ($P = 0.16$).

3.9 Management assessment points

Management assessment points (see Section 1.5) identified several issues of potential concern (Table 3-1, see Figure 4-4). Erosion hazard due to the prevalence of exposed bare soil was identified as a potential issue of management concern on the recently manipulated stabilization plots. In particular, plots C and G had 63% and 53% cover of bare soil without overhead cover, respectively.

The cover of mature biological soil crusts (dark cyanobacteria, lichen, and mosses) could not be differentiated from the assessment point on either monitoring or stabilization plots. Mature biological soil crust cover was less than 10% on two of the three monitoring plots, whereas the third plot (2) had 35% cover. Conversely, two of the stabilization plots had mature biological soil crust cover of ~20%, whereas the third plot (C) had <1%.

Saguaro cacti recruitment was also of potential concern on both monitoring and stabilization plots. The absence of any nurse plants (such as velvet mesquite or yellow paloverde; *Parkinsonia microphylla*), coupled with the absence of any existing saguaros, indicates a lack of likely establishment by this iconic Sonoran Desert plant (Table 3-1).

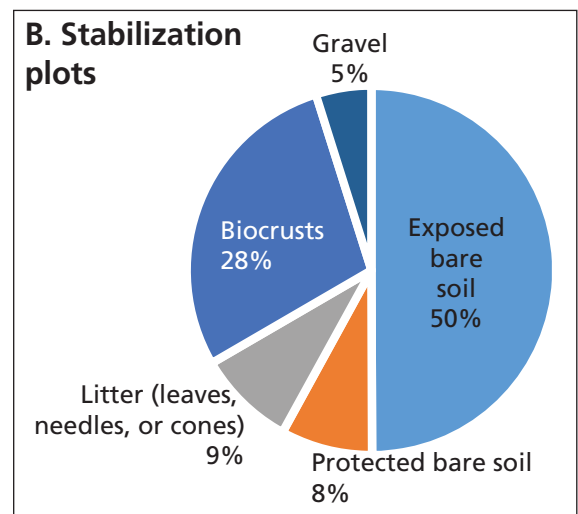
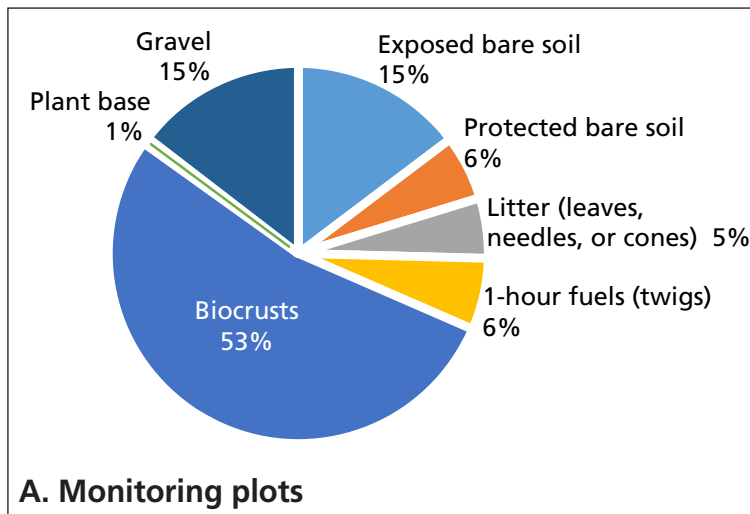


Figure 3-2. Soil substrate cover for (A) monitoring plots (2013), and (B) stabilization plots (2016), Casa Grande Ruins National Monument.

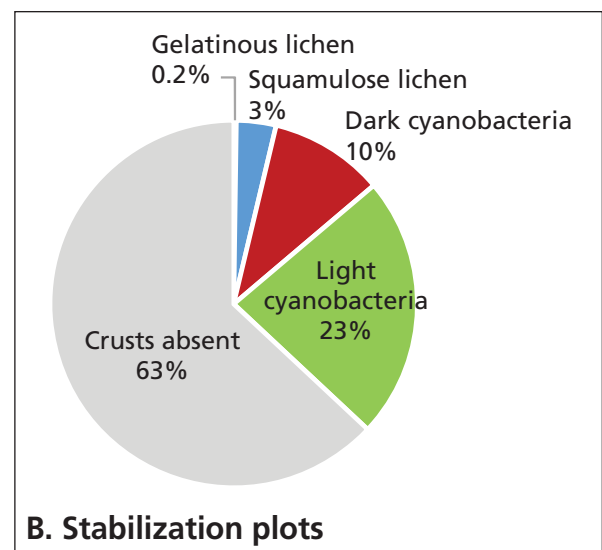
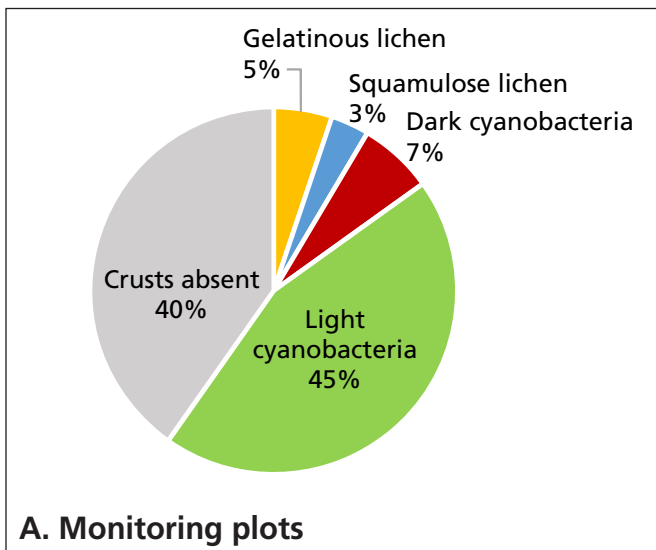


Figure 3-3. Biological soil crust cover, by morphological group and lichen growth form, within available habitat on (A) monitoring plots (2013) and (B) stabilization plots (2016), Casa Grande Ruins National Monument.

Table 3-1. Terrestrial vegetation and soils data for non-rocky valley bottom monitoring plots and stabilization plots in the context of management assessment points, Casa Grande Ruins National Monument, 2008–2016.

Assessment point	Metric	Monitoring plots	Stabilization plots
Site stability and erosion potential	Cover (%) of exposed bare soil is >20%	15% +/- 3	50% +/- 11*
	Surface soil aggregate stability is <Class 3 (moderately stable)	4.9 +/- 0.2	4.0 +/- 0.1
Biological soil crusts	Mature biological soil crust cover is <10% of available habitat	15% +/- 10**	14% +/- 7**
Exotic plant dispersal	Any new species of exotic plant detected on any plot	None	None
	Existing exotic plants detected in any additional plots	None	None
Exotic plant invasion	Exotic plant cover is >5%	0%	0%
	Buffelgrass cover is >1%	0%	0%
	Red brome cover is >1%	0%	0%
Plant community resistance and resilience	Dead plant cover in field layer is >15%	0.1% +/- 0.1	0.3% +/- 0.3
	Dead plant cover in subcanopy layer is >5%	0.1% +/- 0.1	0%
Saguaro cacti occurrence and potential	Nurse plant cover is <10% (trees and shrubs above 2.0 m height)	0%*	0%*
Altered fire regimes	Herbaceous cover is >35%	10% +/- 5	4% +/- 2

*Results are of potential concern (also in red font).

**Results cannot be differentiated from the assessment point (also in orange font).

See Table 2-1 for height classes.

4 Discussion

4.1 Groundwater depletion and vegetation change

Although vegetation composition and abundance at Casa Grande Ruins NM have remained essentially unchanged since our first monitoring efforts in 2008, a broader temporal perspective indicates tremendous change since park establishment. As discussed previously (McIntyre et al. 2011), the last “bit of typical desert land” Frank Pinkley described in 1924 (as related by Clemensen 1992) changed dramatically during the twentieth century. Park records and early visitor accounts describe velvet mesquite (*Prosopis velutina*) woodlands or “bosque” interspersed with native desert shrublands (Clemensen 1992). This is in stark contrast to the recent vegetation mapping effort at the monument (Buckley et al. 2009), which documented only 212 mesquite trees outside maintained areas of the monument—and these were low-growing shrubs, rather than the large trees that characterize mesquite bosques.

By the end of the 1930s, descriptions of accelerating mesquite mortality on the monument were common (Reichhardt 1992), with vegetation shifting sharply toward a near monoculture of creosotebush (*Larrea tridentata*). The homogeneity of the 2009 vegetation map results (Buckley et al. 2009) and our 2008–2016 vegetation monitoring data indicate the apparent endpoint (or at least recent stability) of this directional change: low-diversity desert shrublands (Figure 4-1).

The likely driver of this dramatic change is rapid depletion of local groundwater after the widespread introduction of centrifugal water pumps in the valley during the mid-20th century (Clemensen 1992). The scale of groundwater extraction—effectively, groundwater mining under current climate regimes—is illustrated by soil subsidence (drop in elevation due to collapsing pore space) of as much as a meter in the area by 1978 (Reichhardt 1992). Prior to extensive groundwater pumping, established mesquite trees were tapping a relatively shallow groundwater table, due



Figure 4-1. Typical current vegetation at Casa Grande Ruins National Monument. Annual forbs are common during the winter rainy season. Note dead mesquite tree (*Prosopis velutina*) in the foreground.

to the proximity of the park to the Gila River floodplain. Mesquite is capable of hydraulic lift (Scott et al. 2008), a process by which water in deep soil layers is transported to shallow layers via roots (Caldwell et al. 1998). Enhanced soil moisture in surface soils, combined with reduced air and soil temperatures under tree canopies, would provide a comparatively cool, moist microclimate that could favor establishment of “clusters” of other plants (Brown and Archer 1999) around mature mesquite.

Although a hardy, long-lived species capable of phreatophytic (deep-rooted) root architecture, mature mesquite trees lack the morphological plasticity to shift root allocation quickly enough to keep pace with very rapid changes in groundwater depth (Hubbard 2003). Mesquite currently occurring within the monument are scattered and shrubby, likely persisting only on recent precipitation rather than access to a near-surface water table. With the dramatic decrease in large, mature mesquite trees, the relatively cool and moist microclimates under tree canopies (supported by shading and hydraulic lift) would have rapidly disappeared. The net result has been desertification of the monument’s vegetation since park establishment.

4.2 Surprisingly low perennial plant diversity (and almost no saguaros)

Beyond the dramatic shift to creosotebush shrublands, the exceedingly low diversity of perennial plants at Casa Grande Ruins NM was surprising, even for these comparatively arid valley-bottom locations. Although several species of native desert vegetation occur around the visitor center and other park infrastructure, they are composed of landscaping plants, planted and tended by park staff (see Figure 1-4; Buckley et al. 2009). Natural perennial vegetation is almost exclusively creosotebush, with occasional barrelcactus and desert-thorn. Saguaro cacti, an iconic Sonoran Desert plant commonly found on valley-bottom locations, was absent from all plots and nearly so within the monument, with a few tended plants within the landscaped areas. Similarly, nurse plants, primarily mesquite and paloverde trees, which protect saguaro seedlings from climatic extremes, are greatly reduced on the monument since the early 20th century (Section 4.1).

Non-rocky valley bottoms are found throughout the Sonoran Desert, including large areas of Organ Pipe Cactus NM, Saguaro NP, Cabeza Prieta National Wildlife Refuge

(NWR), and Kofa NWR. This vegetation and soils monitoring protocol is also conducted in these parks and refuges, with results that sharply contrast with the starkly low plant diversity at Casa Grande Ruins NM. In these other parks and refuges, within-plot perennial plant species richness was 3–10 times greater and generally tracked annual average (1981–2010) rainfall at valley-bottom locations (Figure 4-2). Casa Grande Ruins NM was an exception to these patterns.

Rainfall, air temperatures, seed availability, and, to a lesser extent, soils (see Section 1.4.2.1) are somewhat similar across these locations. So why might Casa Grande Ruins NM be unusually species-poor? We suspect that substantial prehistoric soil disturbance may be an important factor in the unusually low perennial plant diversity.

Although existing soil information for the monument is limited to the broad-scale county soil survey, the dominant soil type, Coolidge sandy loam (see Figure 1-2), is well-drained and likely to have been highly impacted by the intensive activities of the Hohokam. Construction of the canal system, irrigated fields, and the large, concentrated clusters of buildings during the Colonial (AD 950–1175) and Classic (AD 1175–1450) periods of the Hohokam likely entailed enormous excavation, modification, and movement of local soils—much as intensive human development activities do in modern times. Excavation of caliche, a dense carbonate clay layer common in desert soils (Schlesinger and Pilmanis 1998), for use in construction of the Great House likely entailed intensive soil disturbance.

These soil disturbances may have reduced effective soil water in the rooting zone by influencing infiltration and/or water-holding properties relative to undisturbed soils. Although our surface bulk-density data are not necessarily indicative of root-limiting conditions ($>1.85 \text{ g/cm}^3$; Muckel 2004) in the upper four inches, deeper compaction layers may exist. Many perennial plants that are adapted to the precipitation regime of the monument appear to be unable to survive and reproduce locally under current conditions. Sufficient soil water (the moisture available to the plant)

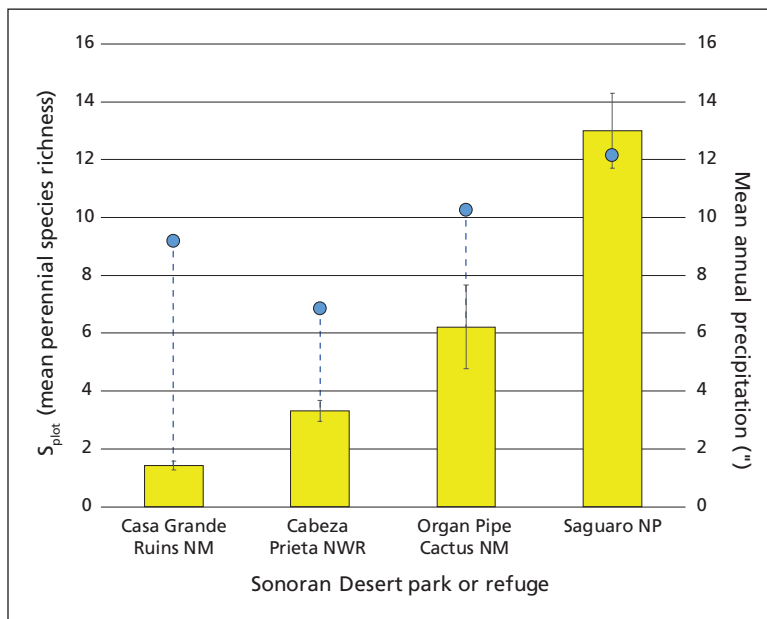


Figure 4-2. Mean annual rainfall (1981–2010; blue circles) and within-plot perennial species richness (S_{plot} ; mean $\pm$ SE, 2008–2016) for non-rocky valley bottom ($<2,500'$ elevation $<35\%$ surface soil rock fragments) plots on four Sonoran Desert parks and refuges that contain extensive areas of valley bottom. Species-richness data are from the SODN database. Climate data are from the NOAA Western Regional Climate Center (WRCC n.d.).

may be the key. We suggest some approaches for evaluating this question in Section 4.7 (#1 and #2).

4.3 Biological soil crusts and erosion hazards

Although perennial plant cover and diversity are unusually low at Casa Grande Ruins NM, the abundance of biological soil crusts is impressive, covering more than half of the available habitat. As we discussed in McIntyre and others (2011), biological soil crusts provide critical ecological services—in particular, mitigating soil erosion (Belnap 2003a) in the largely unvegetated expanse of the monument. Biological crusts—especially, light cyanobacteria—have colonized nearly 60% of the available soil habitat within the monument. This is among the highest rates we have observed on Sonoran Desert parks and refuges. Mature biological soil crusts occupy roughly 15% of available habitat within the monitoring plots (Figure 4-4, see Table 3-1), but cover within a plot was highly variable, ranging from <1% to 35%.

Other measures of soil erosion potential were similarly positive on monitoring plots, with relatively low cover of exposed bare soil (~15%; Figure 4-4, see Table 3-1) and high surface soil aggregate stability (4.9 ± 0.2 ; see Table 2-2). In combination with the nearly flat topography, our results suggest low potential for soil erosion under current conditions. This is good news for management of near-surface archeological sites. However, sites recently subjected to stabilization activities may require additional focus, as they had relatively high cover of exposed bare soil (~50%; Figure 4-4, see Table 3-1). A detailed inventory of biological soil crusts at Casa Grande Ruins NM would allow us to better understand their key ecological role at the monument (see Section 4.7, #3).

4.4 Stabilization plots vs. monitoring plots

Taken collectively, our results reflect the localized soil disturbance associated with recent stabilization of archeological sites. Overall biological soil crust cover was lower on stabilization plots (Figure 4-4, see Table 3-1). Annual plants, while fairly common on

monitoring plots, were nearly absent on stabilization plots (see Figure 3-1).

Variability in rainfall might account for the differences in annual production, although rainfall was similarly low over most of the sampling periods for both kinds of plots (Figure 4-3). On-site and nearby weather stations had substantial gaps during this period, so we report on modeled precipitation values from the PRISM climate group (PRISM 2018). Total water year (October–September) precipitation estimates were well below normal during the initial sampling of monitoring plots (2.18" below normal in 2008) and stabilization plots (2.58" below normal in 2011). Annual precipitation during the resampling of the monitoring plots was approximately normal (0.02" above normal in 2013), whereas the second round of sampling on stabilization plots was the second-driest year since monitoring began (2.58" below normal in 2016).

As previously noted, exposed bare soil was much higher on stabilization plots, exceeding the assessment point. Surface soil aggregate stability was only slightly less on stabilization plots than on monitoring plots (4.0 ± 0.1 vs. 4.9 ± 0.2).

The degree of exposed bare soil on stabilization plots (approximately half of the soil substrate) was the most concerning result

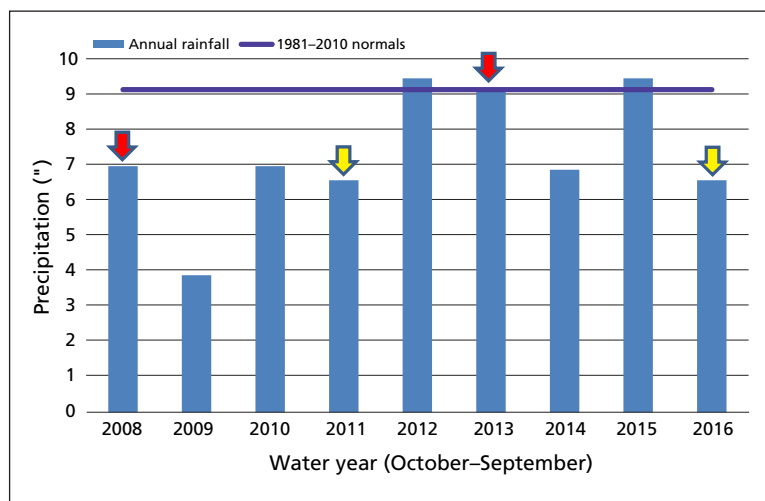


Figure 4-3. Estimated annual precipitation (") for Casa Grande Ruins National Monument, 2008–2016. Precipitation estimated from PRISM climate models as on-site weather stations had substantial data gaps. Arrows indicate years of sampling monitoring plots (red) and stabilization plots (yellow). Precipitation normals for 1981 to 2010 were determined by the NOAA Western Regional Climate Center.

Management Assessment Points Summary

Sonoran Desert Network Terrestrial Vegetation and Soils Monitoring Casa Grande Ruins National Monument, 2008–2016

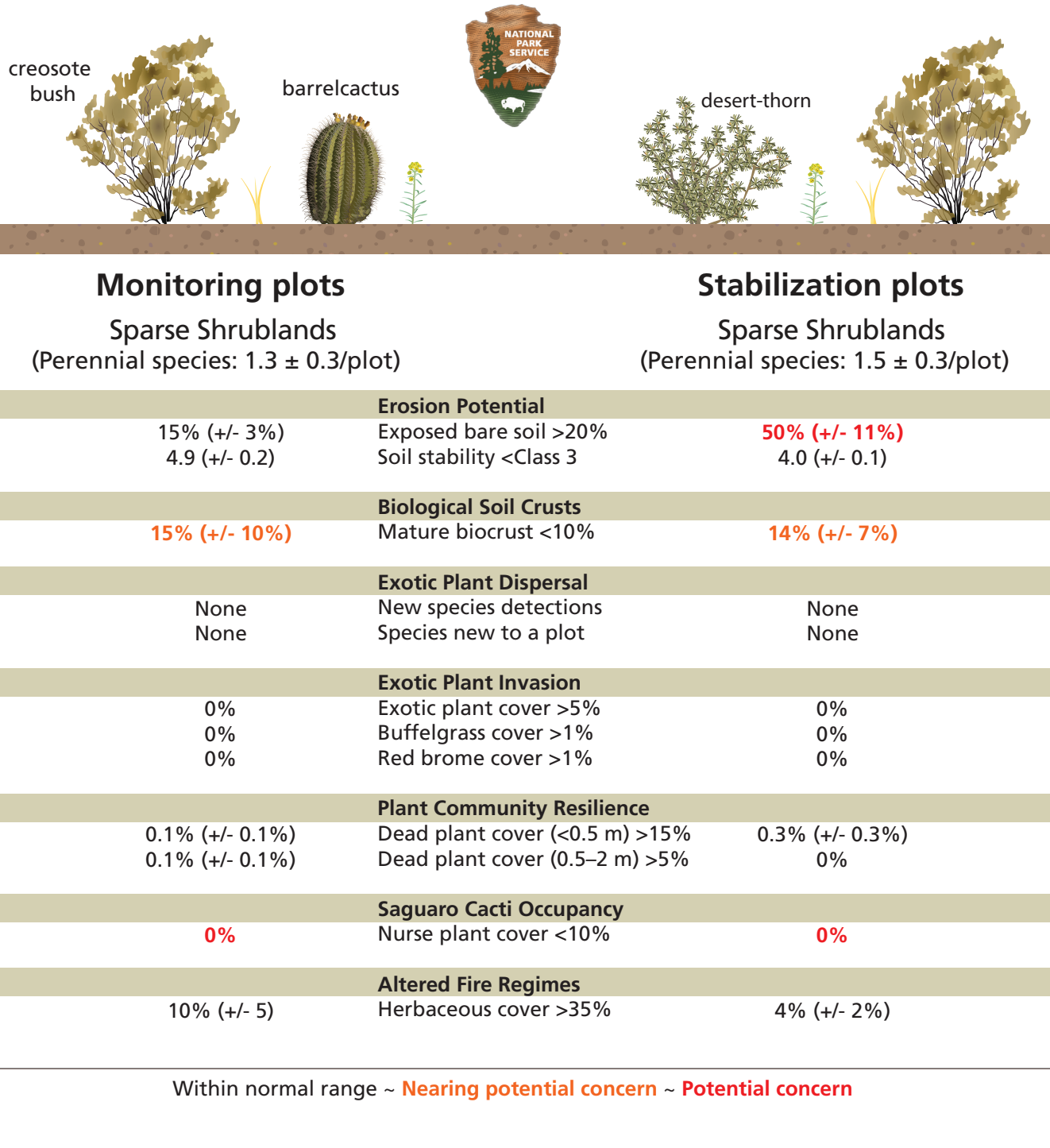


Figure 4-4. Terrestrial vegetation and soils summary for monitoring plots and stabilization plots in the context of management assessment points, Casa Grande Ruins National Monument, 2008–2016. Red results are of potential concern. Orange results cannot be differentiated from the assessment point. Plant symbols courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/). Data provided in this graphic can also be found in Table 3-1.

(Figure 4-4, see Table 3-1). Enhanced water and wind erosion may result. We suggest additional observation of soil conditions on these locations, particularly after major storm events.

4.5 Exotic plants, fire, and community resilience/resistance

Although SODN has documented 35 exotic plants at Casa Grande Ruins NM (Table 1-1), it is striking that we have never observed an exotic plant on any monitoring or stabilization plot (Figure 4-4, see Table 3-1). It may be that the fall timing of our vegetation sampling fails to account for exotic annual plants that key in on winter precipitation—species that would have completed their lifecycles long before the summer monsoon season. Anecdotal evidence (NPS 2015) also suggests that most exotic plants (e.g., *Matthiola parviflora*) are largely confined to roadside swales and other highly disturbed areas of the monument.

It may be that soils within the larger expanses of the monument, which are currently protected but that appear to have been extensively modified in prehistory (Section 4.2) are poor habitat for many of the exotic plants in the area. This question could be addressed through the germination study as described in Section 4.7 (#2), below. We also propose adding our long-term monitoring and stabilization plots to the sampling frame for exotic plant–early detection monitoring to determine if winter exotics occur on these plots. Although the monument appears to be largely free of exotic plant colonization and invasion at this time, we recommend continued vigilance against any new infestations.

In the Arizona Upland subdivision of the Sonoran Desert ecoregion (Brown 1994), altered fire regimes are inextricably linked to the occurrence and spread of exotic plants (Olsson et al. 2012). Therefore, the paucity of invasive exotic plants at Casa Grande Ruins NM means fire hazards under current and recent conditions are very low (Figure 4-4, see Table 3-1). Fuel loads of native annual forbs and grasses were found to be minimal (4–10%), and buffelgrass and red brome—potent exotic grasses that can drive wildfire in valley-bottom systems (McDonald and

McPherson 2013)—were not detected on monitoring plots or stabilization plots from 2008 to the present.

Though somewhat atypical in diversity and overall cover, current perennial vegetation at the monument, dominated by creosotebush, a hardy, long-lived perennial shrub capable of persistence under harsh conditions (Brooks et al. 2007), appears to be both resistant to disturbance (such as drought and frost) and resilient in the face of potential future plant mortality.

4.6 Are terrestrial vegetation and soils within the range of natural variability?

Within the context of the new baseline established by groundwater depletion, we conclude that terrestrial vegetation and soils are within the range of natural variability at Casa Grande Ruins National Monument. Vegetation and dynamic soil factors varied little over time or space from 2008 to 2016. However, the near monoculture of sparse creosotebush shrubland is atypical of valley-bottom locations within parks and refuges of the region, perhaps due to the degree of soil modification during the primary occupation of the site. Dynamic soil function was similarly static over the monitoring period, suggesting a degree of stability. Current and recent terrestrial vegetation and soil attributes appear to well within the “new normal:” the range of bioenvironmental conditions to be expected after the extensive groundwater pumping and apparent soil disturbance of the past.

4.7 Recommendations for additional research

Based on our monitoring results, we have three specific research recommendations for Casa Grande Ruins National Monument.

1. Convene resource experts and stakeholders to determine if a soil inventory is possible

The existing soil survey is at a scale and focus that is much broader than the monument and fails to account for soil disturbances specific to the site. Conducting a detailed

soil survey at Casa Grande Ruins NM would provide insights into this question and provide key information on erosion potential and other important aspects of natural and cultural resource management at the monument. However, doing so in a manner that avoids impact to cultural resources and is sensitive to the concerns of current peoples who are culturally and spiritually connected to the site might prove challenging using current technology, such as excavated soil pits. Despite these challenges, we recommend investigating potential approaches for a site-specific soil survey that addresses the unique ecological and cultural resource issues of the monument.

2. Consider a germination study to better understand the potential soil limitations for native plants

A small-scale manipulative experiment could help determine the potential causes of the monument's limited perennial-plant species richness. A germination experiment, using surface soils and biological soil crusts from within the park, could assess germination and recruitment of expected (but currently absent) native plants under a variety of microclimates that reflect conditions in the monument. The experiment could ide-

ally occur in a controlled greenhouse setting or semi-controlled setting, though an in situ field study could be effective, as well. See Keddy (2007) for examples of this approach and potential design parameters. Plant germination and establishment are also affected by biological soil crusts (Belnap et al. 2003b), so inclusion of biocrusts into the study would be critical given the abundance of biological soil crusts at Casa Grande Ruins NM.

3. Conduct a detailed biological soil crust inventory for Casa Grande Ruins NM

Compared to conditions in other Sonoran Desert parks, biological soil crusts are playing an outsized role in nutrient cycling and erosion mitigation relative to vegetation at Casa Grande Ruins NM. The SODN monitoring effort only differentiates biological soil crusts to morphological groups, due to the challenges of species-level identification in the field. Conducting a comprehensive species-level inventory of biological soil crusts at Casa Grande Ruins NM would provide an important baseline for this important group of organisms, and may provide insights into the soil water, fertility, and erosion questions raised in this and other research (McIntyre et al. 2011; Powell et al. 2006; Reichhardt 1992).

5 Literature Cited

- Aber, J., and J. Melillo. 1991. Terrestrial ecosystems. Philadelphia, Pa.: Saunders College Publishing.
- Belnap, J. 2003a. The world at your feet: Desert biological soil crusts. *Frontiers in Ecology and the Environment* 1:181–189.
- . 2003b. Factors influencing nitrogen fixation and nitrogen release in biological soil crusts. Pages 241–261 *in* J. Belnap and O. L. Lange, eds., *Biological soil crusts: Structure, function, and management*. Ecological Studies Series 150, second edition. Berlin, Germany.
- Belnap, J., B. Büdel, and O. L. Lange. 2003a. Biological soil crusts: Characteristics and distribution. Pages 3–30 *in* J. Belnap and O. L. Lange, eds., *Biological soil crusts: Structure, function, and management*. Ecological Studies Series 150, second edition. Berlin, Germany.
- Belnap, J., and D. Eldridge. 2003. Disturbance and recovery of biological soil crusts. Pages 363–383 *in* J. Belnap and O. L. Lange, eds., *Biological soil crusts: Structure, function, and management*. Ecological Studies Series 150, second edition. Berlin, Germany.
- Belnap, J., J. H. Kaltenecker, R. Rosentreter, J. Williams, S. Leonard, and D. Eldridge. 2001. Biological soil crusts: Ecology and management. BLM Technical Reference 1730-2. Bureau of Land Management, Denver, Colorado.
- Belnap, J., S. L. Phillips, J. E. Herrick, and J. R. Johansen. 2007. Wind erodibility of soils at Fort Irwin, California (Mojave Desert), USA, before and after trampling disturbance: Implications for land management. *Earth Surface Processes and Landforms* 32:75–84.
- Belnap, J., R. Prasse and K. T. Harper. 2003b. Influence of Biological Soil Crusts on Soil Environments and Vascular Plants. Pages 281–300 *in* J. Belnap and O. L. Lange, eds., *Biological soil crusts: Structure, function, and management*. Ecological Studies Series 150, second edition. Berlin, Germany.
- Bennetts, R. E., J. E. Gross, K. Cahill, C. L. McIntyre, B. B. Bingham, J. A. Hubbard, L. Cameron, and S. L. Carter. 2007. Linking monitoring to management and planning: Assessment points as a generalized approach. *The George Wright Forum* 24(2):59–77.
- Bingham, B. B., R. E. Bennetts, and J. A. Hubbard. 2007. Integrating science and management: The road to Rico-Chico. *The George Wright Forum* 24(2):21–25.
- Blake, G. R., and K. H. Hartge. 1986. Excavation method. Pages 367–371 *in* E. A. Klute, ed., *Methods of soil analysis, Part 1: Physical and mineralogical methods*. Soils Science Society of America Book Series 5. Agronomy Monographs 9(1). American Society of Agronomy, Madison, Wisconsin.
- Bonham, C. D. 1989. Measurements for terrestrial vegetation. New York: Wiley-Interscience.
- Bowker, M. A., and J. Belnap. 2008. Spatial modeling of soil biological crusts to support land management decisions. Department of Environmental Science, Northern Arizona University, and U.S. Geological Survey.
- Brooks, M. L., T. C. Esque, and T. Duck. 2007. Creosotebush, blackbrush, and interior chaparral shrublands. Chapter 6 *in* *Fire ecology and management of the major ecosystems of southern Utah*. USDA Forest Service General Technical Report RMRS-GTR-202. Fort Collins, Colorado.
- Brown, D. E., ed. 1994. Biotic communities: Southwestern United States and northwestern Mexico. Salt Lake City: University of Utah Press.
- Brown, J., and S. Archer. 1999. Shrub invasion of grassland: Recruitment is continuous and not regulated by herbaceous biomass or density. *Ecology* 80(7):2385–2396.
- Buckley, S., J. A. Hubbard, S. Studd, S. Drake, M. Villarreal, and J. Greene. 2009. Vegetation classification, distribution, and mapping report: Casa Grande Ruins National Monument.

- Natural Resource Report NPS/SODN/NRR—2009/158. National Park Service, Fort Collins, Colorado.
- Burgess, T. L., J. E. Bowers, and R. M. Turner. 1991. Exotic plants at the desert laboratory, Tucson, Arizona. *Madroño* 38:96–114.
- Caldwell, M. M., T. E. Dawson, and J. H. Richards (1998), Hydraulic lift: Consequences of water efflux from the roots of plants. *Oecologia* 113:151–161.
- Clemensen, A. B. 1992. A centennial history of the first prehistoric reserve: 1892–1992. U.S. Department of the Interior, National Park Service, Washington, D.C.
- Cooley, M. E. 1973. Map showing distribution and estimated thickness of alluvial deposits in the Phoenix area. U.S. Geological Survey Miscellaneous Investigations Series Map I845-C.
- Crawley, M. J. 2013. Generalized linear models. Pages 557–578 in *The R Book*. Second edition. U.K.: J. W. Wiley.
- D’Antonio, C., and P. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. *Annual Review of Ecology and Systematics* 23:63–87.
- Davenport, D. W., D. D. Breshears, B. P. Wilcox, and C. D. Allen. 1998. Viewpoint: Sustainability of pinyon-juniper ecosystems—a unifying perspective of soil erosion thresholds. *Journal of Range Management* 51(2):231–232.
- Deeming, J. E., R. E. Burgan, and J. D. Cohen. 1977. The national fire danger rating system, 1978. General Technical Report INT-39. Intermountain Forest and Range Experiment Station. USDA Forest Service, Ogden, Utah.
- Dimmitt, M. A. 2000. Biomes and communities of the Sonoran Desert region. Pages 3–18 in S. J. Phillips and P. W. Comus, eds., *A natural history of the Sonoran Desert*. Tucson: Arizona-Sonora Desert Museum Press.
- Elzinga, C. L., D. W. Salzer, and J. W. Willoughby. 1998. Measuring and monitoring plant populations. BLM Technical Reference 1730-1. Bureau of Land Management, Denver, Colorado.
- Enright, N. J., J. B. Fontaine, B. B. Lamont, B. P. Miller, and V. C. Westcott. 2014. Resistance and resilience to changing climate depend on plant functional traits. *Journal of Ecology* 102:1572–1581.
- Gori, D. F., and H. Schussman. 2005. State of the La Cienegas National Conservation Area. Part I. Condition and trend of the desert grassland and watershed. Prepared by The Nature Conservancy, Arizona chapter.
- Grime, J. P., V. K. Brown, K. Thompson, G. J. Masters, S. H. Hillier, I. P. Clarke, A. P. Askew, D. Corker, and J. P. Kielty. 2000. The response of two contrasting limestone grasslands to simulated climate change. *Science* 289:762–765.
- Halvorson, W. L., and P. Guertin. 2003. USGS Weeds in the west: Status of introduced plants in southern Arizona Refuges. <http://sdfsnet.snr.arizona.edu/index.php?page=datamenu&lib=2&sublib=13>. Last accessed September 30, 2011.
- Herrick, J. E., J. W. Van Zee, K. M. Havstad, L. M. Burkett, and W. G. Whitford. 2005a. Monitoring manual for grassland, shrubland and savanna ecosystems. Volume 1: Quick start. USDA-ARS Jornada Experimental Range, Las Cruces, New Mexico.
- . 2005b. Monitoring manual for grassland, shrubland, and savanna ecosystems. Volume II: Design, supplementary methods, and interpretation. Tucson: The University of Arizona Press. 200 pp.
- Hubbard, J. A. 2003. Fire-grazing interactions in a mixed grass prairie. PhD dissertation, Department of Range-land Ecology and Management, Texas A&M University, College Station, Texas. 162p.
- Hubbard, J. A., C. L. McIntyre, S. E. Studd, T. Nauman, D. Angell, K. Beaupré, B. Vance, and M. K. Connor. 2012. Terrestrial vegetation and soils monitoring protocol and standard operating

- ing procedures: Sonoran Desert and Chihuahuan Desert networks, version 1.1. Natural Resource Report NPS/SODN/NRR—2012/509. National Park Service, Fort Collins, Colorado.
- Ingram, M. 2000. Desert storms. Pages 41–50 in S. J. Phillips and P. W. Comus, eds., *A natural history of the Sonoran Desert*. Tucson: Arizona-Sonora Desert Museum Press.
- Intergovernmental Panel on Climate Change (IPCC). 2007. Fourth Assessment Report. Available at <http://www.ipcc.ch/index.htm#UHPGaZO1Hy0>.
- Izsák, J., and L. Papp. 2000. A link between ecological diversity indices and measures of biodiversity. *Ecological Modelling*. 130:151–156.
- Keddy, P. A. 2007. *Plants and vegetation: Origins, processes, and consequences*. Cambridge, U.K.: Cambridge University Press.
- Marshall, R. M., S. Anderson, M. Batcher, P. Comer, S. Cornelius, R. Cox, A. Gondor, D. Gori, J. Humke, R. Paredes Aguilar, I. E. Parra, and S. Schwartz. 2000. An ecological analysis of conservation priorities in the Sonoran Desert ecoregion. Prepared by The Nature Conservancy Arizona Chapter, Sonoran Institute, and Instituto del Medio Ambiente y el Desarrollo Sustentable del Estado de Sonora with support from Department of Defense Legacy Program, Agency and Institutional partners. 146 pp.
- 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.
- McDonald, C. J., and G. R. McPherson. 2013. Creating hotter fires in the Sonoran Desert: Buffelgrass produces copious fuels and high fire temperatures. *Fire Ecology* 9(2):26–39.
- McIntyre, C. L., J. A. Hubbard, and S. E. Studd. 2011. Terrestrial vegetation and soils monitoring at Casa Grande Ruins National Monument: 2008 status report. Natural Resource Technical Report NPS/SODN/NRTR—2011/487. National Park Service, Fort Collins, Colorado.
- McLaughlin, S. P., and J. E. Bowers. 1982. Effects of wildfire on a Sonoran Desert plant community. *Ecology* 63:246–248.
- Miller, G., M. Friedel, P. Adam, and V. Chewings. 2010. Ecological impacts of buffelgrass (*Cenchrus ciliaris* L.) invasion in central Australia: Does field evidence support a fire-invasion feedback? *The Rangeland Journal* 32:353–365.
- Muckel, G. B., ed. 2004. *Understanding soil risks and hazards: Using soil survey to identify areas with risks and hazards to human life and property*. U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, Lincoln, Nebraska.
- National Park Service. 2011. Integrated pest management plan, environmental assessment, Casa Grande Ruins National Monument. <https://parkplanning.nps.gov/document.cfm?parkID=36&projectID=24951&documentID=38400>. Last accessed February 10, 2011.
- . 2012. Exotic plant status at Casa Grande Ruins National Monument: 2012. Sonoran Desert Network Field Report. 4p.
- . 2013. Exotic plant status at Casa Grande Ruins National Monument: 2013. Sonoran Desert Network Field Report. 4p.
- . 2015. Exotic plant status at Casa Grande Ruins National Monument: 2015. Sonoran Desert Network Field Report. 4p.
- . 2018a. Annual park recreational visitation report for Casa Grande Ruins National Monument. Available online at: <https://irma.nps.gov/Stats/Reports/Park/CAGR> Last Accessed March 21, 2018.
- . 2018b. Digital geologic-GIS map of Casa Grande Ruins National Monument and vicinity, Arizona (GRI MapCode CAGR). Available online at:

- <https://irma.nps.gov/DataStore/Reference/Profile/1045749> Last Accessed April 12, 2018.
- Natural Resources Conservation Service (NRCS). n.d. Web soil survey. Available online: <https://websoilsurvey.sc.egov.usda.gov/>. Last accessed 3/15/2018.
- Olsson, A. D., J. Betancourt, M. P. McClaran, and S. E. Marsh. 2012. Sonoran Desert ecosystem transformation by a C4 grass without the grass/fire cycle. *Diversity and Distributions* 18:10–21.
- Overpeck, J., G. Garfin, A. Jardine, D. E. Busch, D. Cayan, M. Dettinger, E. Fleishman, A. Gershunov, G. MacDonald, K. T. Redmond, W. R. Travis, and B. Udall. 2013. Summary for decision makers. Pages 1–20 in G. Garfin, A. Jardine, R. Merideth, M. Black, and S. LeRoy, eds., *Assessment of climate change in the southwest United States: A report prepared for the National Climate Assessment. A report by the Southwest Climate Alliance*. Washington, D.C.: Island Press.
- Powell, B. F., E. W. Albrecht, C. A. Schmidt, W. L. Halvorson, P. Anning and K. Docherty. 2006. Vascular plant and vertebrate inventory of Casa Grande Ruins National Monument. USGS OFR 2005-1185. USGS Southwest Biological Science Center, Sonoran Desert Research Station, University of Arizona, Tucson.
- PRISM Climate Group, Oregon State University. 2018. PRISM time series data, precipitation, 4km for 32.9958, -111.5419, 2007-2016. Available at: <http://prism.oregonstate.edu>. Created April 7.
- Reichhardt, K. 1992. Natural vegetation of Casa Grande Ruins National Monument, Arizona. Cooperative National Park Resources Studies Unit. Technical Report NPS/WRUA/NRTR—92/45.
- Robinett, D., J. Norris, L. D. Ellicott, and S. Barker. No date. Provisional ecological site description, Limy Fan 7-10" p.z. Available online: <https://esis.sc.egov.usda.gov/ESDReport/fsReport.aspx?approved=yes&rptLevel=all&id=R040XB207AZ>. Last accessed March 27, 2018.
- Rogers, G. F. 1986. Comparison of fire occurrence in desert and nondesert vegetation in the Tonto National Forest, Arizona. *Madrono* 33:278–283.
- Schlesinger, W. H., and A. D. Pilmanis. 1998. Plant-soil interactions in deserts. *Biogeochemistry* 42:160–187.
- Scott, R. L., W. L. Cable, and K. R. Hultine. 2008. The ecohydrologic significance of hydraulic redistribution in a semiarid savanna. *Water Resource Research* 44.
- Sheppard, P. R., A. C. Comrie, G. D. Packin, K. Angersbach, and M. K. Hughes. 2002. The climate of the U.S. Southwest. *Climate Research* 21:219–238.
- Shinneman, D. J., and W. L. Baker. 2009. Environmental and climatic variables as potential drivers of post-fire cover of cheatgrass (*Bromus tectorum*) in seeded and unseeded semi-arid ecosystems. *International Journal of Wildland Fire* 18:191–202.
- Shreve, F. 1951. *Vegetation of the Sonoran Desert*. Washington, D.C.: Carnegie Institution of Washington Publication no. 591.
- Soil Conservation Service (SCS). 1991. Soil survey of Pinal County, Arizona, western part. Available online: https://www.nrcs.usda.gov/Internet/FSE_MANUSCRIPTS/arizona/AZ659/0/pinal.pdf. Last accessed March 23, 2018.
- Sonoran Desert Network (SODN). 2005. Sonoran Desert Network vital signs monitoring plan. Technical Report NPS/IMR/SODN-003. National Park Service. Denver, Colorado.
- Steenbergh W. F., and C. H. Lowe. 1977. Ecology of the saguaro II: Reproduction, germination, establishment, growth, and survival of the young plant. National Park Service Scientific Monograph Series 8. US Government Printing Office, Washington, DC.
- Studd, S. E., S. Drake, M. Villarreal, E. Fallon, and L. L. Crumbacher. 2013. Vegetation inventory, mapping, and

- classification report, Fort Bowie National Historic Site. Natural Resource Report NPS/SODN/NRR—2013/673. National Park Service, Fort Collins, Colorado.
- Studd, S. E., and C. L. McIntyre. 2007. Invasive plant mapping inventory at Casa Grande Ruins National Monument, Arizona. Natural Resource Technical Report Natural Resource Report NPS/IMR/SODN—2007/001. National Park Service, Denver, Colorado.
- Theobald, D. M., D. L. Stevens, Jr., D. White, N. S. Urquart, A. R. Olsen, and J. B. Norman. 2007. Using GIS to generate spatially balanced designs for natural resource applications. *Environmental Management* 40:134–146.
- Warwick, R. M., and K. R. Clarke. 1995. New biodiversity measures reveal a decrease in taxonomic distinctness with increasing stress. *Marine Ecology Progress Series* 129:301–305.
- Western Regional Climate Center (WRCC). n.d. Casa Grande NM, Arizona, NCDC 1981–2010 monthly normals. Available online: <https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?az1314/>. Last accessed 3/15/2018.
- Whittaker, R. H. 1975. *Communities and ecosystems*. Indianapolis, In.: MacMillan.
- Wilson, W. 1918. Casa Grande Ruins National Monument enabling legislation. Presidential Proclamation No. 1470, August 3, 40 Stat. 1818.
- Zar, J. H. 1999. Paired-sample hypothesis. Pages 161–176 *in* Biostatistical analysis. Fourth edition. New Jersey: Prentice Hall.

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.

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™