



Status and Trends in Grassland Vegetation at Chaco Culture National Historical Park

Upland Vegetation and Soils Monitoring 2007–2018

Natural Resource Report NPS/SCPN/NRR—2022/2348





ON THIS PAGE

Field technicians collect data in grasslands at Chaco Culture National Historical Park.
NPS / MEGAN SWAN

ON THE COVER

View from North Mesa looking into Mockingbird Canyon.
NPS

Status and Trends in Grassland Vegetation at Chaco Culture National Historical Park

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Natural Resource Report NPS/SCPN/NRR—2022/2348

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Executive Summary

This report presents results of upland vegetation and soil monitoring at Chaco Culture National Historical Park (CHCU) by the Southern Colorado Plateau Inventory and Monitoring Network (SCPN) from 2007–2018. Crews collected data on composition and abundance of vegetation, both at the species level and by growth form (e.g., perennial grass, shrub, forb, soil aggregate stability, and soil texture at 30 plots within a target grassland community delineated using NRCS ecological site (ecosite) classification.

From 2007–2018, SCPN crews identified 67 plant species. The ecosite was dominated by warm-season grasses, which comprised about three-quarters of the total cover of vegetation. Shrubs and forbs were a small component of total vegetation cover but were present in all plots monitored. Less than 4% of species detected were nonnative. Russian thistle (*Salsola tragus*), cheatgrass (*Bromus tectorum*) and kiss-me-quick (*Portulaca oleracea*) were the three nonnative species detected. Nonnative plant frequency varied from year to year and cover was very low. We did not detect any species of plants new to the park during monitoring.

Soils in the sandy loam upland ecosite were generally deep and somewhat coarse-textured, although some plots had more clayey-textured horizons, especially in deeper layers. Undifferentiated soil crust comprised the largest component of the soil surface. Cover of biological soil crust (cyanobacteria, lichen and moss) was low. Soil aggregate stability was moderate.

Models revealed that temporal trends for most responses were weak or absent, implying that resources did not show directional change over time other than those explained by precipitation covariates. There was evidence of a decreasing trend in species richness (0.25 species per year), however this may be due to the dry conditions we've encountered during sampling years since 2012 and warrants further examination. Spring season precipitation had the strongest positive effect on total foliar cover in these grasslands, as well as on the cover of the two dominant grass species.

Nearly all the vegetation metrics we modeled increased with increasing spring precipitation. Grassland vegetation dependence on spring precipitation at CHCU is in agreement with another recent study (Andrews et al. 2019). This is a cause for concern given predictions of decreased spring precipitation and increased spring temperatures expected at CHCU in the coming decades (Monahan and Fisichelli, 2014, Andrews et al. 2019). Increasing drought stress in the spring months will almost certainly have a negative effect on the foliar cover of dominant species in these grasslands and could have wide-ranging implications including mortality and/or a shift in the species that these areas support.

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Introduction

The mission of the National Park Service (NPS) is to conserve unimpaired the natural and cultural resources of the National Park System for the enjoyment of future generations. At Chaco Culture National Historical Park (CHCU), grassland vegetation communities are vitally important to the overall character of the park, forming an integral component of the natural and cultural landscape. Due to a long history of protection from grazing, these communities exist much as they may have prior to European expansion. In addition to the inherent value to biodiversity, unique plant assemblages at CHCU stabilize the soil, which, in turn, preserves and protects numerous paleontological and prehistoric resources and cultural relics. Chaco's grasslands provide important habitat for birds, mammals, reptiles, and insects.

The Southern Colorado Plateau Inventory and Monitoring Network (SCPN) began collecting data in CHCU grasslands in 2007 as part of an initiative to provide long-term, scientifically sound monitoring data to inform park management of natural resources. Specifically, SCPN collects data on the structure and abundance and species composition and richness of upland vegetation, soil surface features, and soil stability (DeCoster et al. 2012).

We established a set of 30 long-term plots in the CHCU mixed grassland community using a spatially balanced probability survey design (Figure 1, Stevens and Olsen 2004) and monitor plots to gather data on the condition of this grassland ecosite.

Reporting on status and trend of systems being monitored is a primary goal of the Inventory and Monitoring (I&M) program (NPS 2012). This report presents a summary of selected results from upland monitoring at CHCU from 2007–2018. It seeks to answer the following questions:

1. What were the characteristics of vegetation and soil components in the sandy loam upland ecosite at CHCU during the monitoring period (2007–2018)?
2. How did the condition of these components change between 2007 and 2018?
3. Is there evidence of positive or negative trends in key vegetation and soil metrics?

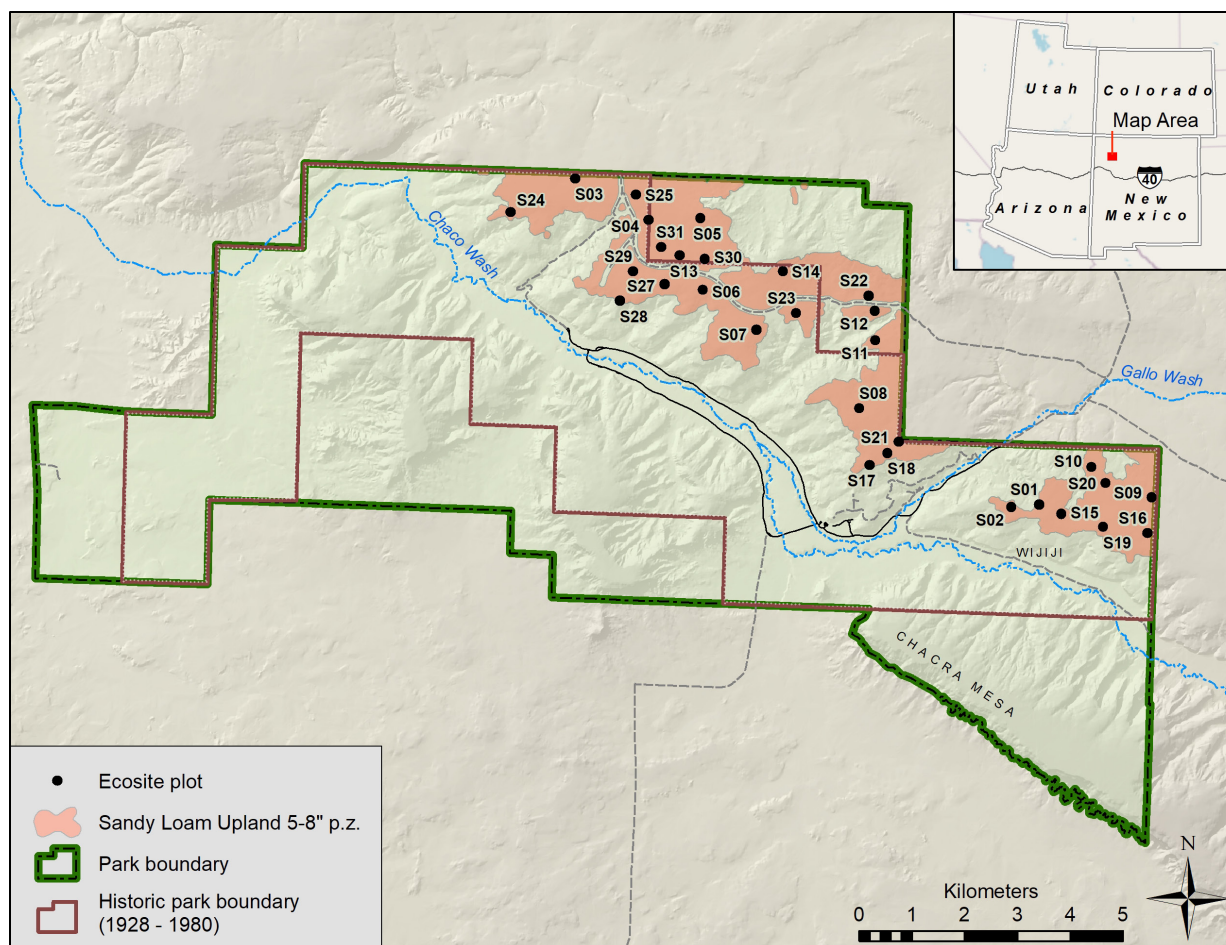


Figure 1. Overview map of Chaco Culture National Historical Park showing the locations of Southern Colorado Plateau Network upland vegetation monitoring plots. Plot S26 (not shown) did not match the ecosite and was removed and replaced by plot S31 in 2014.

Methods

Study area

Chaco Culture National Historical Park (CHCU) is in the central San Juan basin in northwestern New Mexico about 241 miles northwest of Albuquerque, NM (Figure 1). Established as a national monument in 1907, it was elevated to national historical park status in 1980 and designated a UNESCO National Heritage site in 1987. The park covers 13,744 acres and comprises four units—the main Chaco Canyon unit and three smaller outliers: Kin Bineola, Pueblo Pintado, and Kin Ya'a.

The Chaco Canyon unit consists of three distinct land types: 1) The alluvium-filled valley floor which contains the intermittent Chaco River as well as most major archeological sites for which the park is internationally known; 2) shallow side canyons, or rincons, eroded into the sandstone cliffs adjacent to the main canyon floor; and 3) expansive sandstone mesas topped by slickrock outcrops and gently rolling grasslands.

Park elevation ranges from 1,832–2,096 m (Jones 1972). Winters are cold and dry, and summers are hot. Annual precipitation averages 223 mm per year, with the majority falling in the summer (July–September) as a result of the North American Monsoon. Average mean daily temperature ranges from a low of -10.7°C in January to a high of 32.4°C in July (WRCC 2021).

Mixed shrubland is the dominant vegetation in CHCU and comprises about 78% of park area (Salas et al. 2011). Grasslands occur mainly on the mesa tops north and south of the main canyon. Woodlands are limited to a narrow riparian zone along Chaco and Gallo washes and a small portion of Chacra Mesa that supports higher density pinyon-juniper (Salas et al. 2011). CHCU historically experienced intense grazing from domestic sheep, goats, and cattle. When the boundary fence was completed in 1948, domestic livestock were excluded (NPS 1994) making CHCU one of the largest and oldest grazing exclosures in the western United States, with much of the park protected from domestic grazing for over 60 years (Salas et al. 2011). An additional 8,000 acres added to the park in 1980 were fenced in 1993.

The long history of grazing exclusion at CHCU makes these grasslands unique and highly significant. Few protected grasslands exist in the Southwest United States (Henwood 2010). Park grasslands provide forage and cover for native wildlife species including large and small herbivores (pronghorn (*Antilocapra americana*), mule deer (*Odocoileus hemionus*), elk (*Cervus canadensis*), jackrabbits (*Lepus californicus*), mesocarnivores (coyote (*Canis latrans*)), rodents (rock squirrel (*Spermophilus variegatus*), cliff chipmunks (*Neotamias quadrivittatus*)), and numerous bird and reptile species (Bogan et al. 2007).

Sampling frames

We used Natural Resources Conservation Service (NRCS) ecological sites (ecosites) to define areas for monitoring. An ecosite represents a unique combination of soils and potential vegetation (Caudle et al. 2013). We selected an ecosite closely associated with mesa top mixed grass and shrubland communities within CHCU for upland monitoring: Sandy Loam Upland (6–10” precipitation zone (p.z.); R035XB030NM) (DeCoster et al. 2012).

When developing the sampling frame, we included soil map units containing high percentages of the target ecosite (NRCS SSURGO dataset, Zshetzsche and Clark 2004). We then modified the sampling frame by removing areas not appropriate for monitoring, including areas surrounding infrastructure (roads and buildings), heavily disturbed areas, and areas with slopes >20%. Using Generalized Random Tessellation Stratified (GRTS) design (Stevens and Olsen 2004), we generated a set of spatially distributed potential sampling points within the final sampling frame and field-screened these points to remove any plots that did not align with soil or ecosite characteristics.

Sandy Loam Upland Ecosite

The sandy loam upland ecosite occurs on the mesa tops on either side of Chaco Canyon (Figure 1). Slopes are generally minimal (0–5%). Soils are deep (>100 cm) and have a relatively high proportion of sand. Water is absorbed quickly but holding capacity of these soils tends to be low (Zshetzsche and Clark 2004). Vegetation typically consists of a mix of warm season grasses and shrubs, including galleta grass (*Hilaria jamesii*), blue grama (*Bouteloua gracilis*), dropseeds (*Sporobolus* spp.), four-wing saltbush (*Atriplex canescens*), and snakeweed (*Gutierrezia sarothrae*) with a small component of cool season grasses and forbs (Figure 2).



Figure 2. An example of the sandy loam upland ecosite at Chaco Culture National Historical Park (NPS/MEGAN SWAN).

Monitoring plots

This report presents data from 30 permanent monitoring plots at CHCU. We established 10 plots in 2007 and sampled them every year through 2011 to better understand interannual variability at the site. We subsequently established an additional 20 plots (6 in 2010, 13 in 2011, and one in 2014), and initiated a structured panel revisit (monitoring) design in 2012. Plots were randomly assigned to one of three monitoring panels ($n=10$ plots/panel). Two of these panels were sampled every other year in a rotating design. A complete panel revisit cycle, in which all plots are sampled twice, takes six years. During the monitoring period (2007–2018), the maximum number of revisits to a single plot was six and one plot (S31, established in 2013) was sampled twice. A complete sampling history for plots monitored at CHCU is provided in Appendix A.

Monitoring plots are 50 m x 52 m and consist of three parallel 50 m transects spaced 25 m apart (Figure 3). Within this area, field crews collect data on shrub and herbaceous vegetation and soil attributes using quadrat and transect-based sampling. See the integrated upland monitoring protocol for detailed explanation (DeCoster et al. 2012). Plots were sampled at approximately the same time

each year (late September to late October, usually mid-October), as close to maximal plant growth as possible given seasonal schedule constraints.

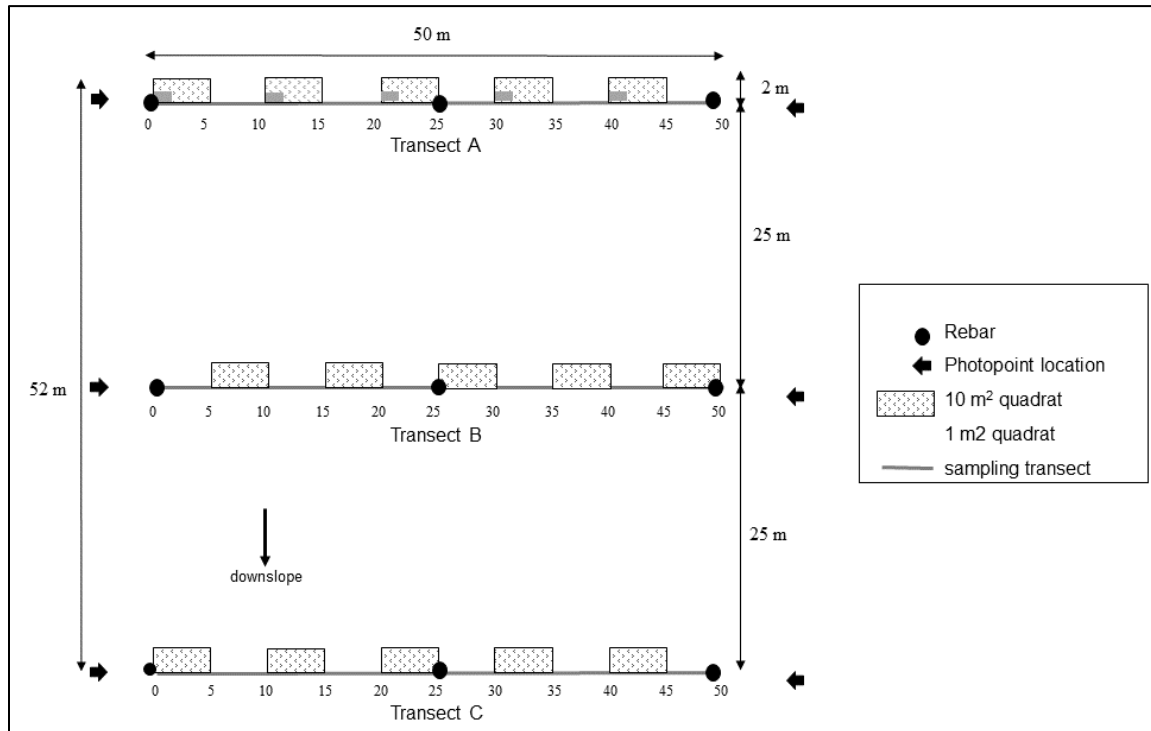


Figure 3. Diagram of a Southern Colorado Plateau Network upland monitoring plot. Shrub and herbaceous cover are measured in 10 m² quadrats, soil surface features in 1 m² quadrats. Basal gaps are sampled along each 50 m transect and photopoints are taken at each transect end facing towards the center of the transect. Soil stability samples are taken from six random locations along each transect.

Herbaceous and shrub vegetation

Within each plot, we estimated percent cover of live herbaceous and shrub vegetation in fifteen 10 m² (2 m × 5 m) quadrats. We placed five quadrats at 10 m intervals along each transect and identified all live vascular plants observed in each quadrat to species (or the lowest taxonomic level possible). We then made an ocular estimate of absolute cover for each species detected using one of 12 cover class intervals ranging from >0.1% to 75–100% (Table 1). We considered plants live if there was evidence they were living at any point during the current growing season, even if they were dead or senescent during sampling. Plants that had foliar cover within the quadrat but were rooted outside the quadrat were assigned a cover class, but not a frequency.

Table 1. Cover classes used by the Southern Colorado Plateau Network for estimating ocular cover during upland monitoring.

Cover Class	Range	Midpoint
0	0	0
1	<0.1%	0.05%
2	0.1–0.5%	0.30%
3	>0.5–1%	0.75%
4	>1–2%	1.50%
5	>2–5%	3.50%
6	>5–10%	7.50%
7	>10–15%	12.50%
8	>15–25%	20.00%
9	>25–35%	30.00%
10	>35–50%	42.50%
11	>50–75%	62.50%
12	>75–100%	87.50%

All species present were then aggregated into growth form categories, which include perennial grass, annual grass, forb, shrub, and cacti/succulent. We estimated cover for each growth form, accounting for layering and overlap, and recorded a cover class for each growth form category detected in the 10 m² quadrat. We also assigned a cover class for total foliar which represents the aggregated total of all grass, forb and shrub cover in a plot and for dead herbaceous and dead shrub vegetation within the 10 m² quadrat.

Soil profile and surface features

When establishing a plot, we collect a soil profile sample using a 1½” diameter soil auger. Soil is extracted to the maximum depth possible (or 100 cm), then divided into 10 cm increments. Soil effervescence, color and texture is assessed in the field using standard methods for each depth increment.

When sampling, we assessed soil surface features and biological soil crust attributes in 1 m² quadrats nested within the 10 m² quadrats and located at 10 m intervals along each transect (Figure 3). We made ocular estimates of absolute cover for each of the fourteen categories of soil surface features including surface gravel and rocks (characterized by size class), live and dead plant bases, duff and litter, woody debris, cyanobacteria, lichen, and moss using one of 12 possible cover classes (Table 1).

Soil stability

Soil aggregate stability is determined by collecting soil surface fragments from six random locations along each transect (18 per plot) and immersing the collected soil fragments repeatedly in distilled water, then rating the degree to which the soil particles hold together (Herrick et al. 2009). We rated soil samples on a scale of 1–6. Values close to one indicate lowest particle aggregation. A rating of six is reserved for extremely stable samples that withstand being soaked and dipped in water with no change in volume. From 2007 to 2015, when we encountered deep litter, surface stones, or exposed bedrock during sampling, we did not take the sample. In 2016, we changed our protocol to select a new random location to sample when the soil surface was obstructed at the original random sampling point. As a result, in years prior to 2016, fewer than 18 soil samples were sometimes collected within a plot.

Data management and analysis methods

Sampling data were entered into Access databases, converted to SQL Server, and analyzed using the R statistical software package (R Core Team 2017, version 3.6.0). All data went through a rigorous Quality Assurance /Quality Control process with valid value constraints and complex logical tests before being loaded into a production database. Scientific names, common names, growth form, and duration information for plant species were obtained from USDA PLANTS database (USDA NRCS 2021). Taxonomy was standardized using the Integrated Taxonomic Information System (ITIS, www.itis.gov). A complete list of plant species encountered at CHCU grassland sites is provided in Appendix B.

Status estimates describe the characteristics of the site over the monitoring period (2007–2018). For status estimates, we summarized data across all years to minimize inter-annual variability in plots and responses, which provides a more robust characterization of the ecosite than a single year value. Status estimates are presented as plot averages except for species richness, which is presented at 3 scales (10 m² quadrat, 50 x 52 m plot, entire ecosite). Since plots were sampled unequal numbers of times, for cover, we first averaged all quadrat observations for each plot and year to get single-year, plot-level means, then averaged the plot means across years to get a single plot mean for the monitoring period. Finally, we averaged plot means across the ecosite.

For plant cover, we used the midpoints of each cover class as a metric value to represent the category and calculated arithmetic means of midpoints. An exception was exotic plant frequency, for which we present absolute frequency (total number of quadrats containing species divided by total number of quadrats sampled). Our approach of using cover class midpoints for status estimates treats categorical data (ordinal cover classes) as numeric data (percent cover) by using arbitrarily based midpoint values which is not statistically supported (Herpigny and Gosselin 2015). However, this approach is commonly used in ecology (Johnson et al 2006, Evangelista et al. 2016). In contrast, the trend models we used to examine change over time correctly modeled percent cover as a latent continuous variable, rather than category midpoints. When we compared across-year means derived using cover class midpoints to modeled latent continuous means, the results were similar. We are working on a more statistically supported approach for summarizing our cover class data for status, which we will include in future reports.

Climate data were obtained from two sources: 1) temperature anomaly data and long-term average precipitation totals from the Chaco Canyon climate station (1922–2018) (source: <http://www.climateanalyzer.us/coop/chacocanyon>); and 2) plot-scale precipitation data were obtained from United States Stage IV Quantitative Precipitation Archive (Lin and Mitchell, 2005). Missing days were filled in using DayMet (Thornton et al. 2016). All summaries and figures were created using R. Models were run using R and the rjags package (rjags version 4.9, Plummer 2019).

Bayesian hierarchical models of trend

We employed a Bayesian hierarchical modeling approach to investigate change over time in seven response variables (see Appendix C). These methods were chosen to partially account for several challenges with the data set: data were intentionally missing as a result of sampling design; sample sizes were not stable across the initial six years; we collected categorical data using cover class estimates; and responses were not normally distributed. See Zachmann et al. (2021) and Irvine et al. (2016) for details on this modeling approach.

We used the basic form of a general linear model, interpreted as the change in the prediction of the response variable (e.g., foliar cover of perennial grass) per unit time. Model specifications varied based on characteristics of the response variable. Species richness models used a linear deterministic model with a Poisson likelihood; soil stability models also were linear and used an ordinal latent normal likelihood. Cover class values were modeled using a hurdle at 0, an inverse logit deterministic model, and an ordinal latent beta model. This mixed model used a beta distribution to model a continuous latent cover percentage and includes a hurdle term to separate the presence/absence response from cover when present (Irvine et al. 2016). For responses like total foliar cover which are present in every plot, we dropped the presence/absence component of the model to improve model fit. Additional model details are provided in Appendix C. Model selection results are provided in Appendix D.

In addition to time, mechanistic predictor variables (covariates) were included in all models to account for factors, such as precipitation, that are known to affect responses, such as plant cover. We modeled change in the response variable by incorporating covariates in two ways. The first model examined **change over time** while including the effect of changes in the covariates on the response. These models (species richness, plant cover, soil stability) reflect interannual variation in response to seasonal precipitation and spring temperature. We used a second model to make inference on **trend**, which we define as directional change over time that is unexplained by interannual variation in the covariates. For example, a reduction in grass cover over time that is not explained by low monsoon precipitation. Trend models removed interannual variation in the covariates. Each covariate was centered and standardized at its mean for the monitoring period; values varied by site, but not by year. This approach essentially removes the effect of interannual variation in covariates on the trend of the response, so that trend represents change in the response over time not explained by environmental covariate(s).

As an example, we may choose to look at change over time in plant cover in relation to annual precipitation. First, we examined change over time using the model-predicted means at each time step, *including* the effect of variation in precipitation. These results will present the effect that wet or

dry years have on plant cover, conditional on the model we selected. Second, we removed the effect of interannual differences in precipitation by controlling for precipitation in the models, such that each site and year received the same average amount of precipitation. This allowed us to determine whether plant cover is increasing or decreasing over time regardless of interannual difference in precipitation totals.

Trend results represent model-predicted probabilities of the average change per year. Probabilities are based on distributions of predictions accumulated over many iterations of model predictions. Models predict parameters for each site and year, whether or not the plot was sampled, which minimizes the effect of missing data that results from our panel design (Zachmann et al. 2021). Plots sampled relatively more often have greater influence on model-predicted parameters, while plots sampled less often contribute more uncertainty.

Results present change over time as the mean of the posterior distribution (i.e., modeled predictions of the mean response) for each year and the corresponding 95% credible intervals. Credible intervals are similar to confidence intervals used in frequentist analyses and are correctly interpreted as a 95% probability that the true mean of the response falls within the interval. Whether or not a response shows a trend is determined based on the distribution of the change in response per year (i.e., the distributions of slope in the model output) and is presented as a histogram of this distribution. There is no evidence of trend if the limits of the posterior distribution include zero. The distance and direction of the center of the distribution from zero indicates the strength and direction of the trend.

We initially investigated a suite of potential climate covariates to include in our models using stepwise regression (data not provided). We focused on seasonal variables, based on significant relationships found between spring season soil moisture and annual productivity as measured by the normalized difference vegetation index (NDVI) at CHCU (Andrews et al. 2019). We explored both current year values and the previous year's values because previous year's climate conditions can affect current year productivity (Wu et al. 2015). Candidate covariates included Standardized Precipitation-Evaporation Index (SPEI), a multiscalar drought index based on climatic data (Vicente-Serrano et al. 2010), seasonal precipitation variables, seasonal temperatures, soil moisture and deficit effects, (unpublished data). We ultimately focused on seasonal precipitation variables because they are readily available and ranked as more important than soil moisture variables in explaining dynamics in C4 grasslands on the Colorado Plateau (Gremer et al. 2015).

To determine the effect of included covariates, we report the mean of the coefficient of each covariate with its standard deviation (see Appendix C, Table C-2). These values are comparable within a model, but interpretation of these values varies based on which model was used. For linear models, the means of the coefficient represent the change per standard deviation, while for inverse logit models, the interpretation is defined as the additive change in log odds per standard deviation.

For each of the seven models (see Appendix C), we developed several candidate models and assessed model fit using posterior predictive simulation to generate Bayesian p-values. Bayesian p-values > 0.1 and < 0.9 indicate lack of fit. We checked all models for convergence using the Gelman-Rubin diagnostic (Gelman diagnostic < 1.1 , Gelman and Rubin 1992). We then selected our final models by

choosing those that minimized posterior predictive losses (PPL) (Hobbs and Hooten 2015). More details about the final models used in our analysis are available in Appendix C. Model selection details can be found in Appendix D.

Results and Discussion

Ecosite status

Plots overview

Monitoring plots at CHCU are divided between the North Mesa (22 plots) and Wijiji Mesa (8 plots, Figure 1). Eight of the North Mesa plots are within the boundary expansion area added to the park in 1980. Domestic grazing of these 8 plots ended more recently (1993) than the other 22 plots, which have been protected from domestic grazing since 1948. No clear delineation is evident in the field between plots grazed until 1993 and those grazed before 1948. Both mesas are distant from developed roads and trails and are rarely accessed by park visitors.

Climate overview

Annual fluctuations in precipitation and temperature result in changing vegetation conditions in the field (Figure 4). There was considerable variation in mean monthly temperature and seasonal precipitation over the monitoring period (Figure 5). Since 2012, precipitation for most plots at CHCU has exceeded the long-term average in alternating years, while most plots received less than average precipitation during intervening years (Figure 5). The structured panel revisit design sampled plots every other year but failed to collect data during wetter than normal conditions (2012–2018; Figure 5; also see Appendix B).



Figure 4. Examples of wet year (left panel, taken 2007) and dry year (right panel, taken 2012) vegetation in the sandy loam upland ecosite at Chaco Culture National Historical Park.

Monthly temperature also varied considerably from long-term averages over the monitoring period (Figure 6). From 2012–2018, average high temperature was >2 degrees above the long-term average during 13 months, while average low temperatures >2 degrees cooler than the long-term average were recorded during only 3 months (Figure 6, for months for which there was data). Evaluation of climate change exposure in national park units showed 5 temperature variables were in the “extreme warm” percentile, indicating recent climatic conditions are already shifting above the historical temperature range at CHCU (Monahan and Fisichelli 2014).

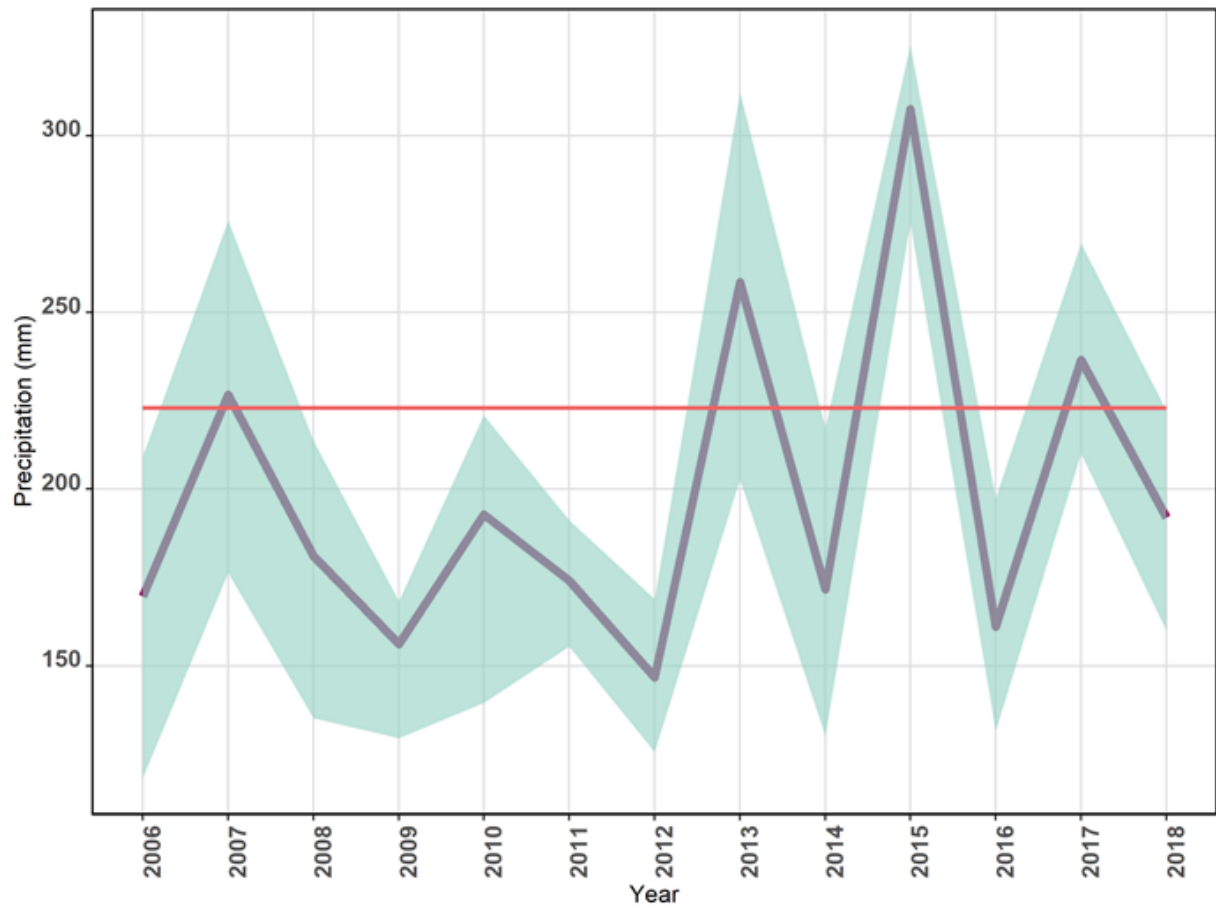


Figure 5. Mean and range of annual precipitation for plots in the sandy loam upland ecosite for water years (October–September) 2006–2018. The shaded area represents the range in plot-level annual precipitation. The darker line represents mean annual precipitation across all plots. The horizontal red line represents the long-term average precipitation total at CHCU climate station (1909–2018) (source: <https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?nm1647>). Precipitation data were obtained from United States Stage IV Quantitative Precipitation Archive (Lin and Mitchell 2005). Missing days were filled in using DayMet (Thornton et al. 2016).

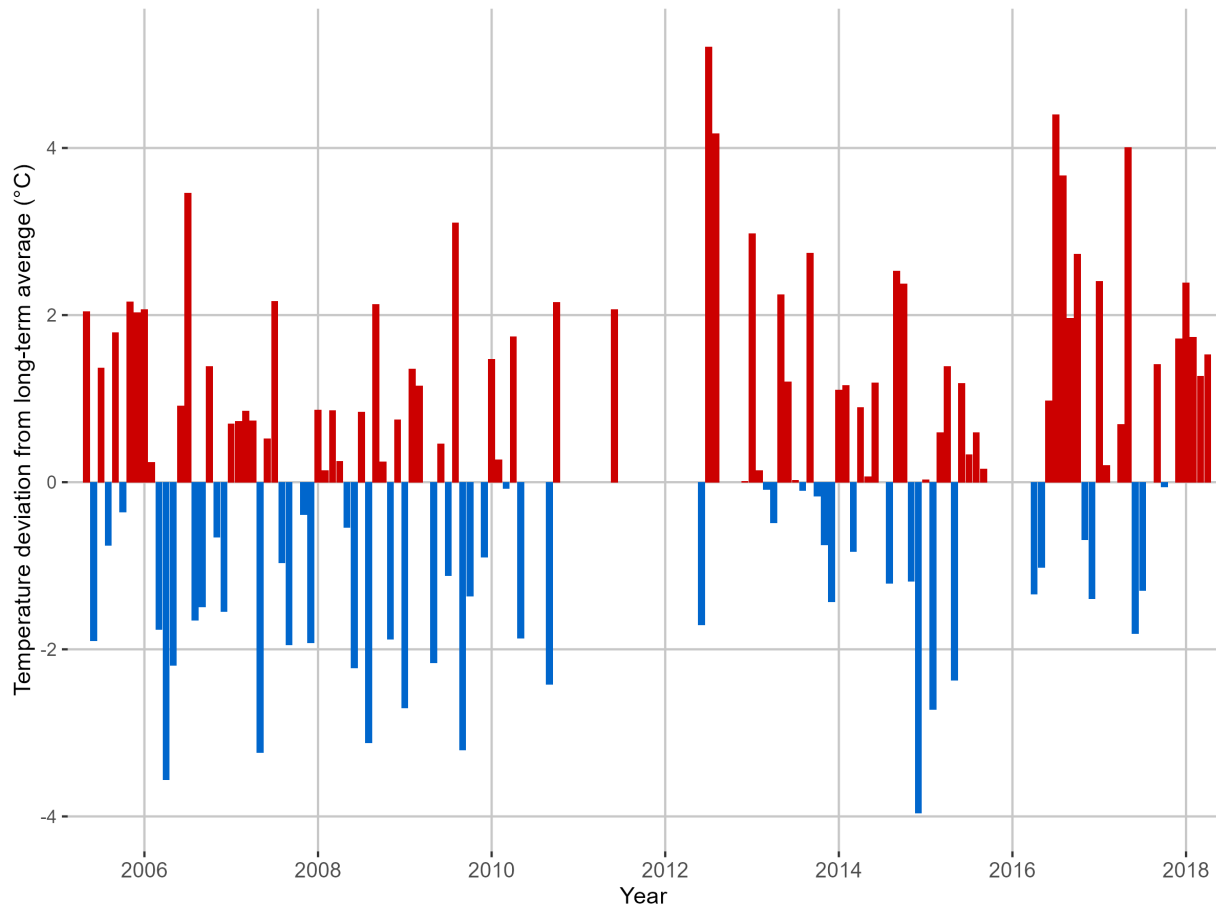


Figure 6. Monthly maximum temperature anomaly 2006–2018 at the Chaco Canyon weather station in Chaco Canyon NHP. Blue bars indicate months that were cooler than normal and red indicates months that were warmer than normal (source: <http://www.climateanalyzer.us>). Temperature anomaly is the difference between average temperature for a single month and the long-term average (1981–2010) for that month. Missing bars indicate months without sufficient data to calculate anomaly.

Soil overview

Twenty of 30 sandy loam upland plots were 100 cm deep or greater (Figure 7). Only two plots, S01 and S10, had soil profile depths ≤ 40 cm. Sandy textures were common, but soils were not uniform; many plots and layers contained considerable clay (Figure 7). Surface rocks and gravelly horizons were uncommon (Figure 7).

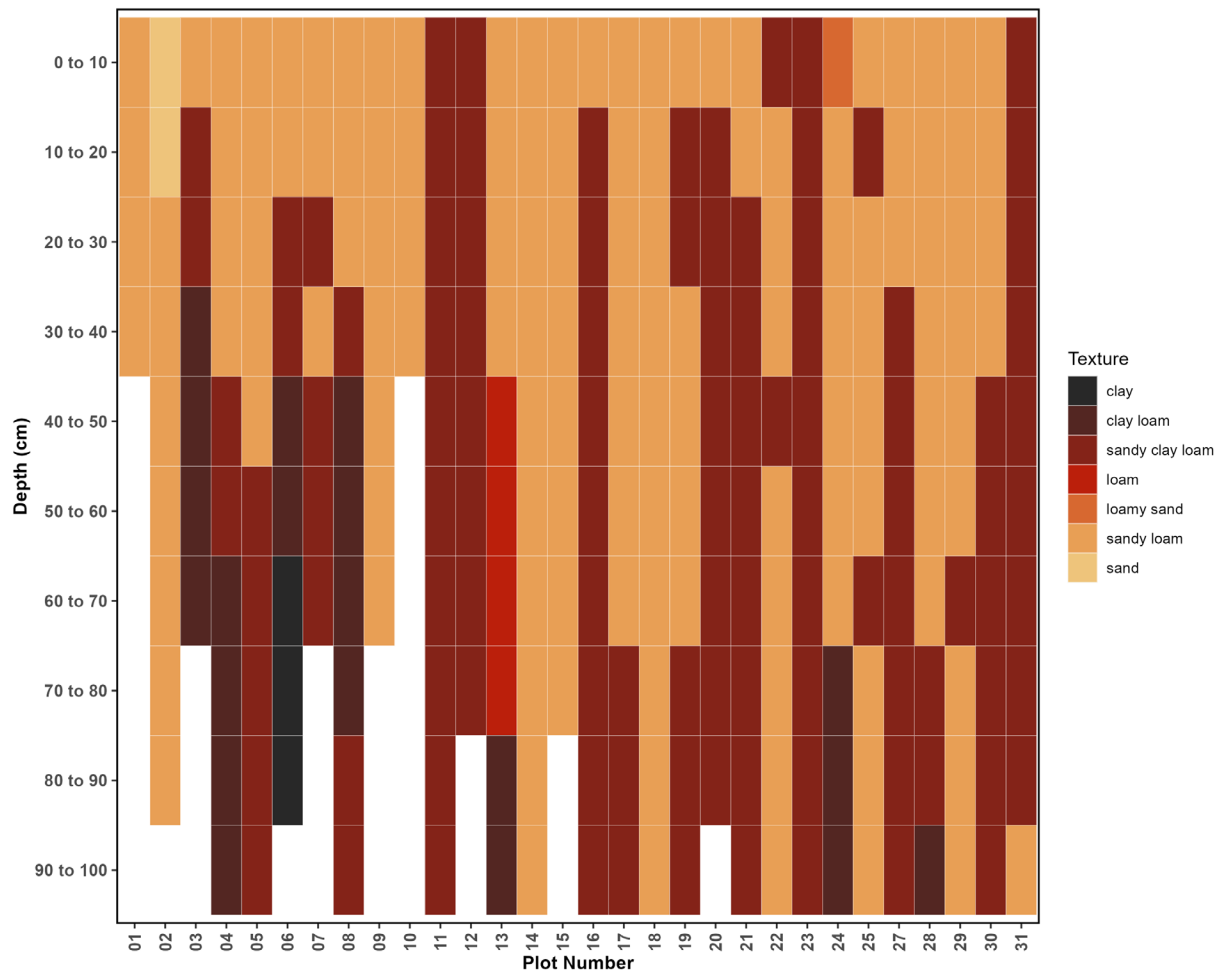


Figure 7. Texture and depth of soil profile samples collected during plot establishment from each monitoring plot in the sandy loam upland ecosite at Chaco Culture NHP.

Undifferentiated crust was the largest component of ground cover in the plots we sampled (Figure 8). This category includes both physical crusts formed from raindrop impact on exposed soil (non-biologic), as well as cyanobacteria-dominated biologic soil crusts that have not yet developed surface roughness or distinct coloration, since these can't be distinguished effectively in the field (Belnap et al. 2008). Bare ground (unconsolidated surface soil) and undifferentiated crust cover were both highly variable across plots and years. Some of this variation may be attributed to weather conditions during sampling, since distinguishing light cyanobacteria on wet soils can be difficult in the field, and physical crusts are most evident following rainfall events, and break down quickly during dry conditions, especially in sandy soils.

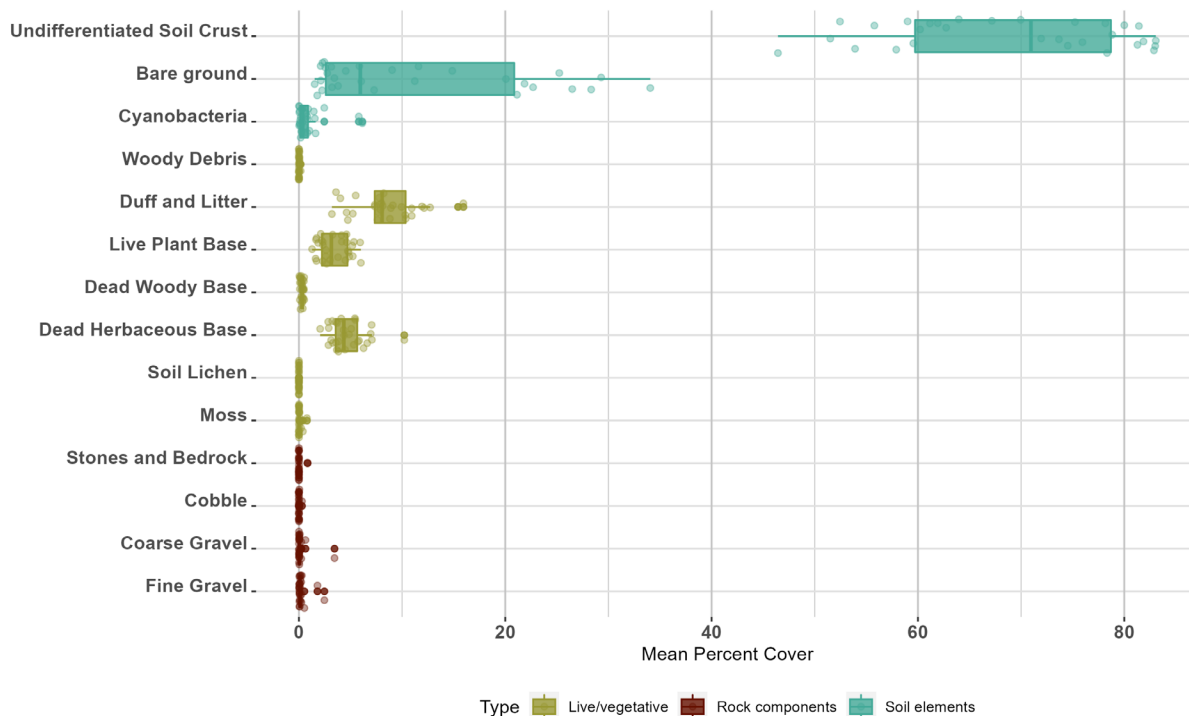


Figure 8. Mean percent cover of soil surface features in the sandy loam upland ecosite in Chaco Culture NHP, 2007–2018, based on cover class midpoints. Boxplots indicate median and range of values for each soil surface category observed. Dots indicate plot-level means.

Soil aggregate stability is widely accepted as an indicator of rangeland health, although evidence of direct linkages is lacking (Reinhart et al. 2015). Each plot at CHCU had soil samples that ranged over the full expression of stability, from least stable (1) to most stable (6). Stability was higher in samples obtained under perennial vegetative cover compared to samples taken from locations with no cover (Permutation test, difference of means = 1.40, p -value $1e-04$, $R = 10000$) (Table 2). Mean soil stability over the monitoring period (2007–2018) was in the midrange (3.40), indicating soils that were intermediately stable.

Table 2. Mean soil stability rating class for the sandy loamy upland ecosite at Chaco Culture NHP, 2007–2018. Soil stability rating class ranges from 1 (low soil aggregate stability) to 6 (high soil aggregate stability). In the Canopy Type column, “Vegetated” indicates samples were taken from under perennial vegetation canopy and “Bare” indicates samples had no canopy.

Ecosite	Canopy Type	Mean Rating	Min	Max
		Class		
Sandy loam upland	Overall	3.40	1	6
	Vegetated	4.01	1	6
	Bare	2.68	1	6

Vegetation overview

Average foliar cover on plots was 16%, with perennial grass composing nearly three-quarters of cover (Table 3). Shrub cover was a smaller component of total vegetation, but shrubs were present in every plot sampled. Forbs were also present in every plot but comprised very little of the overall vegetative cover. Cactus and yucca are not common at this ecosite and occurred in very few plots (Table 3). Cover by growth form differed somewhat among plots within the ecosite (Figure 9). Plot S31 is notable for having higher total foliar cover and perennial grass cover compared to other plots (Figure 9). Shrub cover varied between plots, but never exceeded 10%.

Table 3. Average percent cover of growth forms for the sandy loam upland ecosite in Chaco Culture NHP based on cover class midpoints, 2007–2018. Min and Max represent minimum and maximum plot means observed during the monitoring period. Cover estimates are not strictly additive due to canopy overlap and use of cover classes midpoints.

Ecosite	Growth form	Mean % Cover	Min	Max
Sandy loam upland	Total live foliar	16.00	3.18	43.17
	Perennial grass	11.45	1.88	35.83
	Shrub	3.39	0.83	12.30
	Forb	0.64	0.23	3.67
	Annual grass	0.02	0.00	0.59
	Cactus and yucca	0.10	0.00	0.89

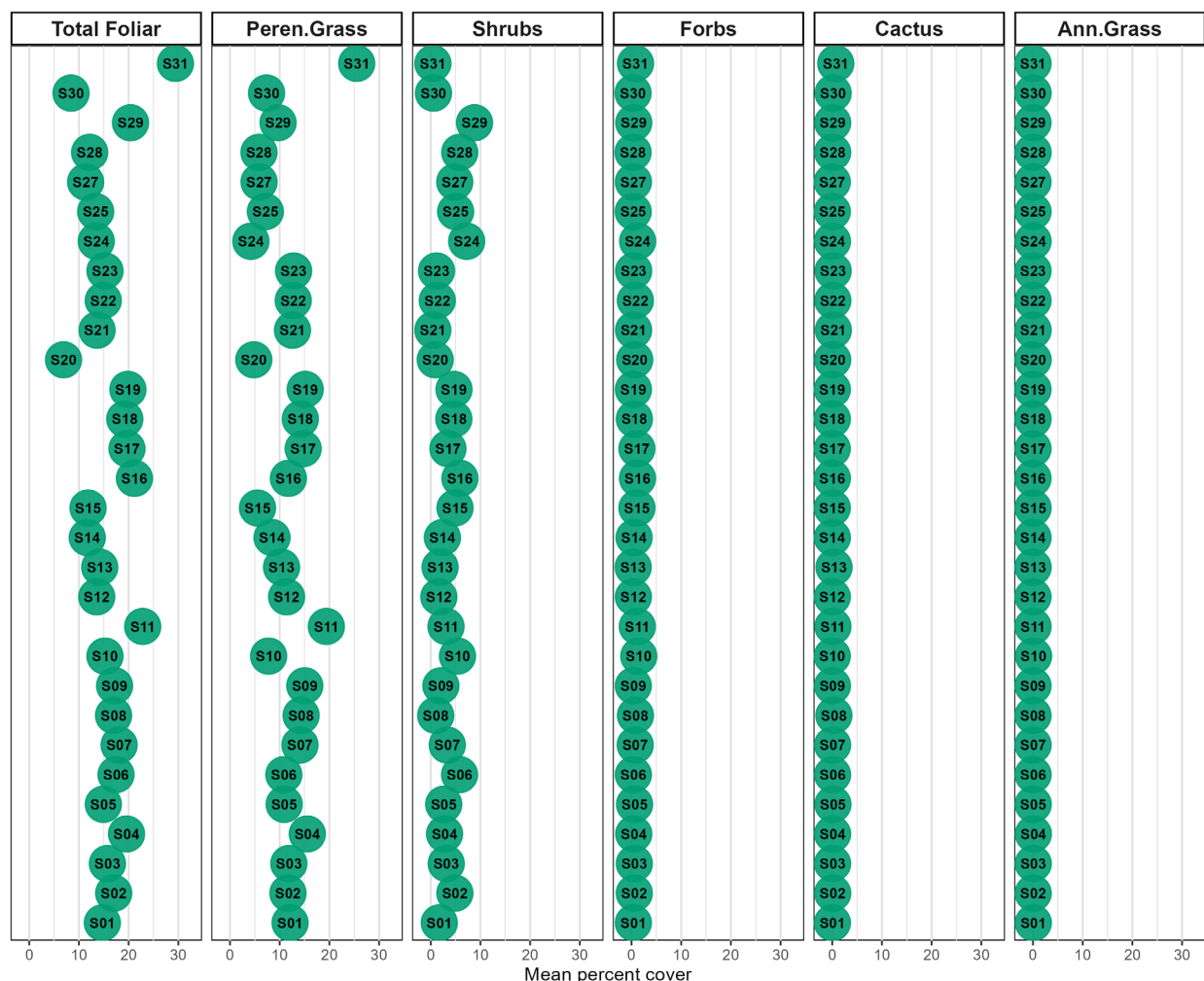


Figure 9. Mean percent cover by growth form in the sandy loam upland ecosite monitored at Chaco Culture NHP. Plot means were calculated for each year, then averaged across all years. Perennial grass cover was dominant. Shrub cover is generally low, but variable, while cover of forbs and annual grass was uniformly low across all plots in the ecosite.

We identified 67 plant species at CHCU between 2007 and 2018. We also recorded 16 genera for plants we were not able to reliably distinguish to species. Thirteen unknowns were recorded, which were unable to be identified because they were in very poor condition or without flowers or fruit. Most unknowns (11 of 13) occurred only once in a single quadrat. Cover was dominated by warm season grasses, including blue grama (*Bouteloua gracilis*), galleta grass (*Hilaria jamesii*) and dropseeds (*Sporobolus* spp.) (Figure 10). Dropseeds are represented primarily by *S. cryptandrus* in this ecosite, but also includes *S. airoides*, *S. contractus* and *S. flexuosus*. Indian ricegrass, (*Achnatherum hymenoides*), a cool-season native bunchgrass, was also among the most encountered species but had low cover.

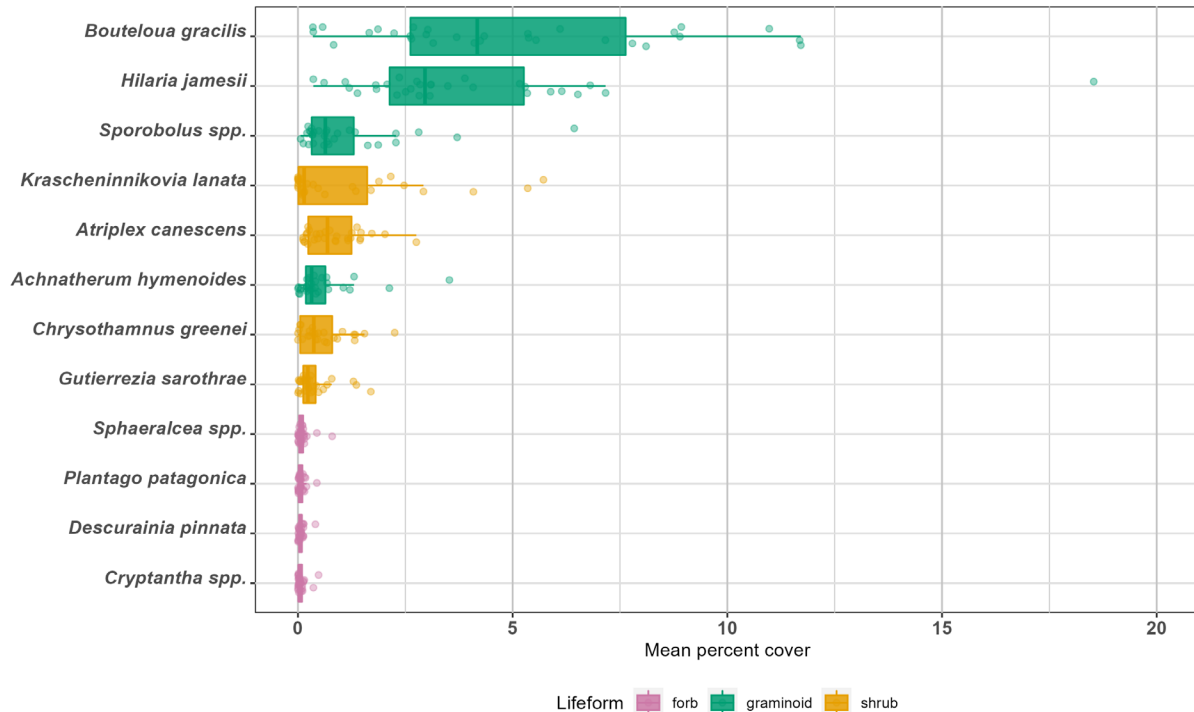


Figure 10. Mean percent foliar cover based on cover class midpoints of the 12 most frequently sampled species at the sandy loam upland ecosite in Chaco Culture NHP, 2007–2018. Boxplots indicate median and range of values for each species. Dots indicate plot-level means and color represents growth form.

Shrubs occurred in every plot sampled but had low foliar cover averaged across the ecosite. Winterfat (*Krascheninnikovia lanata*) and four-wing saltbush (*Atriplex canescens*) were the most frequently encountered shrubs along with Greene’s rabbitbrush (*Chrysothamnus Greenei*) and snakeweed (*Gutierrezia sarothrae*). The most encountered forbs were annuals, with the exception of *Sphaeralcea* spp. Appendix A contains a list of all species identified during sampling.

Except for a few species, most plants at this ecosite occur infrequently and at low cover (Figure 11). Over three-quarters (77%) of species detected during the monitoring period averaged less than 1% cover and < 10% frequency (including unknowns and genera-only identifications).

We assessed species richness at three scales: the 10 m² (quadrat) scale, the 50 x 52 m plot scale, and for the entire ecosite. Species richness was highly variable across plots and years at the quadrat and plot scales. At the smallest scale (10 m²), richness ranged from 2–20 species per quadrat with an average of 8.5 species per quadrat. At the plot scale, the lowest richness encountered during sampling was 13 and the highest was 35 species (at plot S04 in 2012). Average number of species per plot was 21. The wide range of richness at these scales reflects the patchy distribution of species in these grasslands over both space and time.

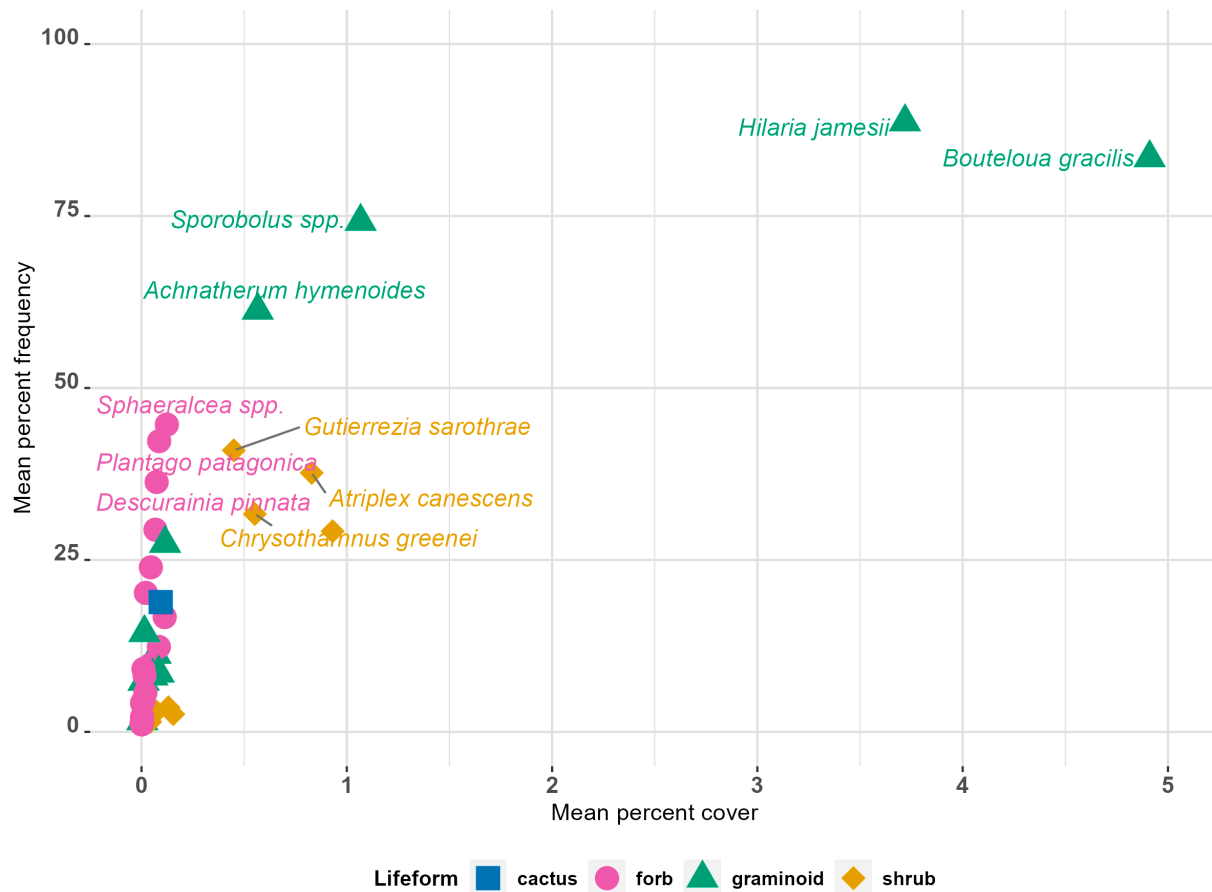


Figure 11. Percent cover and frequency for plant species in sandy loam upland ecosite at Chaco Culture NHP (2007–2018). Species that occur in less than 1% of plots are not shown, and species that occur in less than 15% of plots are not labelled (n=30 plots).

At the ecosite scale, richness is not comparable across the initial years of monitoring since we sampled different numbers of plots each year. Richness estimates based on data collected under the structured panel revisit design (2012–2018; equal number of plots sampled each year) remained fairly consistent between years (52–63 species). Beta diversity (the ratio between regional diversity and local diversity, defined here as ecosite richness/average plot richness across all years) was 4.5 for the sandy loam upland ecosite.

Three non-native species were encountered during the monitoring period (4% of all species detected): hogweed (*Portulaca oleracea*), cheatgrass (*Bromus tectorum*) and Russian thistle (*Salsola tragus*). Of these, only cheatgrass is listed on the state noxious species list and is widespread and well established in the state (New Mexico Department of Agriculture 2016). See Table 5 for the percent quadrat frequency of these three species over the monitoring period.

Table 4. Common native plant species frequency of occurrence (quadrat frequency) at Chaco Culture NHP over the sampling period (2007–2018). Common name, growth form, and duration are based on USDA Plants database (<https://plants.sc.egov.usda.gov/java>). C4 and C3 denote photosynthetic pathways. C4 species are warm season grasses adapted to grow under warmer temperatures while C3 species are cool season grasses.

Scientific Name	Common Name	Growth form	Duration	Quadrat Frequency
<i>Hilaria jamesii</i> (C4)	galleta grass	grass	perennial	89.1%
<i>Bouteloua gracilis</i> (C4)	blue grama	grass	perennial	82.9%
<i>Sporobolus</i> spp. (C4)	dropseed	grass	perennial	74.6%
<i>Achnatherum hymenoides</i> (C3)	Indian ricegrass	grass	perennial	60.9%
<i>Sphaeralcea</i> spp.	globemallow	forb	perennial	42.0%
<i>Plantago patagonica</i>	wooly plantain	forb	annual	40.0%
<i>Atriplex canescens</i>	four-wing saltbush	shrub	perennial	37.6%
<i>Gutierrezia sarothrae</i>	snakeweed	shrub	perennial	36.8%
<i>Descurainia pinnata</i>	western tansy-mustard	forb	annual	36.0%
<i>Chrysothamnus Greenei</i>	Greene's rabbitbrush	shrub	perennial	31.5%

Table 5. Proportion of quadrats where three nonnative species were detected at plots sampled in the sandy loam upland ecosite during Southern Colorado Plateau Network monitoring at Chaco Culture NHP (2007–2018). Note: the same plots were not sampled each year, and the number of plots sampled per year varied annually prior to 2021 as shown in Appendix B.

Ecosite	Scientific Name	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Sandy loam upland	<i>Bromus tectorum</i>	14	1.33	1.33	0	0	0.33	NS	0	NS	0.67	NS	1.0
	<i>Portulaca oleracea</i>	0	0	0	0	0	1.33	NS	0	NS	0	NS	0
	<i>Salsola tragus</i>	9.33	4.67	1.33	3.33	4.10	9.69	NS	11.67	NS	1.33	NS	2.67

Trend

Assessing trend

I&M networks are tasked with reporting on status and trend of selected natural resources. While the definition of status is clear, the concept of trend is more ambiguous. For this analysis, trend is defined as a directional change over time that is not explained by included weather covariates.

While significant change in vegetation communities commonly occurs over decades or centuries, some metrics (e.g., richness, plant cover and frequency) typically exhibit high variability from year to year in response to mechanistic driver variables, such as rainfall and temperature (e.g., de Dios Miranda et al. 2009, Schwinning and Ehleringer 2001). Therefore, assessing trend over relatively short durations, such as the 11-year monitoring period at CHCU, offers many challenges. Non-directional, year-to-year weather variation can have a large effect on perceived linear trends, especially if years with extreme highs or lows occur at the start or end of the monitoring period. We partially accounted for annual variation in weather by adding predictor variables (covariates) to our models. However, climate change is now influencing precipitation patterns and driving temperatures consistently higher every year on a global scale. These trend results present our best assessment based on the current toolset. A critical next step will be to explicitly link changes in response variables to system drivers (e.g., weather) to refine estimates.

Covariates

Final covariates and specifications for models are shown in Appendix C. Of the covariates we tested, seasonal precipitation totals performed similarly to derived variables, such as SPEI, in step-wise regression, so we chose to use them since their interpretation is simpler (data not shown). Our final set of potential covariates included winter precipitation (November–March), spring precipitation (April–June), spring temperature (April–June) and monsoon precipitation (July–September). For most responses, we found our models had the lowest posterior predictive loss (PPL) when we included the three seasonal precipitation variables in the model. Only the richness model includes spring temperature. Figure 12 displays the temporal patterns of the covariates we included in the final models for the monitoring period (2007–2018) to better interpret the effects of the included covariates on the change of a response over time.

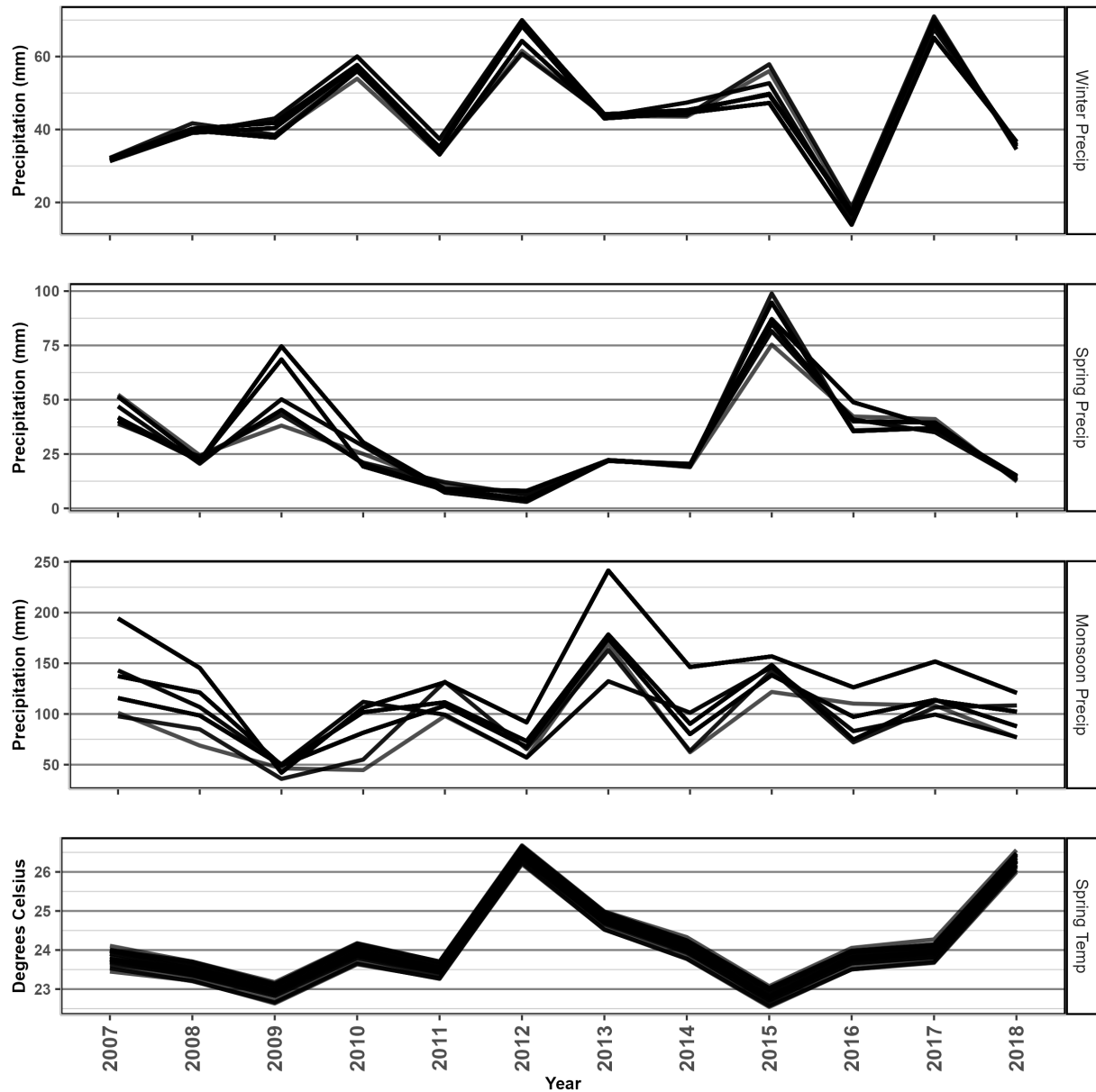


Figure 12. Annual patterns of climate covariates included in trend models. Each line represents precipitation for a monitored plot in the sandy loam upland ecosite at Chaco NHP (2007–2018). Seasonal precipitation totals for winter (November–March) spring (April–June), and monsoon (July–September) were obtained from the United States Stage IV Quantitative Precipitation Archive (Lin and Mitchell 2005). Note: y-axis varies in scale and units.

Trend in species richness

Our best fit model for species richness included spring temperature and three seasonal precipitation variables as covariates (see Appendix D). Conditional on the model, warmer spring temperatures led to a greater number of species detected per quadrat (mean of coefficient = 0.18; see Appendix C, Table C-2). Compared to temperature, effects of variation in precipitation were relatively weaker (range of mean coefficients -0.04 to -0.06) and negatively related to species richness (see Appendix C, Table C-2).

When we controlled for interannual variation in weather variables (by constraining their values at the mean throughout the monitoring period), there was a negative trend in model-predicted species richness (equivalent to the loss of 0.25 species per year, 95% CI [-0.279263362 , -0.16808745]) (Figure 13). This represents directional change in species richness during the monitoring period that is not explained by temperature or precipitation variables included in the model.

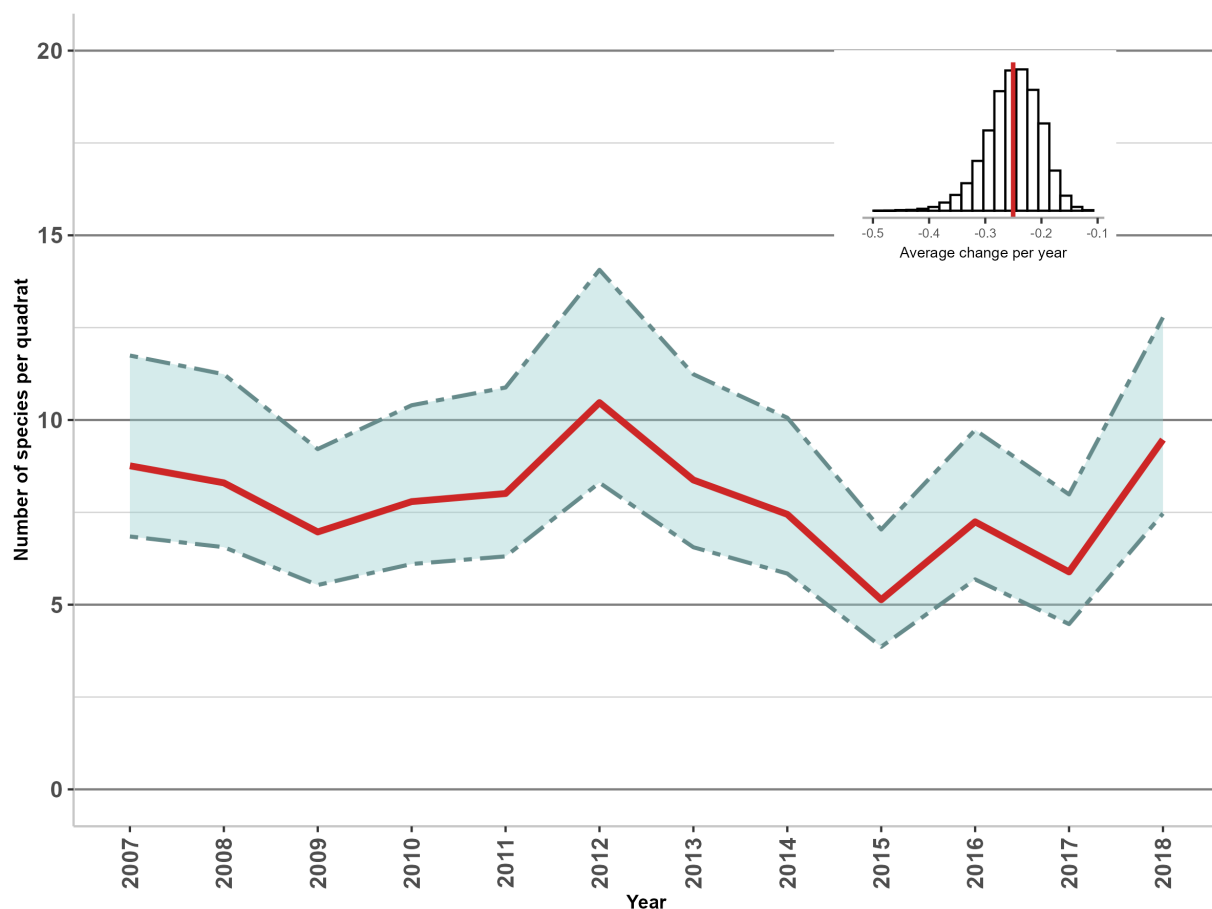


Figure 13. Change over time in mean model-predicted quadrat-level species richness (2007–2018) at sampled plots in the sandy loam upland ecosite at Chaco Culture NHP as a function of seasonal precipitation and spring temperature. The solid line indicates the mean richness at sampled plots, and the shaded area represents the 95% credible intervals. Inset shows posterior distribution of change over time is centered below 0, indicating a decreasing trend of .25 species per year.

Interannual variation in species richness at this ecosite is primarily driven by changes in annual forbs species that tend to exhibit species-specific responses to weather conditions. The first year of monitoring (2007) was the only year with average precipitation during the monitoring period; data from all other years was collected under dryer than normal conditions (Figure 5). It's possible that higher diversity during the initial (average precipitation) year coupled with lack of data collected during subsequent average precipitation years could bias model estimates of trend. Or the on-going mega-drought in the US Southwest could have had a negative effect on diversity in the ecosystem in a way not adequately captured by seasonal precipitation variables (Williams et al. 2020). Future modeling efforts that include data from normal or wetter than normal conditions should improve richness estimates.

Trend in total foliar cover

The best fit model for total foliar cover included the three seasonal precipitation variables. All three had positive effects on vegetative cover; spring precipitation had the strongest effect (mean of the coefficient 0.25; see Appendix C, Table C-2) and the effect of winter precipitation was the weakest (0.12). Andrews et al. (2019) also reported vegetative cover at CHCU was positively related to spring precipitation. Future foliar cover at CHCU may be uncertain, given climate predictions indicate winter and summer precipitation may remain relatively unchanged but drier springs will become more common at CHCU in the near future (Andrews et al. 2019).

CHCU experienced low spring precipitation from 2010 through 2014. Wet spring and winter conditions resulted in the highest predicted mean cover during 2015, a year we didn't sample (Figure 14). Because all but one year's sampling was during drier than average conditions, estimates of total foliar cover may be biased. When we removed the effect of interannual variation in seasonal precipitation, we saw no evidence of trend in total foliar cover during the monitoring period.

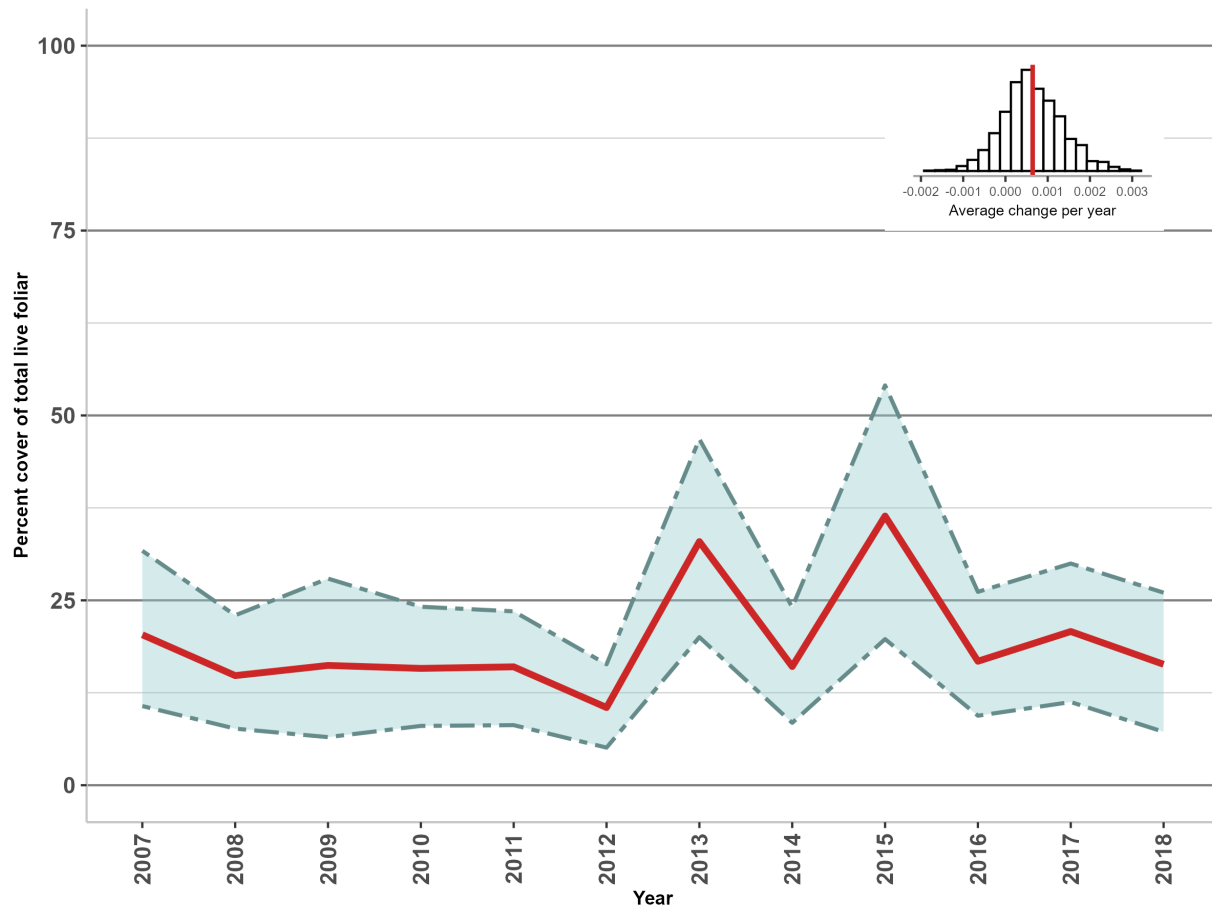


Figure 14. Model-based prediction of the change over time in mean total foliar cover (2007–2018) as a function of seasonal precipitation at plots sampled in the sandy loam upland ecosite at Chaco Culture NHP. The solid line indicates the predicted mean at sampled plots, and the shaded area represents the 95% credible intervals. Inset shows posterior distribution of change over time is centered near 0% indicating no evidence of a trend.

Trends in perennial grass cover

Bouteloua gracilis

The best fit model for *Bouteloua gracilis* included the three seasonal precipitation variables. Foliar cover of blue grama varied little from year to year (Figure 15). Conditional on the model, increased spring precipitation had a positive effect on *Bouteloua gracilis* cover (mean of the coefficient 0.09; see Appendix A, Table A-2). Monsoon season precipitation had a relatively weaker positive effect (0.02). Winter precipitation had a negative effect on *Bouteloua gracilis* cover, which reduced the strong peak observed in total foliar cover in 2015 (a year with increased winter *and* spring precipitation) (mean of the coefficient of winter precipitation = -0.15). When we controlled for the effect of annual variation in seasonal precipitation by holding the variables constant at their mean over the monitoring period, there was no evidence of trend (Figure 15, inset).

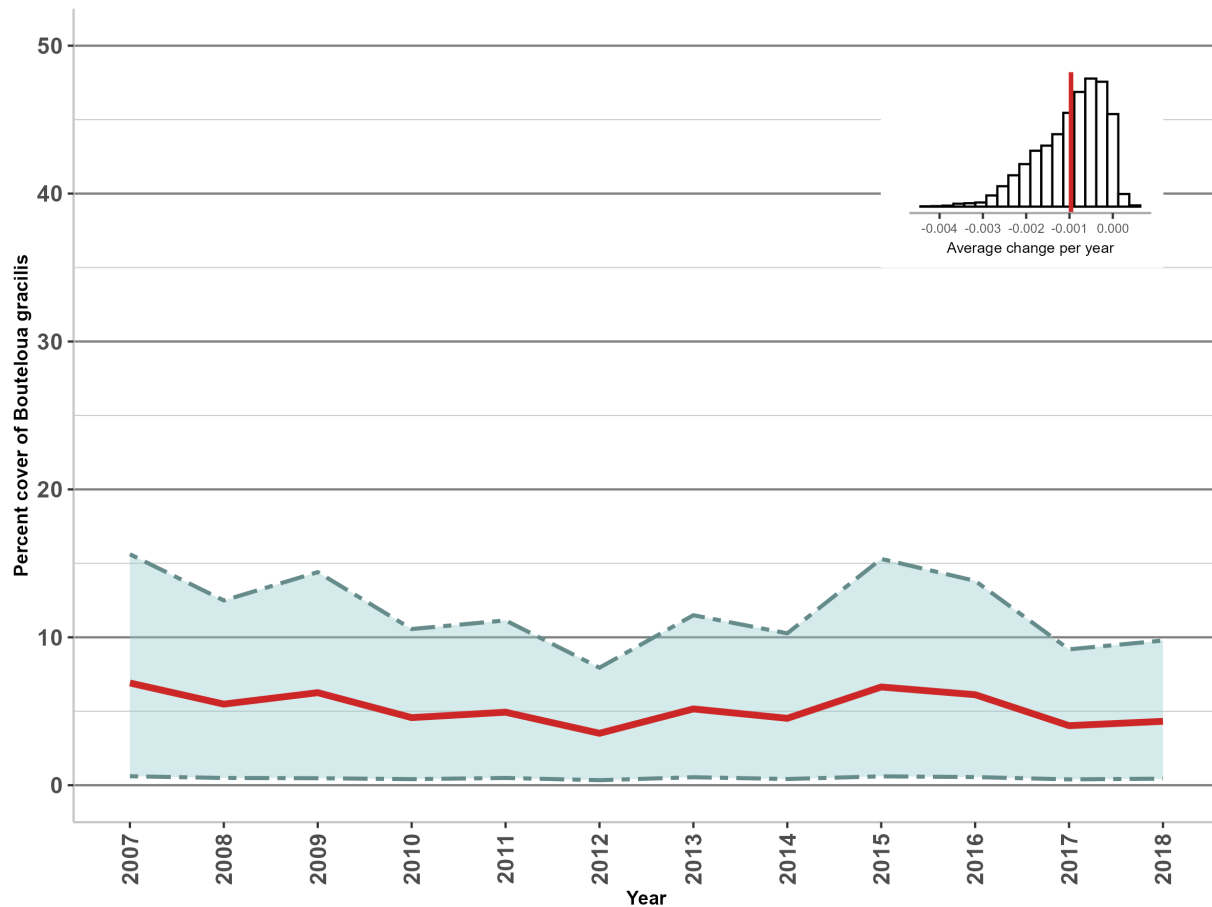


Figure 15. Model-based prediction of the change over time in mean percent cover of *Bouteloua gracilis* (2007–2018) as a function of seasonal precipitation at plots sampled in the sandy loam upland ecosite at Chaco Culture NHP. The solid line indicates the predicted mean at sampled plots, and the shaded area represents the 95% credible intervals. Inset shows posterior distribution of change over time is centered near 0% indicating no evidence of trend.

Hilaria jamesii

The best fit model for *Hilaria jamesii* included the three seasonal precipitation variables. Conditional on the model, all three seasonal precipitation variables had a positive effect on galleta grass cover (i.e., increased precipitation increased galleta grass cover), but the effects varied in magnitude with seasonality. The effect of spring season precipitation was strongest (coefficient mean 0.22; see Appendix A, Table A-2), followed by monsoon (0.08) and winter precipitation (0.05). The model predicted highest *Hilaria jamesii* cover in 2015, the year with the wettest spring during the monitoring period (and a year we didn't sample). When we controlled for the effect of annual variation in seasonal precipitation over the monitoring period, there was no evidence of a trend (Figure 16, inset).

Of the covariates considered, vegetated cover of the two dominant perennial grass species at CHCU was most strongly affected by spring precipitation. Climate models predict CHCU will experience drier and warmer springs in the near-term future due to climate change (Andrews et al. 2019) which

will likely have a negative effect on *Hilaria jamesii* and *Bouteloua gracilis* cover. However, the magnitude of this effect and the implications for the overall ecosystem are unknown.

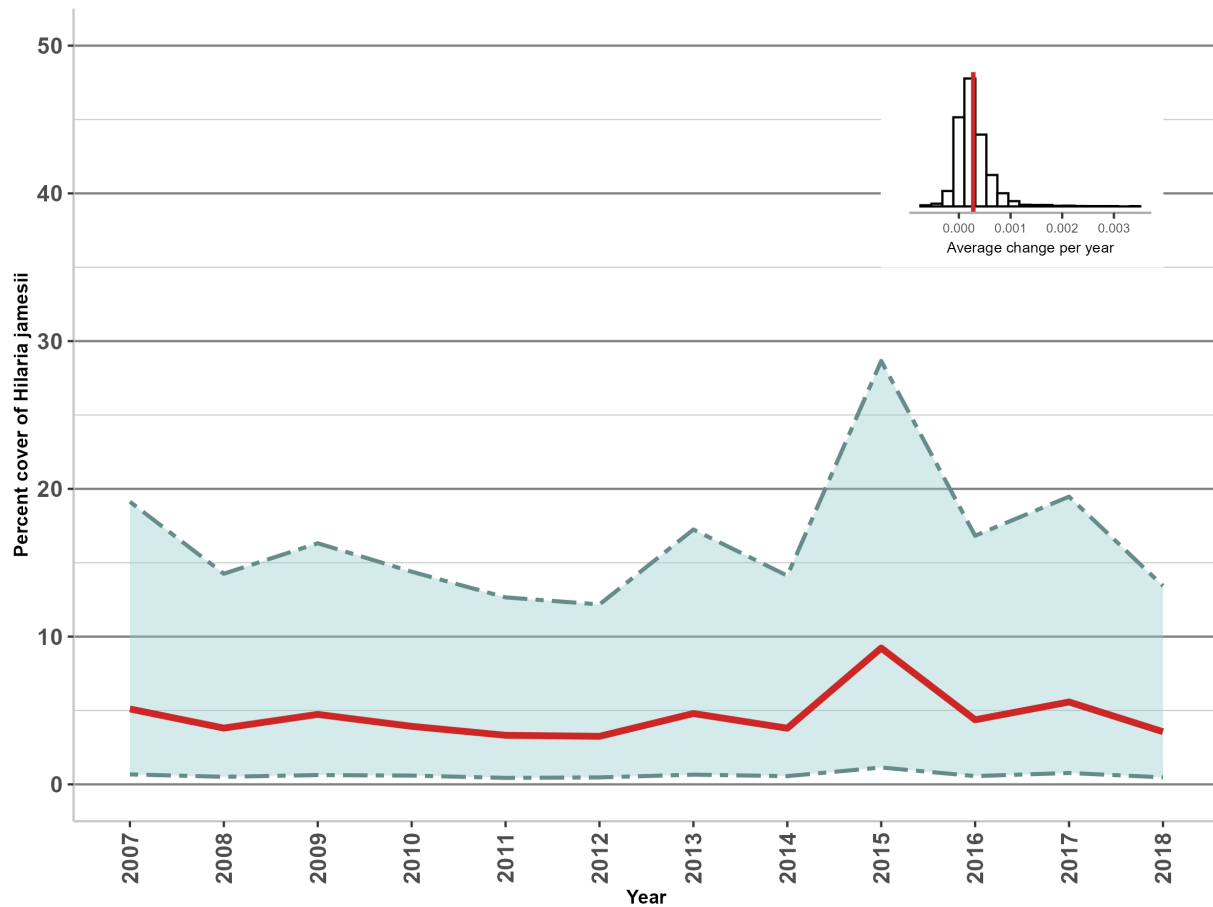


Figure 16. Model-based prediction of the change over time in mean percent cover of *Hilaria jamesii* (2007–2018) as a function of seasonal precipitation at plots sampled in the sandy loam upland ecosite at Chaco Culture NHP. The solid line indicates the predicted mean at sampled plots, and the shaded area represents the 95% credible intervals. Inset shows posterior distribution of change over time is centered near 0% indicating no evidence of a trend.

Trend in shrub cover

The best fit model for shrub cover included the three seasonal precipitation variables (see Appendix D). Mean model-predicted shrub cover increased in response to higher amounts of monsoon and spring precipitation (means of coefficient 0.08 and 0.07 respectively; see Appendix A, Table A-2). Winter precipitation had a negative effect (-0.07). When we removed the effect of weather covariates, there was no evidence of trend (Figure 17, inset).

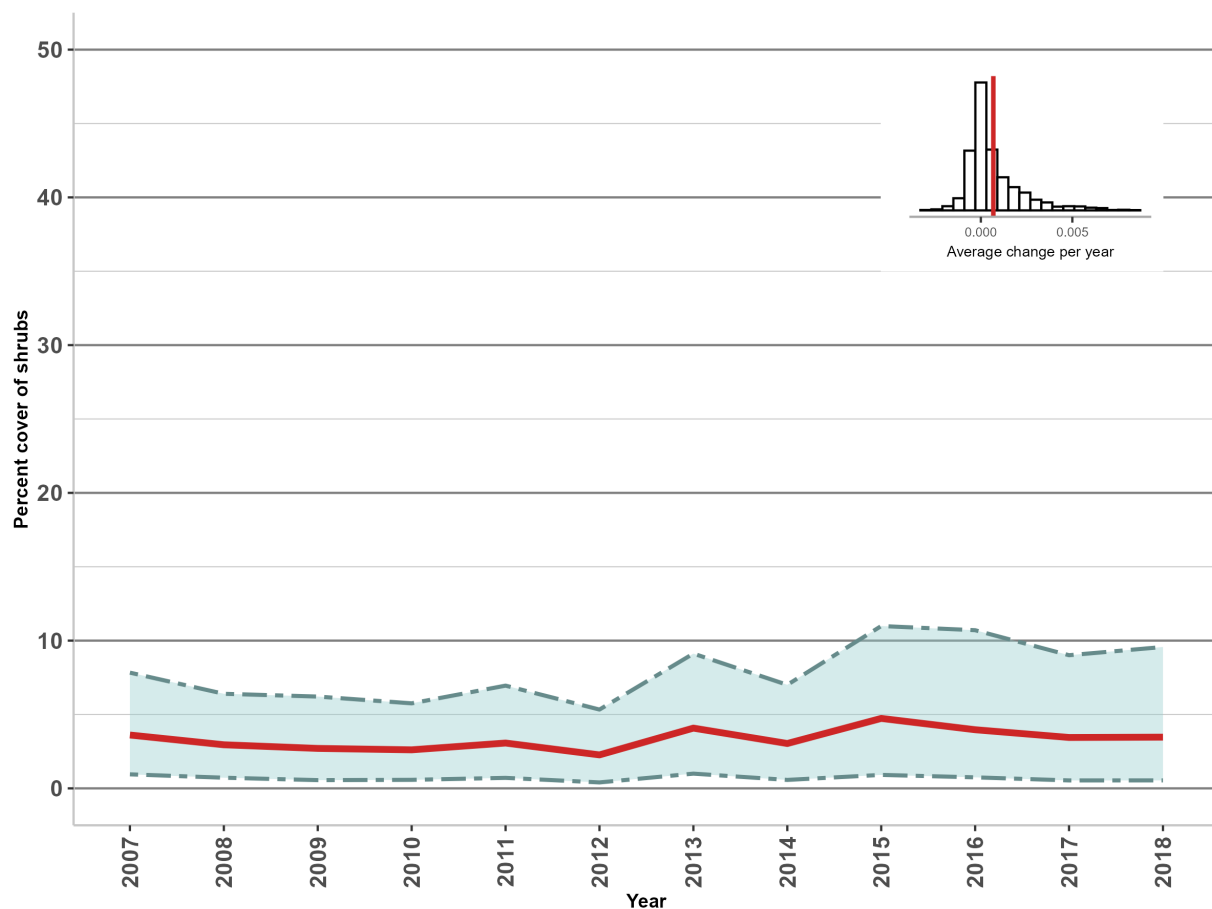


Figure 17. Model-based prediction of the change over time in shrub cover (2007–2018) as a function of seasonal precipitation at plots sampled in the sandy loam upland ecosite at Chaco Culture NHP. The solid line indicates the predicted mean at sampled plots, and the shaded area represents the 95% credible intervals. Inset shows posterior distribution of change over time is centered near 0% indicating no evidence of trend.

Trend in forb presence and cover

The best fit model for forbs included the three seasonal precipitation variables. Forb cover was relatively low throughout the monitoring period with little variation detected (Figure 18). All precipitation variables had a negative effect on forb cover, indicating less forb cover during wetter conditions. One explanation for this unexpected result is that higher cover of grass and shrubs during wet years may reduce forb detection rates or bias estimates of forb cover. Additional data (especially during wet years) are needed to better understand this response. When we held the seasonal precipitation variables constant at their mean over the monitoring period, there was no evidence of trend (Figure 18, inset).

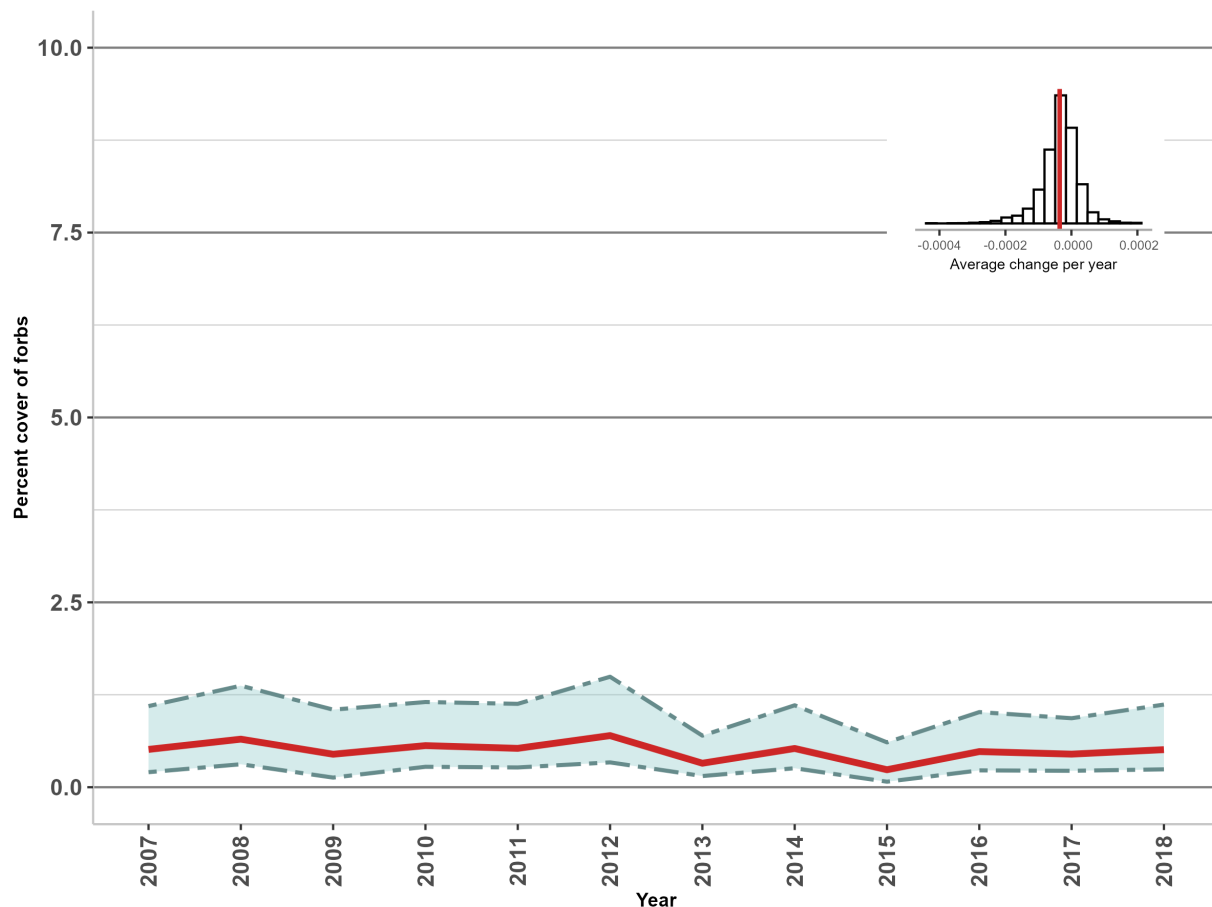


Figure 18. Model-based prediction of the change over time in mean percent cover for forbs (2007–2018) as a function of seasonal precipitation at plots sampled in the sandy loam upland ecosite at Chaco Culture NHP. The solid line indicates the predicted mean at sampled plots, and the shaded area represents the 95% credible intervals. Inset shows posterior distribution of change over time is centered near 0% indicating no evidence of a trend.

Trend in soil stability

Several models performed similarly for this response; we chose the model that included only winter precipitation since it was the simplest. Conditional on the model, increasing winter precipitation had a negative effect on soil stability ratings (mean of coefficient -0.40 ; see Appendix A, Table A-2). Increasing aridity has been shown to have a negative effect on the presence of soil aggregates with strong seasonal controls (Lavee et al. 1996). However, increasing winter moisture during freeze-thaw cycles has been shown to negatively impact soil aggregates (Oztas and Fayetorbay 2003). When we removed the effect of year-to-year variation in winter precipitation there was no evidence of a trend (Figure 19).

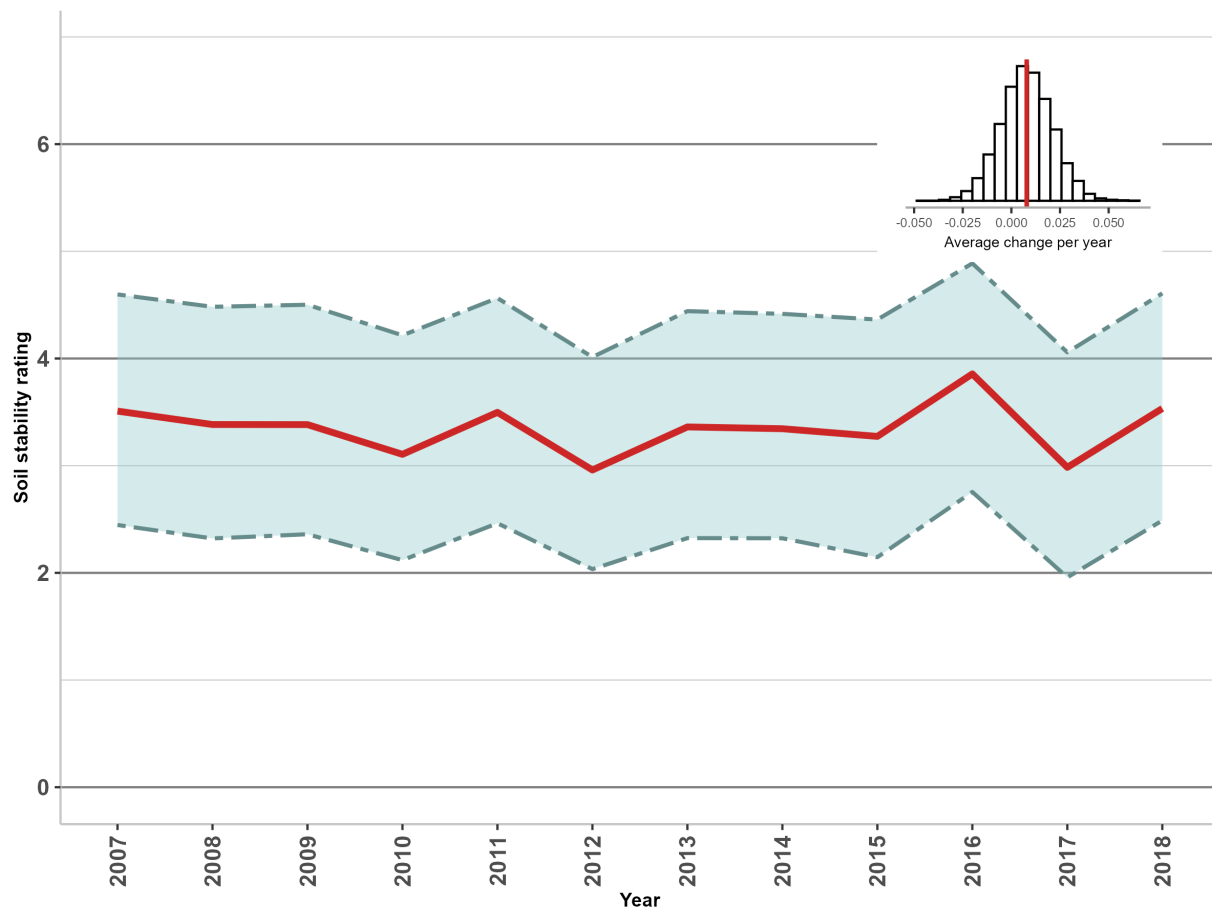


Figure 19. Model-based prediction of the change over time in soil stability ratings (2007–2018) as a function of winter precipitation at plots sampled in the sandy loam upland ecosite at Chaco Culture NHP. The solid line indicates the predicted mean at sampled plots, and the shaded area represents the 95% credible intervals. Inset shows posterior distribution of change over time is centered near 0%, indicating no evidence of trend.

Conclusions

This report presents the results of grassland vegetation and soil monitoring at Chaco Culture National Historical Park (CHCU) by the Southern Colorado Plateau Inventory and Monitoring Network from 2007–2018. We sampled 30 plots in a grassland ecosite on the mesa tops above Chaco Canyon. We summarized data over the monitoring period to better characterize ecosite composition and condition and explored how key metrics changed over the monitoring period to answer the following questions:

1. What were the characteristics of selected vegetation and soil components in the sandy loam upland ecosite at CHCU during the monitoring period (2007–2018)?

This ecosite has deep sandy loam and sandy clay loam soils. Undifferentiated crust was the largest component of ground cover, followed by litter. Unconsolidated bare soil was a lesser component on average but was highly variable. Soil aggregate stability was in the mid-range and was higher under vegetation than when samples were taken from areas with no vegetation canopy.

Total cover of live vegetation averaged 16%. Perennial grass was the largest component of vegetation cover, comprising just less than two-thirds of the total. Shrubs and forbs were a smaller component of overall cover but occurred in every plot sampled. Annual grass and cactus and yucca cover were low. Nonnative species were infrequent and comprised a very small component of the overall vegetation.

We identified 67 unique plant species, not including unknowns and genera-level identifications. Plot vegetation was co-dominated by two grass species: blue grama (*Bouteloua gracilis*) and galleta grass (*Hilaria jamesii*). We found just 3 nonnative species in our plots: cheatgrass (*Bromus tectorum*), Russian thistle (*Salsola tragus*) and kiss-me-quick (*Portulaca oleracea*). They occurred in few plots at low cover. No new species were detected during sampling.

2. How did the condition of these components change between 2007 and 2018?

Change over time was modeled by looking at the effect of year-to-year variation in seasonal precipitation on mean foliar cover, soil stability rating and species richness.

In general, cover of vegetation increased with increasing seasonal precipitation. Spring season precipitation had the strongest positive effect on total foliar cover in these grasslands, as well as on the cover of the two dominant grass species

Shrub cover increased with increasing spring and monsoon precipitation, and monsoon season precipitation had the largest effect on shrub cover.

Increased seasonal precipitation had a negative effect on species richness and forb cover; however, data was collected during drier than normal years. More data on richness from normal, or wetter than normal years, will improve estimates and may change this result.

Average soil stability remained in the mid-range over the monitoring period and decreased with increasing winter precipitation.

3. Is there evidence of positive or negative trends in key vegetation and soil metrics?

During the monitoring period (2007–2018), no response examined showed evidence of a strong negative trend that would be cause for concern when we controlled for year-to-year variation in seasonal precipitation and temperature.

Although species richness exhibited a weak negative trend during the monitoring period, and should be closely tracked in the future, estimates could be biased during the drier than average years we sampled. Additional data collected throughout the natural range of weather variation in this system would improve richness estimates and enable further consideration of this pattern.

Overall, the sandy loam upland ecosystem appears to be in good condition based on the metrics of vegetation cover, species richness, and soil stability we examined. While we provide evidence of considerable interannual variability in monitored metrics, there were few trends in the indicators we modeled.

Nearly all the vegetation metrics we modeled were positively related to spring precipitation. Continued grassland monitoring in this system is vital, as Andrews et al. (2019) also reported a strong relationship between spring precipitation and grassland vegetation in CHCU. Climate predictions indicate decreased spring precipitation and increased spring temperatures expected in the coming decades (Monahan and Fisichelli 2014, Andrews et al. 2019). Increasing drought stress in the spring months will almost certainly have a negative effect on the foliar cover of the dominant species in these grasslands with potential implications for system composition and function of unknown scale and magnitude.

SCPN will continue upland vegetation and soils monitoring at CHCU in the coming decades. Annual data summaries will be provided to the park each year in the spring following fieldwork.

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Appendix A: Plot Sampling History for the Sandy Loam Upland Ecosite at Chaco Culture National Historical Park (2007–2018)

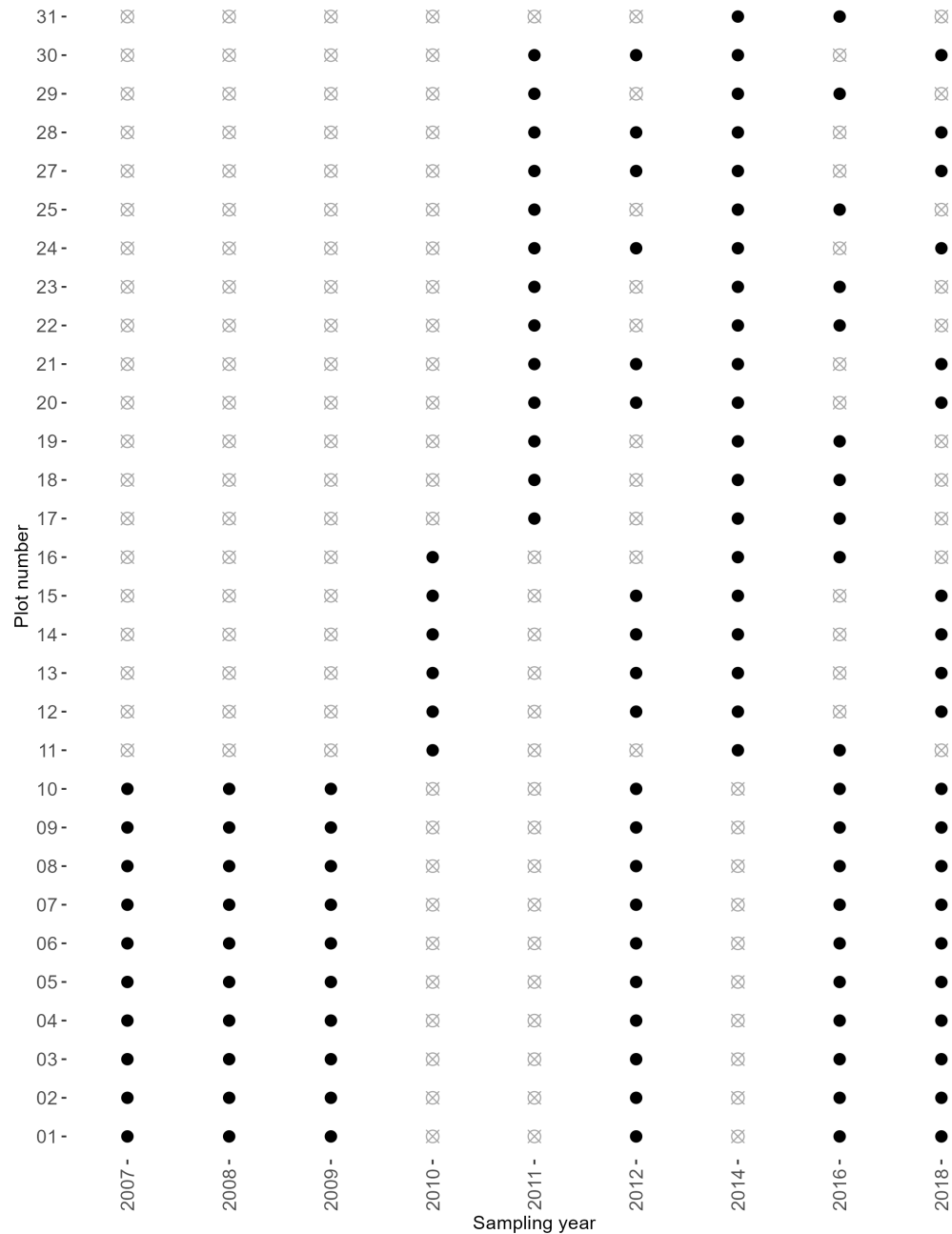


Figure A-1. Plot numbers are provided in the y-axis, sampling year is the x-axis. Black dots indicate plot was sampled during a year. Plot S26 was removed and replaced with Plot S31 in 2014. Data from S26 are not included in this report.

Appendix B: Vascular Plant Species Detected at Chaco Culture National Historical Park (2007–2018)

Table B-1. This table lists all species detected during Southern Colorado Plateau Network upland monitoring in Chaco Culture National Historical Park, 2007–2018. Nativity, growth form and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>).

Family	Scientific Name	Common Name	Duration	Growth form	Nativity
<i>Amaranthaceae</i>	<i>Amaranthus</i> spp.	NA	NA	forb	NA
<i>Amaranthaceae</i>	<i>Atriplex canescens</i>	fourwing saltbush	perennial	shrub	native
<i>Amaranthaceae</i>	<i>Atriplex obovata</i>	mound saltbush	perennial	shrub	native
<i>Amaranthaceae</i>	<i>Chenopodium</i> spp.	NA	NA	forb	NA
<i>Amaranthaceae</i>	<i>Krascheninnikovia lanata</i>	winterfat	perennial	shrub	native
<i>Amaranthaceae</i>	<i>Salsola tragus</i>	prickly Russian thistle	annual	forb	nonnative
<i>Amaranthaceae</i>	<i>Sarcobatus vermiculatus</i>	greasewood	perennial	shrub	native
<i>Amaryllidaceae</i>	<i>Allium macropetalum</i>	largeflower onion	perennial	forb	native
<i>Asclepidaceae</i>	<i>Asclepias macrotis</i>	longhood milkweed	perennial	forb	native
<i>Asteraceae</i>	<i>Artemisia bigelovii</i>	Bigelow sage	perennial	shrub	native
<i>Asteraceae</i>	<i>Artemisia filifolia</i>	sand sagebrush	perennial	shrub	native
<i>Asteraceae</i>	<i>Artemisia frigida</i>	prairie sagewort	perennial	forb	native
<i>Asteraceae</i>	<i>Artemisia tridentata</i>	big sagebrush	perennial	shrub	native
<i>Asteraceae</i>	<i>Chaetopappa ericoides</i>	rose heath	perennial	forb	native
<i>Asteraceae</i>	<i>Chrysothamnus Greenei</i>	Greene's rabbitbrush	perennial	shrub	native
<i>Asteraceae</i>	<i>Dieteria canescens</i>	hoary tansyaster	annual	forb	native
<i>Asteraceae</i>	<i>Ericameria nauseosa</i>	rubber rabbitbrush	perennial	shrub	native
<i>Asteraceae</i>	<i>Erigeron</i> spp.	NA	NA	forb	NA
<i>Asteraceae</i>	<i>Gutierrezia sarothrae</i>	broom snakeweed	perennial	shrub	native
<i>Asteraceae</i>	<i>Helianthus annuus</i>	common sunflower	annual	forb	native
<i>Asteraceae</i>	<i>Heterotheca villosa</i>	hairy false goldenaster	perennial	forb	native
<i>Asteraceae</i>	<i>Hymenopappus filifolius</i>	fineleaf hymenopappus	perennial	forb	native
<i>Asteraceae</i>	<i>Lorandersonia pulchella</i>	southwestern rabbitbrush	perennial	shrub	native
<i>Asteraceae</i>	<i>Sanvitalia abertii</i>	Abert's creeping zinnia	annual	forb	native

Table B-1 (continued). This table lists all species detected during Southern Colorado Plateau Network upland monitoring in Chaco Culture National Historical Park, 2007–2018. Nativity, growth form and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>).

Family	Scientific Name	Common Name	Duration	Growth form	Nativity
Asteraceae	<i>Schkuhria multiflora</i>	manyflower false threadleaf	annual	forb	native
Asteraceae	<i>Senecio spartioides</i>	broom-like ragwort	perennial	forb	native
Asteraceae	<i>Stephanomeria</i> spp.	NA	perennial	NA	NA
Asteraceae	<i>Tetradymia canescens</i>	spineless horsebrush	perennial	shrub	native
Asteraceae	<i>Townsendia annua</i>	annual Townsend daisy	annual	forb	native
Asteraceae	<i>Verbesina encelioides</i>	golden crownbeard	annual	forb	native
Boraginaceae	<i>Cryptantha</i> spp.	NA	NA	forb	NA
Boraginaceae	<i>Lappula occidentalis</i>	flatspine stickseed	annual	forb	native
Boraginaceae	<i>Lappula</i> spp.	NA	NA	forb	NA
Boraginaceae	<i>Lithospermum multiflorum</i>	manyflowered stoneseed	perennial	forb	native
Boraginaceae	<i>Nama dichotoma</i>	wishbone fiddleleaf	annual	forb	native
Boraginaceae	<i>Phacelia</i> spp.	NA	NA	forb	NA
Brassicaceae	<i>Boechera</i> spp.	NA	NA	forb	NA
Brassicaceae	<i>Descurainia pinnata</i>	western tansymustard	annual	forb	native
Brassicaceae	<i>Erysimum capitatum</i>	sanddune wallflower	biennial	forb	native
Brassicaceae	<i>Thelypodium wrightii</i>	Wright's thelypody	biennial	forb	native
Cactaceae	<i>Cylindropuntia whipplei</i>	Whipple cholla	perennial	cactus	native
Cactaceae	<i>Echinocereus triglochidiatus</i>	kingcup cactus	perennial	cactus	native
Cactaceae	<i>Escobaria vivipara</i>	spiny star	perennial	cactus	native
Cactaceae	<i>Opuntia</i> spp.	NA	perennial	cactus	NA
Convolvulaceae	<i>Evolvulus nuttallianus</i>	shaggy dwarf morning-glory	perennial	forb	native
Ephedraceae	<i>Ephedra cutleri</i>	Cutler's jointfir	perennial	shrub	native
Ephedraceae	<i>Ephedra torreyana</i>	Torrey's jointfir	perennial	shrub	native
Ephedraceae	<i>Ephedra viridis</i>	mormon tea	perennial	shrub	native
Euphorbiaceae	<i>Euphorbia fendleri</i>	Fendler's sandmat	perennial	forb	native
Euphorbiaceae	<i>Euphorbia</i> spp.	NA	NA	forb	NA
Fabaceae	<i>Astragalus</i> spp.	NA	NA	forb	NA

Table B-1 (continued). This table lists all species detected during Southern Colorado Plateau Network upland monitoring in Chaco Culture National Historical Park, 2007–2018. Nativity, growth form and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>).

Family	Scientific Name	Common Name	Duration	Growth form	Nativity
Linaceae	<i>Linum puberulum</i>	plains flax	annual	forb	native
Loasaceae	<i>Mentzelia albicaulis</i>	whitestem blazingstar	annual	forb	native
Malvaceae	<i>Sphaeralcea</i> spp.	NA	NA	forb	NA
Onagraceae	<i>Oenothera</i> spp.	NA	NA	forb	NA
Orobanchaceae	<i>Orobanche ludoviciana</i>	Louisiana broomrape	annual	forb	native
Plantaginaceae	<i>Plantago patagonica</i>	woolly plantain	annual	forb	native
Plantaginaceae	<i>Penstemon</i> spp.	NA	NA	forb	NA
Poaceae	<i>Achnatherum hymenoides</i>	Indian ricegrass	perennial	graminoid	native
Poaceae	<i>Aristida purpurea</i>	purple threeawn	perennial	graminoid	native
Poaceae	<i>Bouteloua barbata</i>	sixweeks grama	annual	graminoid	native
Poaceae	<i>Bouteloua gracilis</i>	blue grama	perennial	graminoid	native
Poaceae	<i>Bromus tectorum</i>	cheatgrass	annual	graminoid	nonnative
Poaceae	<i>Elymus elymoides</i>	squirreltail	perennial	graminoid	native
Poaceae	<i>Hesperostipa comata</i>	needle and thread	perennial	graminoid	native
Poaceae	<i>Hilaria jamesii</i>	galleta	perennial	graminoid	native
Poaceae	<i>Muhlenbergia pungens</i>	sandhill muhly	perennial	graminoid	native
Poaceae	<i>Muhlenbergia torreyi</i>	ring muhly	perennial	graminoid	native
Poaceae	<i>Munroa squarrosa</i>	false buffalograss	annual	graminoid	native
Poaceae	<i>Sporobolus coromandelianus</i>	Madagascar dropseed	annual	graminoid	native
Poaceae	<i>Sporobolus</i> spp.	NA	NA	graminoid	NA
Poaceae	<i>Vulpia octoflora</i>	sixweeks fescue	annual	graminoid	native
Polemoniaceae	<i>Gilia</i> spp.	NA	NA	forb	NA
Polemoniaceae	<i>Ipomopsis pumila</i>	dwarf ipomopsis	annual	forb	native
Polygonaceae	<i>Eriogonum cernuum</i>	nodding buckwheat	annual	forb	native
Polygonaceae	<i>Eriogonum corymbosum</i>	crispleaf buckwheat	perennial	shrub	native
Polygonaceae	<i>Eriogonum leptocladon</i>	sand buckwheat	perennial	shrub	native
Polygonaceae	<i>Rumex hymenosepalus</i>	canaigre dock	perennial	forb	native

Table B-1 (continued). This table lists all species detected during Southern Colorado Plateau Network upland monitoring in Chaco Culture National Historical Park, 2007–2018. Nativity, growth form and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>).

Family	Scientific Name	Common Name	Duration	Growth form	Nativity
<i>Portulacaceae</i>	<i>Portulaca oleracea</i>	little hogweed	annual	forb	nonnative
<i>Santalaceae</i>	<i>Comandra umbellata</i>	bastard toadflax	perennial	forb	native
<i>Solanaceae</i>	<i>Chamaesaracha coronopus</i>	greenleaf five eyes	perennial	forb	native
<i>Solanaceae</i>	<i>Lycium pallidum</i>	pale desert-thorn	perennial	shrub	native
<i>Solanaceae</i>	<i>Solanum jamesii</i>	wild potato	perennial	forb	native

Appendix C: Bayesian Models

Table C-1. Model specifications for all responses presented in this report. Model indicates the type of deterministic model used. Model type indicates whether slope only (b0) or slope and intercepts (b1) varied by site. For the hurdle ordinal model, slopes and intercepts could vary by percent cover response (b0-b1) as well as by present/not present response (g0-g1). Variance type indicates how variance was treated in the model. Fixed site indicates that each site has its own independent variance. Hierarchical site indicates the variance for a site was drawn from an underlying distribution of variances. Likelihood indicates what distribution was used for the likelihood in the model. Covariates used in the model are listed. For model checking, we used P_{mean} the Bayesian p-value for the mean and is used to indicate lack of fit. P_{sd} is the same for the variance. Models used for cover are mixed models and have two sets of model-checking values, the first represents the percent cover response, and the second set of P values represents the presence/absence response. PPL is posterior predictive loss, models with lowest posterior predictive loss were selected. The Gelman diagnostic is an indicator of convergence and should be close to one. See Zachmann et al. 2021 for more detail.

Response	Model	Model type	Variance level and type	Likelihood	Covariates	P_{mean}	P_{sd}	for mixed models		PPL	Gel
								P_{mean}	P_{sd}		
Species richness	linear	b0	stratum, fixed	poisson	Winter precipitation, spring temperature, spring precipitation, monsoon precipitation	0.74	0.48	NA	NA	2293929	1.02
Total live foliar cover	Inverse logit	b0-g0	site, hierarchical	hurdle-ordinal-latent-beta	Winter precipitation, spring precipitation, monsoon precipitation	0.55	0.78	1	1	5303	1.02
<i>Bouteloua gracilis</i> cover	Inverse logit	b0-g0	site, hierarchical	hurdle-ordinal-latent-beta	Winter precipitation, spring precipitation, monsoon precipitation	0.96	0.72	0.52	0.53	7646	1.06
<i>Hilaria jamesii</i> cover	Inverse logit	b0-g0	site, hierarchical	hurdle-ordinal-latent-beta	Winter precipitation, spring precipitation, monsoon precipitation	0.86	0.68	0.51	0.53	7330	1.01

Table C-1 (continued). Model specifications for all responses presented in this report. Model indicates the type of deterministic model used. Model type indicates whether slope only (b0) or slope and intercepts (b1) varied by site. For the hurdle ordinal model, slopes and intercepts could vary by percent cover response (b0-b1) as well as by present/not present response (g0-g1). Variance type indicates how variance was treated in the model. Fixed site indicates that each site has its own independent variance. Hierarchical site indicates the variance for a site was drawn from an underlying distribution of variances. Likelihood indicates what distribution was used for the likelihood in the model. Covariates used in the model are listed. For model checking, we used Pmean the Bayesian p-value for the mean and is used to indicate lack of fit. Psd is the same for the variance. Models used for cover are mixed models and have two sets of model-checking values, the first represents the percent cover response, and the second set of P values represents the presence/absence response. PPL is posterior predictive loss, models with lowest posterior predictive loss were selected. The Gelman diagnostic is an indicator of convergence and should be close to one. See Zachmann et al. 2021 in prep for more detail.

Response	Model	Model type	Variance level and type	Likelihood	Covariates	P _{mean}	P _{sd}	for mixed models		PPL	Gel
								P _{mean}	P _{sd}		
Shrub cover	Inverse logit	b0-b1 g0	site, hierarchical	hurdle-ordinal-latent-beta	Winter precipitation, spring precipitation, monsoon precipitation	0.78	0.50	0.49	0.51	7018	1.07
Forb Cover	Inverse logit	b0-g0	site, hierarchical	hurdle-ordinal-latent-beta	Winter precipitation, spring precipitation, monsoon precipitation	0.63	0.46	0.54	0.54	3862	1.01
Soil aggregate stability	linear	b0	site, hierarchical	ordinal-latent-normal	Winter precipitation	0.47	0.48	NA	NA	10129	1.01

Table C-2. Means and standard deviations of the coefficients for each model. Coefficient effects can be compared within a model. Direction of effect is indicated by +/- sign.

Response	Covariate	Coefficient Mean	Coefficient Standard Deviation
Species richness	Winter precipitation	-0.05615	0.01697
	Spring precipitation	-0.0367	0.01232
	Monsoon precipitation	-0.03643	0.01099
	Spring temperature	+0.1769	0.01415
Total live foliar cover	Winter precipitation	+0.12155	0.02888
	Spring precipitation	+0.25303	0.01599
	Monsoon precipitation	+0.21771	0.01442
<i>Bouteloua gracilis</i> cover	Winter precipitation	-0.15015	0.03378
	Spring precipitation	+0.08743	0.03121
	Monsoon precipitation	+0.02143	0.02441
<i>Hilaria jamesii</i> cover	Winter precipitation	+0.05748	0.03156
	Spring precipitation	+0.21514	0.03025
	Monsoon precipitation	+0.08366	0.02685
Shrub cover	Winter precipitation	-0.07121	0.03255
	Spring precipitation	+0.08501	0.02503
	Monsoon precipitation	+0.07047	0.03137
Forb Cover	Winter precipitation	-0.09951	0.03185
	Spring precipitation	-0.15918	0.02223
	Monsoon precipitation	-0.0692	0.02183
Soil aggregate stability rating	Winter precipitation	-0.3964	0.05734

Appendix D: Model Selection Results

For each of the seven models (D-1 to D-7), we developed several candidate models and assessed model fit using posterior predictive simulation to generate Bayesian p-values. Bayesian p-values > 0.1 and < 0.9 indicate lack of fit. We checked all models for convergence using the Gelman-Rubin diagnostic (Gelman diagnostic < 1.1 , Gelman and Rubin 1992). We then selected our final models by choosing those that minimized posterior predictive losses (PPL) (Hobbs and Hooten 2015). AMJP is spring accumulated precipitation, JASP is summer accumulated precipitation, NDJFMP is winter precipitation. AMJT is spring temperature. NA indicates no covariates were included in the model.

Table D-1. Species richness.

Covariates	Group level effects	Variance Level	Variance Type	Pmean	Psd	Gelman	PPL
AMJP, NDJFMP, JASP, AMJT	b0	stratum	fixed	0.48	0.74	1.02	2293929
AMJP, NDJFMP, JASP	b0	stratum	fixed	0.52	0.56	1.01	2576092
NDJFMP, JASP, AMJP	b0	stratum	fixed	0.5	0.59	1	2584329
JASP	b0-b1	stratum	fixed	0.59	0.57	1.01	2757410
NDJFMP, JASP	b0-b1	stratum	fixed	0.59	0.55	1.04	2763275
NA	b0-b1	stratum	fixed	0.57	0.64	1.01	2776671
NDJFMP, JASP	b0	stratum	fixed	0.5	0.62	1	2802383
JASP	b0	stratum	fixed	0.51	0.57	1.01	2805285
NA	b0	stratum	fixed	0.51	0.61	1	2825369

Table D-2. Total live foliar cover. Due to high frequency of observations, inference on the presence/absence component of the model (zeros) was dropped.

Covariates	Group level effects	Group level effects (zeros)	Variance level	Variance type	Pmean	Psd	Gelman	Pmean (zeros)	Psd (zeros)	PPL	DIC
NDJFMP, JASP, AMJP	b0	g0	site	hier	0.55	0.78	1.02	1	1	5303	5993
NDJFMP, JASP, AMJP	b0	g0	stratum	fixed	0.74	0.86	1.02	1	1	5517	6173
NA	b0	g0	site	hier	0.39	0.69	1.02	1	1	6297	6407
NA	b0	g0	stratum	fixed	0.67	0.72	1.01	1	1	6548	6537

Table D-3. *Bouteloua gracilis* cover.

Covariates	Group level effects	Group level effects (zeros)	Variance level	Variance type	Pmean	Psd	Gelman	Pmean (zeros)	Psd (zeros)	PPL	DIC
NDJFMP, JASP, AMJP	b0-b1	g0	site	hier	0.96	0.72	1.06	0.52	0.53	7646	6041
NDJFMP, JASP, AMJP, AMJT	b0	g0	site	hier	0.94	0.75	1.01	0.51	0.52	7848	6062
NDJFMP, JASP, AMJP, Mesa	b0	g0	site	hier	0.93	0.76	1.05	0.53	0.53	7859	6060
NDJFMP, JASP, AMJP	b0	g0	site	hier	0.94	0.74	1.01	0.52	0.53	7862	6060
NDJFMP, JASP, AMJP, AMJT, Mesa	b0	g0	site	hier	0.93	0.75	1.05	0.52	0.53	7867	6063
AMJP, AMJT	b0	g0	site	hier	0.91	0.64	1.01	0.52	0.53	8070	6097
NDJFMP, JASP	b0-b1	g0	site	hier	0.8	0.55	1.06	0.52	0.54	8214	6145
JASP	b0-b1	g0	site	hier	0.77	0.55	1.07	0.52	0.54	8299	6148
NA	b0-b1	g0	site	hier	0.74	0.58	1.01	0.52	0.53	8403	6171
JASP	b0	g0	site	hier	0.58	0.59	1.01	0.53	0.54	8833	6214
NA	b0	g0	site	hier	0.58	0.59	1	0.54	0.55	8848	6222
JASP	b0-b1	g0	stratum	fixed	0.98	0.6	1.07	0.53	0.54	9225	6348
NA	b0-b1	g0	stratum	fixed	0.98	0.65	1.03	0.52	0.54	9335	6366

Table D-4. *Hilaria jamesii* cover.

Covariates	Group level effects	Group level effects (zeros)	Variance level	Variance type	Pmean	Psd	Gelman	Pmean (zeros)	Psd (zeros)	PPL	DIC
NDJFMP, JASP, AMJP	b0	g0	site	hier	0.86	0.68	1.01	0.51	0.53	7330	6186
JASP	b0-b1	g0	site	hier	0.84	0.64	1.02	0.54	0.55	7436	6244
NDJFMP, JASP	b0-b1	g0	site	hier	0.83	0.62	1.1	0.53	0.55	7450	6250
NA	b0-b1	g0	site	hier	0.82	0.61	1.03	0.54	0.55	7509	6261
NA	b0	g0	site	hier	0.68	0.58	1.01	0.55	0.56	7855	6289

Table D-5. Shrub cover.

Covariates	Group level effects	Group level effects (zeros)	Variance level	Variance type	Pmean	Psd	Gelman	Pmean (zeros)	Psd (zeros)	PPL	DIC
NDJFMP, JASP, AMJP	b0-b1	g0	site	hier	0.78	0.5	1.07	0.49	0.51	7018	5850
NDJFMP, JASP, AMJP, AMJT	b0-b1	g0	site	hier	0.78	0.55	1.06	0.53	0.54	7049	5851
AMJP, JASP	b0-b1	g0-g1	site	hier	0.77	0.48	1.03	0.52	0.53	7073	5854
AMJP, JASP	b0	g0	site	hier	0.8	0.47	1.01	0.52	0.53	7170	5864
NDJFMP, JASP, AMJP	b0	g0	site	hier	0.82	0.49	1.01	0.5	0.52	7150	5866
JASP	b0-b1	g0	site	hier	0.64	0.5	1.07	0.48	0.5	7296	5892
JASP	b0	g0	site	hier	0.72	0.62	1.07	0.51	0.53	7516	5929
NA	b0-b1	g0-g1	site	hier	0.62	0.52	1.07	0.53	0.54	7432	5930
NA	b0-b1	g0	site	hier	0.59	0.49	1.05	0.5	0.53	7429	5932
NA	b0	g0	site	hier	0.58	0.47	1.03	0.52	0.54	7626	5955

Table D-6. Forb cover.

Covariates	Group level effects	Group level effects (zeros)	Variance level	Variance type	Pmean	Psd	Gelman	Pmean (zeros)	Psd (zeros)	PPL	DIC
NDJFMP, JASP, AMJP	b0	g0	site	hier	0.63	0.46	1.01	0.54	0.54	3862	4913

Table D-7. Soil stability rating. The top three models performed similarly. We chose to present the NDJFMP model because it had the lowest DIC.

Covariates	Group level effects	Variance level	Variance type	Pmean	Psd	Gelman	PPL	DIC
NDJFMP, JASP	b0	site	hier	0.48	0.5	1.01	10128	6174
NDJFMP, AMJP, JASP	b0	site	hier	0.48	0.5	1.04	10128	6176
NDJFMP	b0	site	hier	0.47	0.48	1.01	10129	6172
AMJT, AMJP, NDJFMP, JASP	b0	site	hier	0.48	0.52	1.03	10134	6179
NDJFMP, AMJP	b0	site	hier	0.47	0.5	1.01	10135	6175
JASP, AMJP	b0	site	hier	0.48	0.5	1.01	10218	6190
AMJP	b0	site	hier	0.47	0.51	1.01	10228	6188
JASP	b0	site	hier	0.49	0.48	1.01	10276	6203
NA	b0	site	hier	0.5	0.49	1	10337	6210

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