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Natural Resource Stewardship and Science

Petrified Forest Grasslands, Status and Trends

Vegetation and Soils Monitoring 2007–2018

Natural Resource Report NPS/SCPN/NRR—2020/2068

ON THIS PAGE
Dramatic clouds over the clayey fan ecosystem at Petrified Forest National Park.
NPS/Megan Swan

ON THE COVER
Badlands form the backdrop of the sandy loam upland ecosystem at Petrified Forest National Park.
NPS/Megan Swan

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Executive Summary

This report presents results of upland vegetation and soil monitoring at Petrified Forest National Park (PEFO) 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 life form (e.g. perennial grass, shrub, forb), soil aggregate stability, and soil texture at 60 plots within two target grassland communities. The two communities were delineated using NRCS ecological site (ecosite) classifications and included clayey fan and sandy loam upland ecological sites.

During the monitoring period, crews identified 165 plant species. Both ecosites were dominated by warm-season grasses, which comprised about three-quarters of the total cover of vegetation. Shrub cover was a small component of both ecosites, but cover was both greater and more variable across sandy loam upland plots. Annual grasses were more common in the clayey fan ecosite. Less than 7% of the total species detected were nonnative. Russian thistle (*Salsola tragus*) was encountered most frequently, occurring more commonly in the clayey fan ecosite but frequency varied widely from year to year. We detected seven species of plants new to the park during monitoring and added them to the park's species list. Soils were generally deeper in the sandy loam ecosite and contained less clay. Undifferentiated soil crust comprised the largest component of the soil surface. Cover of biological soil crust (cyanobacteria, lichen and moss) was low in both sites.

Models revealed that temporal trends in indicator responses were weak or absent, implying that resources did not show directional change during the monitoring period. Soil aggregate stability was mid-range for both ecosites, but showed disparate trends, decreasing in the clayey fan and increasing in the sandy loam. Total foliar and perennial grass cover showed evidence of slight decreasing trends. There was evidence of increasing trend in species richness in both ecosites. Based on our results, we believe that the vegetation and soil in the monitored ecosites are in good condition. We did not detect strong trends in any category examined; species richness showed evidence of increasing over the period monitored; and there was low cover and frequency of nonnative species in both ecosites monitored.

Acknowledgments

Thanks to all members of the SCPN field crews (2007-2018) for collecting the data analyzed in this report including: Chris Carlson, Parker Davis, Theresa DeKoker, Lara Dickson, Jessica Erickson, Maria Gaetani, Hillary Hudson, Anna Lowell, Sean Mahoney, Ryan Manuel, Natalie Melaschenko, Ryan Meszaros, Jesse Mike, Jessica Mullins, Mare Nazaire, Jeff Organ, Emily Palmquist, Wade Plafcan, James Roemer, Susan Singley, Nell Smith, Steve Till, Daniel Torres, Eric Vasquez, and Karen Weber. James DeCoster, Chris Lauver, Allison Snyder and Lisa Thomas were all instrumental to the development of upland monitoring at SCPN. Kristin Straka provided GIS support for this project and Cindy Parker supported field data entry and management. Luke Zachmann and Tom Hobbs developed the Bayesian hierarchical models and jags scripting. This report would not have been possible without their assistance. Dana Witwicki, Erin Borgman, and Cheryl McIntyre contributed many ideas and served as a sounding board on Bayesian analysis. John Paul Schmidt, Chris Davis, and Suzanne Sanders provided helpful and thorough reviews that improved the content of this report immensely. Thanks also to the staff of Petrified Forest National Park, particularly Bill Parker and Brad Traver, for their support of this project and help with field logistics.

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 Petrified Forest National Park (PEFO), grassland vegetation communities are vitally important to the overall character of the park, forming an integral component of the natural and cultural landscape, including the expansive viewshed for which the park is known. Grassland vegetation stabilizes the soil, which, in turn, preserves and protects numerous prehistoric resources and cultural relics. Grasslands also provide habitat that contributes to species diversity and nutrient cycling.

The Southern Colorado Plateau Inventory and Monitoring Network (SCPN) began collecting data in grassland systems at PEFO 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 of upland vegetation, species composition and richness, soil surface features, and soil stability (DeCoster et al. 2012).

We established a set of 30 long-term plots in each of two grassland community types within the park using a spatially balanced probability survey design (Stevens and Olsen 2004). Beginning in 2007, we visited subsets of plots every year to gather data on the condition of the park's grassland ecosites.

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 PEFO from 2007–2018. It seeks to answer the following questions:

1. What were the characteristics of selected vegetation and soil components in the clayey fan and sandy loam ecosites at PEFO 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 trend in key vegetation and soil metrics?

Methods

Study area

Petrified Forest National Park was established as a monument in 1906 by Theodore Roosevelt to preserve some of the most valuable paleontological resources in the world (NPS 1986). Subsequent proclamations expanded the park boundary and scope and elevated it to a National Park in 1962. In 2004, another boundary expansion that doubled the size of the park was authorized, and the park has been slowly acquiring those lands, which include a checkerboard of BLM, ranch, state and private land. The recently expanded area is not included in the scope of current SCPN monitoring due to service-wide I&M guidance.

The park encompasses 88,437 ha in east central Arizona (Figure 1). Park elevation ranges from 1,618–1,900 m. The highest elevations are found on Pilot Rock, and Chinde Mesa near the northern boundary of the park. Annual precipitation averages 200 mm per year, with the majority falling in the summer months (July-September) as a result of the North American Monsoon (NPS 2019). Average mean daily temperature ranges from an average low of -6°C in January to an average high of 33.5°C in July.

The vegetation of PEFO includes arid grasslands, xeric shrublands, and sparsely vegetated badlands, as well as a narrow riparian zone along the Puerco River, which runs through the park (Thomas et al. 2009). Although the park was once subject to intense grazing from domestic sheep, goats, and cattle, domestic livestock grazing has been excluded from the pre-2004 boundary expansion area of the park entirely since 1963 (NPS 2003). As a result, PEFO's grasslands are likely the best example remaining of the shortgrass prairie ecosystem in the southwest (NPS 2003). Park grasslands provide forage and cover for wildlife species including pronghorn, jackrabbits coyote, and recently re-introduced Gunnison prairie dogs, as well as numerous species of birds and reptiles. A mission of the park is that "ecosystems are restored and/or maintained where appropriate, as they existed prior to disturbance by recent human settlement and technology" (NPS 2003).

Sampling frames

We used Natural Resources Conservation Service (NRCS) ecological sites (ecosites) as the basis for defining areas for monitoring. Every ecosite represents a unique combination of soils and potential vegetation (Caudle et al. 2013). Two ecological sites closely associated with grassland communities within PEFO were selected for upland monitoring: Sandy Loam Upland (10-14" precipitation zone (p.z.); RO35XA117AZ), and Clayey Fan (6-10" p.z.; RO35XA105AZ) (DeCoster et al. 2012).

We developed a sampling frame for each ecosite based on the distribution of soil map units containing high percentages of the target ecological sites (NRCS SSURGO dataset (U.S. Department of Agriculture, Natural Resources Conservation Service [USDA NRCS] 2002), then modified by removing areas not appropriate for monitoring. Excluded areas include those 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 fieldscreened these points in order to remove any plots that did not align with soil or ecological site characteristics.

Sandy Loam Upland Ecosite

The sandy loam upland ecosite occurs throughout the park on several soil types, including Sheppard, Palma, Fruitland, and Clovis. These soils are deep (>100 cm) and sandy in the upper profile, sometimes forming rolling dunes, but vary in amount of clay in lower profile layers, and gravel throughout (NCRS 2002). Slopes are generally minimal (0-5%). Vegetation consists primarily of warm season grasses and mixed shrubs, including galleta grass (*Hilaria jamesii*), blue grama (*Bouteloua gracilis*), dropseeds (*Sporobolus* spp.) and four-wing saltbush (*Atriplex canescens*), with a small percentage of cool season grasses and forbs (Figure 2).

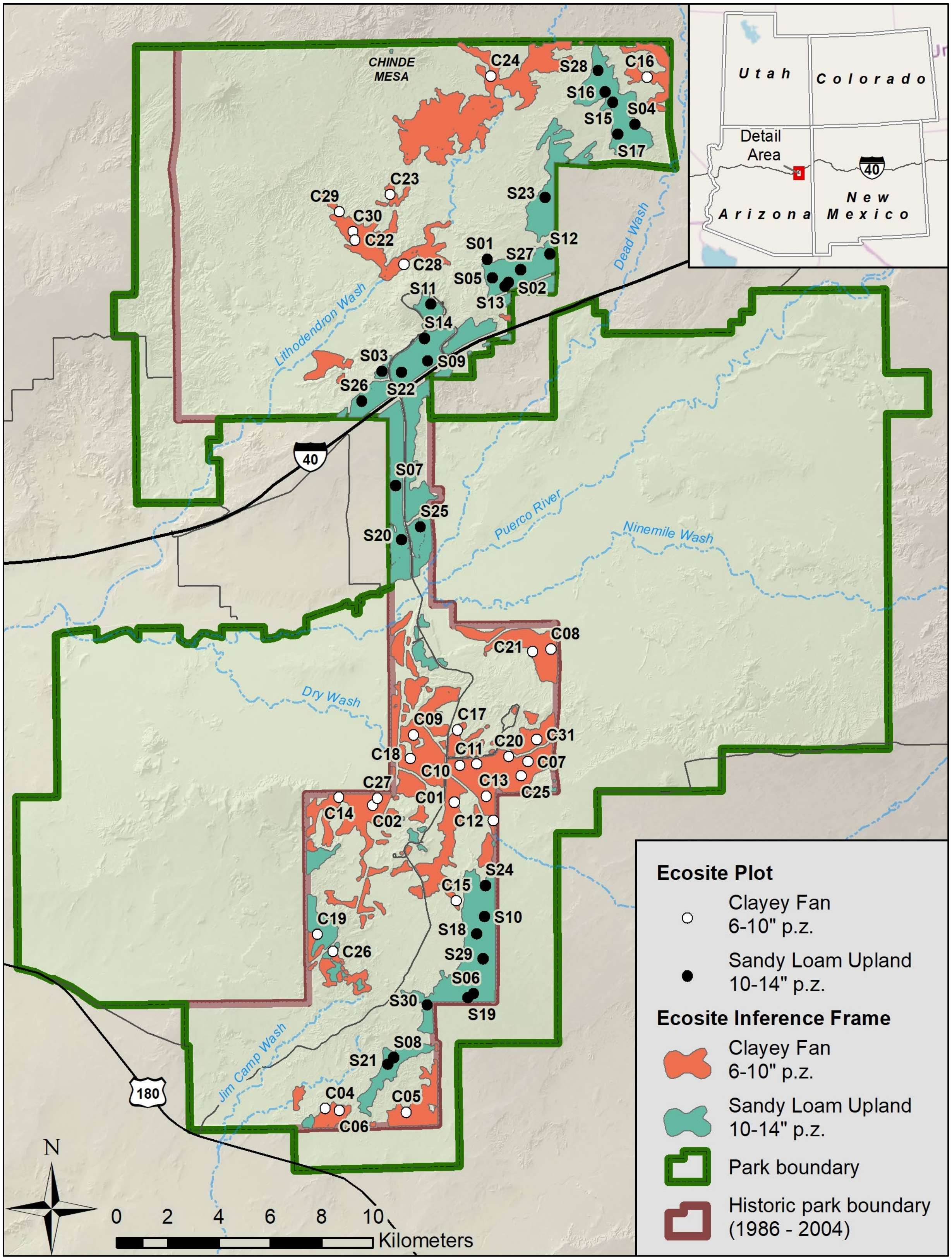

Figure 1. Overview map of Petrified Forest National Park and the Southern Colorado Plateau Network upland sampling plots included in this report.

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

Clayey Fan Upland Ecosite

The clayey fan ecosite occurs in the park primarily in the Painted Desert Wilderness and in the middle of the park between the railroad and I-40. Soils are represented by the Jocity component. Sandy clay loam textures dominate the upper profile, but underlying soils have more clay and are generally shallower than in the sandy loam upland ecosite. Vegetation here is dominated by dropseed (*Sporobolus* spp.) with lesser amounts of other warm season grasses, such as galleta grass (*Hilaria jamesii*) and blue grama (*Bouteloua gracilis*), and dwarf shrubs, such as mound saltbush (*Atriplex obovata*) (Figure 3). Small areas of heavy clay soils with little vegetation are common throughout this ecosite, which tends to proliferate with annual grasses and forbs during wet years (Figure 3, inset).

Figure 3. An example of the clayey fan ecosite at Petrified Forest National Park (NPS/MEGAN SWAN). Inset photo shows short-term water ponding during wet years.

Sampling plots

This report presents data from 60 plots at PEFO, 30 plots from each ecosite. We established 26 plots in 2007, 33 plots in 2010, and one plot in 2014. Sampling between 2007–2011 was considered an initial period for monitoring. During this time, we first sampled 10 plots annually to better understand year-to-year variability, then installed additional plots and sampled them opportunistically. In 2012, we began a structured panel revisit design. The 30 plots in each ecosite were randomly assigned to one of three panels (n=10). Two-thirds of the plots within each ecosite are sampled every other year. A complete panel revisit cycle for the two ecosites, in which all plots are sampled twice, takes six years. A complete sample history for each plot is provided in Appendix B.

Monitoring plots are 50 m x 52 m and consist of three parallel 50 m transects spaced 25 m apart (Figure 4). Within this area, field crews collect data on shrub and herbaceous vegetation and selected soil attributes using quadrat and transect-based sampling. Within each ecosite, plots are sampled at approximately the same time each season, and as close to maximal plant growth as possible given seasonal schedule constraints. At PEFO, plots are typically sampled in mid to late October. A brief summary of sampling methods follows. See the integrated upland monitoring protocol (DeCoster et al. 2012) for a more detailed explanation.

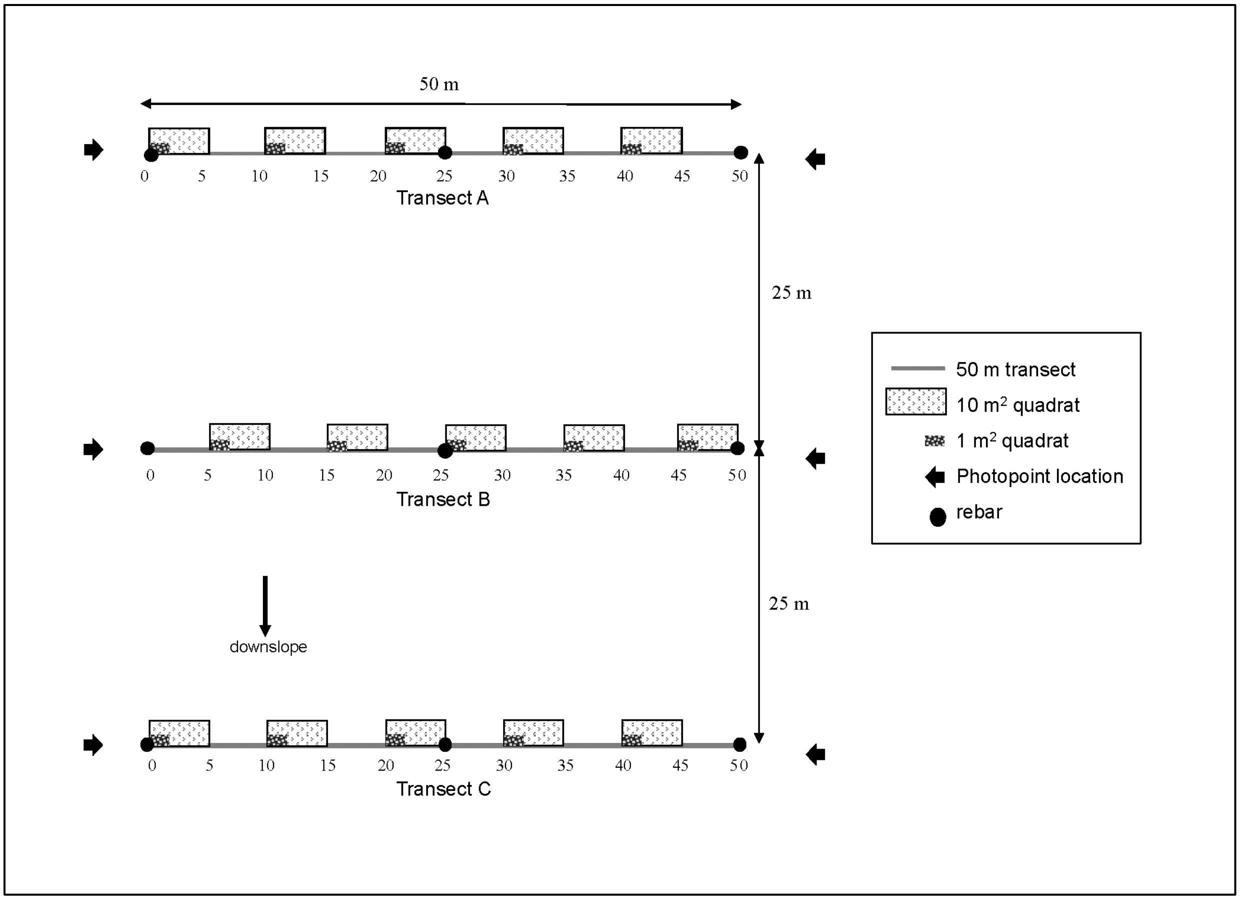

Figure 4. Diagram of a Southern Colorado Plateau Network upland monitoring plot. Shrub and herbaceous cover are measured in 10 m^2 quadrats, soil surface features in 1 m^2 quadrats. Basal gaps are sampled along each 50 m transect and photopoints are taken at each transect end facing towards the center 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 m^2 (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.

All species present were then aggregated into life form categories, which include perennial grass, annual grass, forb, shrub, and cacti/succulent. We estimated cover for each life form, accounting for layering and overlap, and recorded a cover class for each life form category detected in the 10 m^2 quadrat. We also assigned a cover class for total cover of all live shrub and herbaceous vegetation and for dead herbaceous and dead shrub vegetation within the 10 m^2 quadrat.

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

Soil profile and surface features

During the initial visit to each 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.

Soil surface features and biological soil crust attributes were assessed in 1 m^2 quadrats nested within the 10 m^2 quadrats and located at 10 m intervals along each transect (Figure 4). 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 tested 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 held 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 statistics software package (R Core Team 2017, version 3.6.0). Scientific names, common names, and lifeform and duration information for plant species were obtained from USDA PLANTS database (USDA NRCS 2019). Taxonomy was standardized using the Integrated Taxonomic Information System (ITIS, www.itis.gov). Scientific and common names as well as lifeform and duration for every plant encountered at PEFO is provided in Appendix A.

For status estimates, we chose to summarize the data across all years to minimize inter-annual variability in plots and responses, and to provide a robust characterization of the ecosites. We used the midpoints of each cover class as a metric value to represent the category and took means of these midpoints. Since plots were sampled unequal numbers of times, 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 plot means for the monitoring period. Finally, we averaged plot means across the ecosite. For trend analysis, Bayesian models used quadrat-level cover class categories and the results represent means at the quadrat level.

It is important to note that our approach of using cover class midpoints for status estimates treats categorical data (ordinal cover classes) as metric (percent cover) by using arbitrarily based midpoint values which is not statistically supported (Herpigny and Gosselin 2015). However, this approach is still common in vegetation ecology and alternative analyses were beyond the scope of this report. In contrast, the trend models we used to examine change over time correctly modeled a latent continuous variable (percent cover), rather than the category midpoints. When we compared across-year midpoint-means to modeled means for the responses we modeled for trend, 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: temperature anomaly data and long-term average precipitation totals from the Painted Desert climate station (1948–2005) (source: https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?azpetr); 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 for trend

The data presented in this report present several challenges to classical (frequentist) statistical methods: data were intentionally missing as a result of our 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. Due to the complex nature of our dataset, we employed a Bayesian hierarchical modeling approach to investigate change over time of select response variables. See Hobbs et al. (in prep.) for more details.

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. The type of model and distribution used depends on the characteristics of the response variable. Model specifications varied by response. Species richness models use a linear deterministic model and a Poisson likelihood; soil stability models were also linear and used an ordinal latent normal likelihood. Cover class values are modeled using a hurdle at 0, an inverse logit deterministic model, and an ordinal latent beta model. This mixed model uses a beta distribution to model a continuous latent cover percentage and includes a hurdle term to separate the presence/absence response from the cover when present as described by Irvine et al. (2016). More details about the models used in trend analysis are provided in Appendix C.

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

As an example, we may choose to look at change over time in plant cover in relation to annual precipitation. First, we present change over time as the model-predicted mean at each time step *including* the effect of variation in precipitation, which shows the effect that wet or dry years have on plant cover, conditional on the model we selected. Then we remove the effect of differences in precipitation between years by controlling for precipitation to test for trend. In these models, every year receives the same average amount of precipitation, which allows us to determine whether plant cover is increasing or decreasing over time in exclusion of the year-to-year difference in precipitation totals.

All results presented in the trend section of this report represent model-predicted probabilities. Probabilities are based on distributions of many iterations of model predictions. We make predictions for each site and year, whether or not the plot was actually sampled, which minimizes the effect of missing data that results from our panel design. Plots that have been sampled more often have more influence on the model predicted means, while plots that have been sampled less often contribute more uncertainty.

Results present the change over time as the mean of the posterior distribution (i.e., modeled predictions) 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. Distance of the center of the distribution from zero indicates the strength and direction of the trend.

We investigated a suite of potential climate covariates to include in our models. We focused on seasonal variables, based on significant relationships found between monsoon season soil moisture and annual productivity as measured by the normalized difference vegetation index (NDVI) in the two ecosites monitored at PEFO (Andrews et al. 2019a, 2019b). Significant relationships have been identified between spring soil moisture and annual productivity in nearby Chaco Culture National Historical Park (CHCU), which has many of the same dominant species (Andrews et al. 2019c). We explored both current year values and previous year's values because in some cases previous year's climate conditions can affect current year productivity. Candidate covariates included SPEI (Standardized Precipitation-Evaporation Index), a multiscalar drought index based on climatic data (Vicente-Serrano et al. 2010), seasonal precipitation variables, seasonal temperatures, soil moisture and deficit, and selected interaction effects (Vicente-Serrano et al. 2010). We ultimately focused on seasonal precipitation variables, since they ranked as more important than soil moisture variables in explaining dynamics in C4 grasslands on the Colorado Plateau (Gremer et al. 2015).

For each response, we ran many models with the candidate covariates, and used a process of model selection to select the best fit model to use for reporting. We checked all models for convergence using the Gelman-Rubin diagnostic (Gelman and Rubin 1992). Lack of fit was evaluated using posterior predictive simulation to generate Bayesian p-values. Values > 0.1 and <0.9 indicate a lack of fit. We then selected our final models by choosing those that minimized posterior predictive losses (PPL) (Hobbs and Hooten 2015). More details about the models used in our analysis are available in Appendix C.

Results and Discussion

Ecosite status

Climate overview

Annual fluctuations in precipitation and temperature result in changing vegetation conditions in the field (Figure 5). There was considerable variation in both spring temperature and seasonal precipitation over the monitoring period. During 2007, 2010, and 2012, precipitation for most plots exceeded the long-term average (Figure 6). In contrast, 2009 and 2018 were much drier than average. In 2018, precipitation was just 32% of normal in the driest plots (78 mm). Since 2015, PEFO has experienced a pattern of increasingly drier than normal conditions in both ecosites. Monthly temperature also varied considerably from long term averages over the monitoring period (Figure 7). Many months were significantly warmer or cooler than long-term averages, but sustained periods of warmer or cooler months were not apparent.

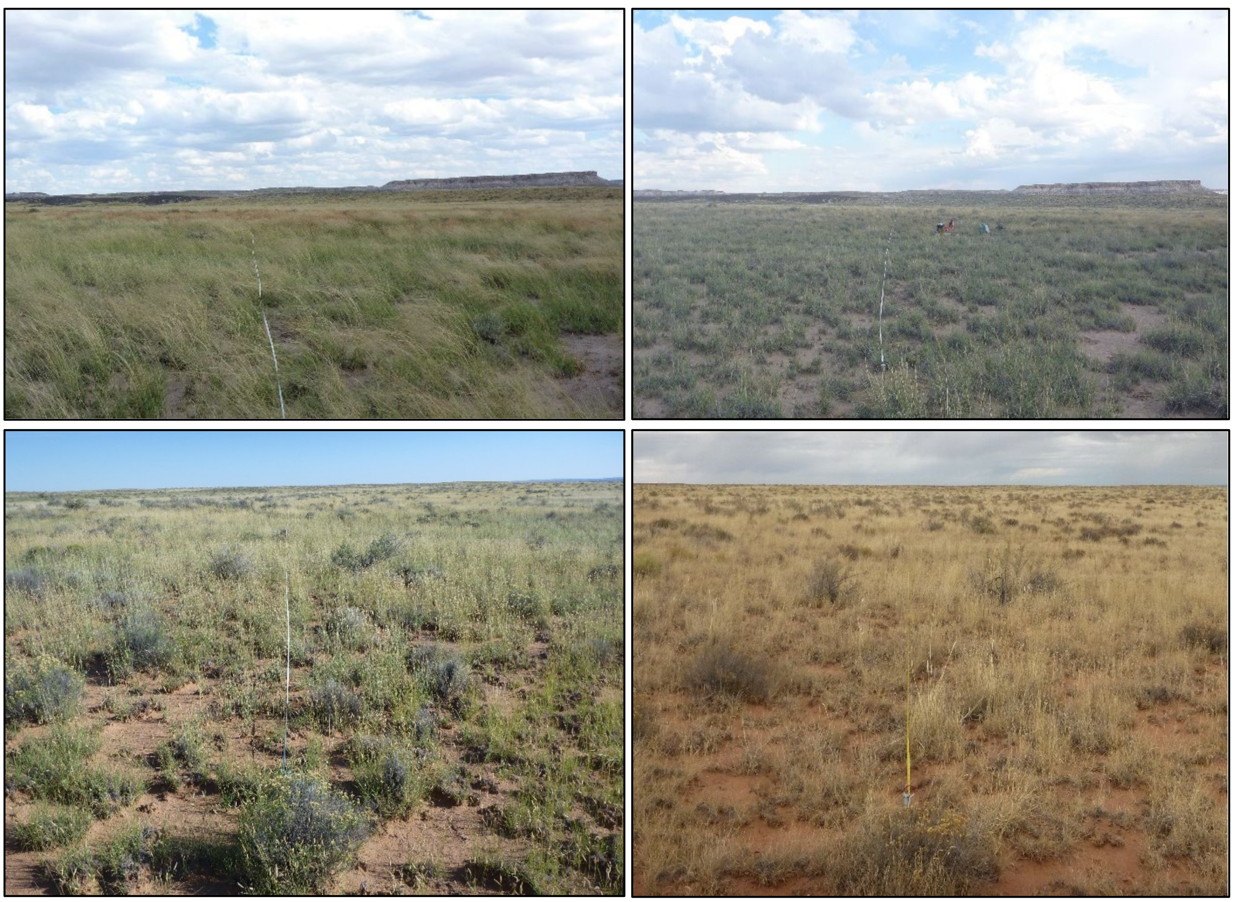

Figure 5. Examples of wet year (left panel) and dry year (right panel) vegetation in the clayey fan (top panel) and sandy loam upland (bottom panel) ecosites at Petrified Forest National Park.

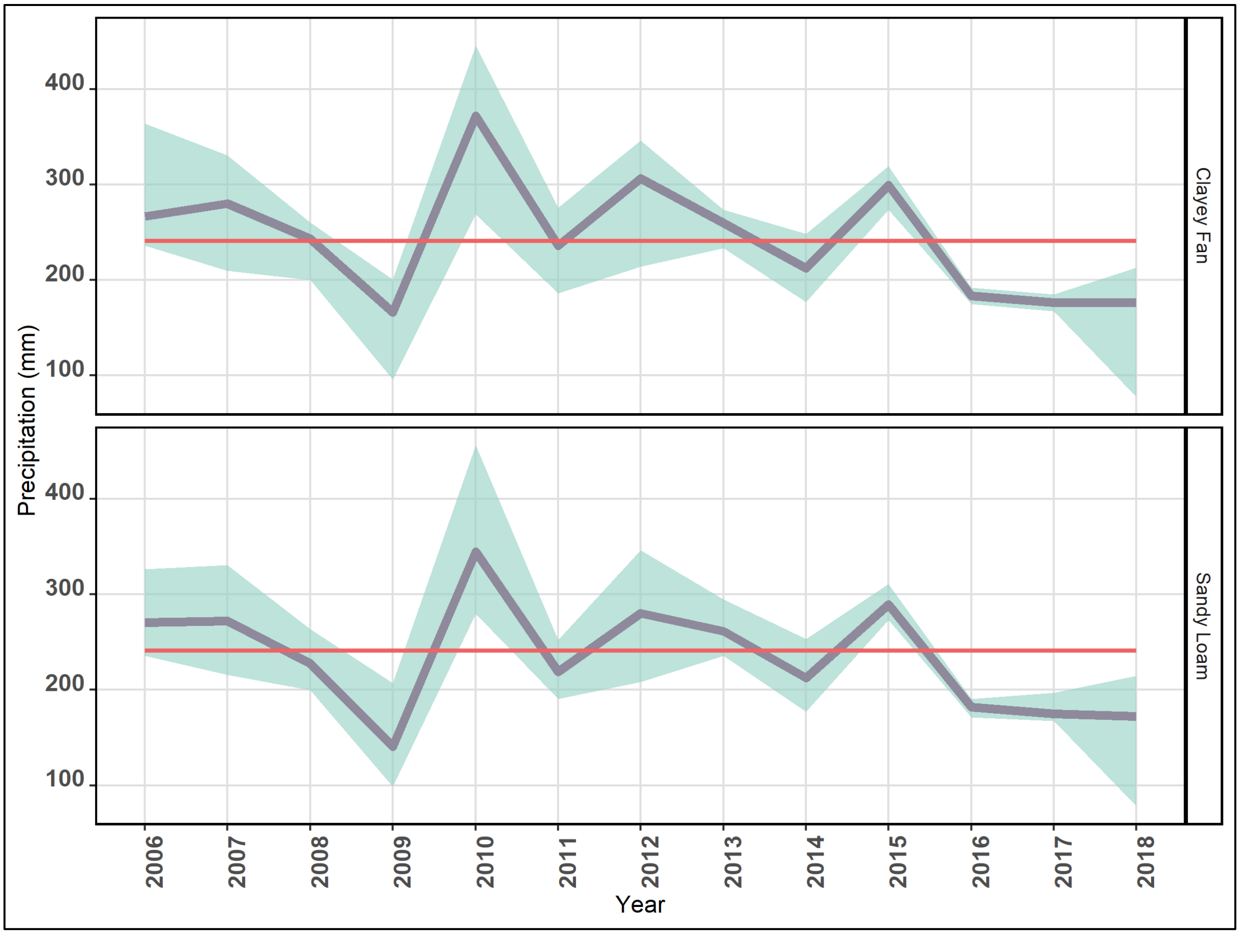

Figure 6. Water year (October–September) precipitation for plots in the clayey fan and sandy loam upland ecosites, monitored at Petrified Forest NP (2006–2018). The shaded area represents the range in annual precipitation totals for all plots. The line represents mean for the plots together. The horizontal line represents the long-term average precipitation total at PEFO climate station (1948–2005) (source: https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?azpetr). 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).

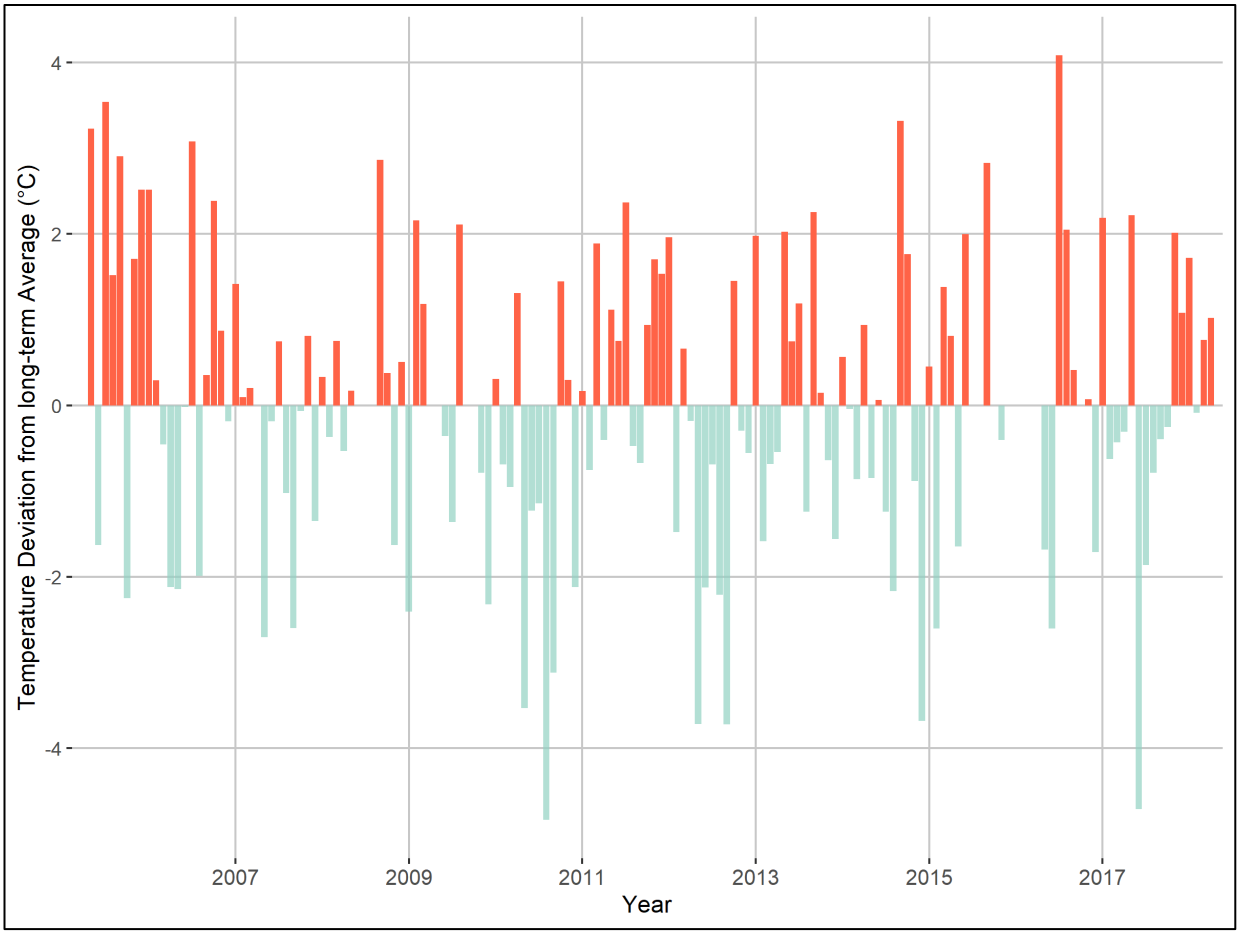

Figure 7. Monthly maximum temperature anomaly 2006–2018 at the Painted Desert weather station in Petrified Forest NP. Blue bars indicate months that were cooler than normal and red indicates months that were warmer than normal (source: http://www.climateanalyzer.us). Temperature anomaly is the difference 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

Soil depth was generally greater in the sandy loam upland ecosite. Twelve of 30 clayey fan plots had soil profiles less than 100 cm in depth, while only two of the sandy loam plots were less than 100 cm deep. There was considerable overlap in soil textures between the two ecosites, although profiles from the sandy loam upland ecosite contained less clayey-textured soils overall. Gravelly horizons were uncommon in both ecosites. Figure 8 shows the texture and depth of soils profiles for all plots included in this report.

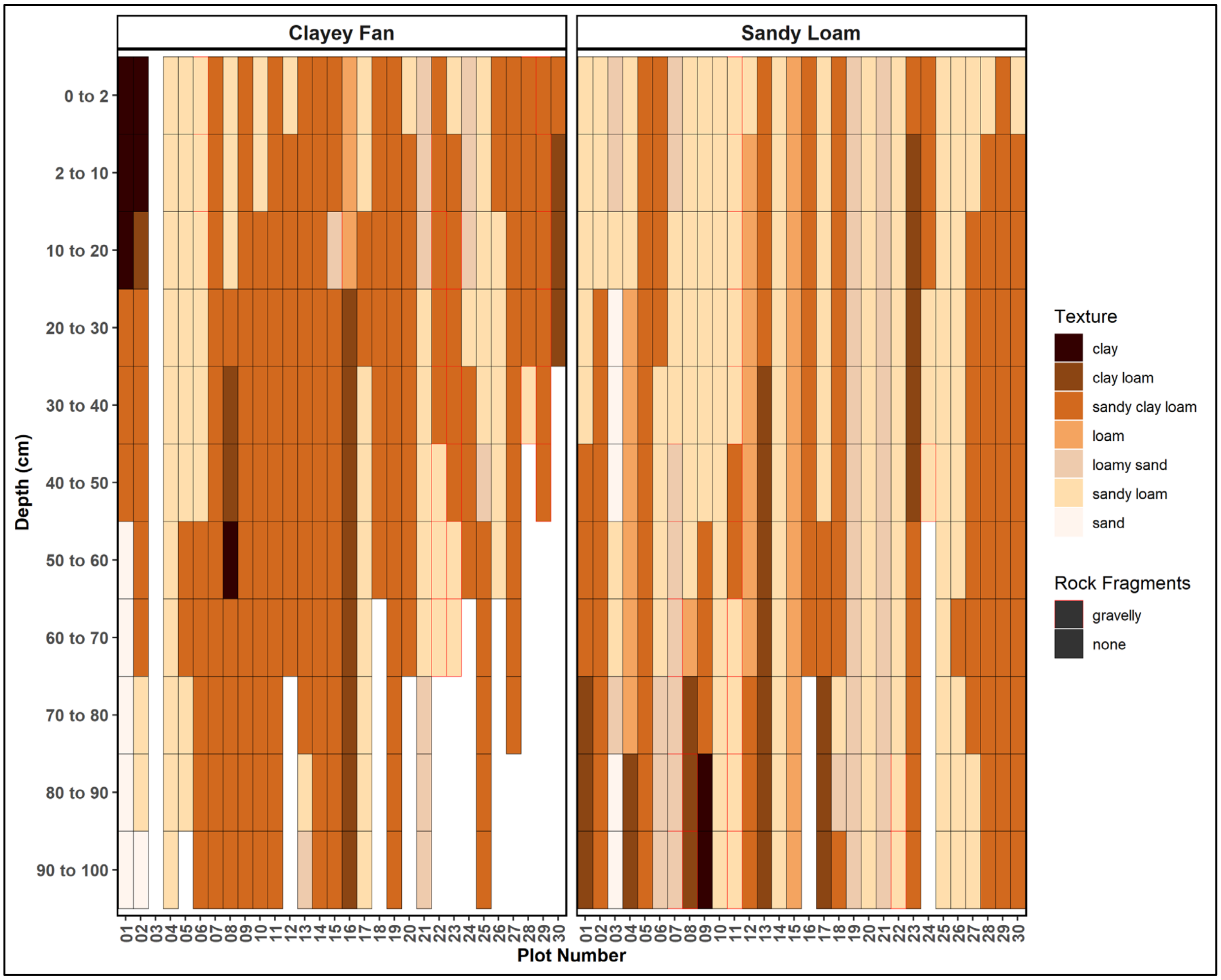

Figure 8. Texture and depth of soil profile samples collected from each monitoring plot in the clayey fan and sandy loam upland ecosites at Petrified Forest NP. Sandy loam sites had soils that were more consistently deep and contained generally less clay.

Undifferentiated crust is the largest component of ground cover in both ecosites (Figure 9). 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 cyanobacteria cover are both highly variable across plots and years, especially in the sandy loam upland site. Some of this variation can be attributed to weather conditions during sampling, since it is much harder to distinguish the darker color of cyanobacteria on wet soils.

Soil stability is widely accepted as an indicator of rangeland health, although the evidence of direct linkages seems to be lacking (Reinhart et al. 2015). Each plot at PEFO had samples that ranged over the full expression of stability, from least stable (1) to most stable (6). Mean soil stability over the monitoring period (2007–2018) was slightly higher in the clayey fan ecosite (3.43) than the sandy loam (3.16). Both values are in the midrange of the scale, indicating intermediately stable soils.

Stability was generally higher in samples obtained under perennial vegetative cover than in samples with no cover (Table 2).

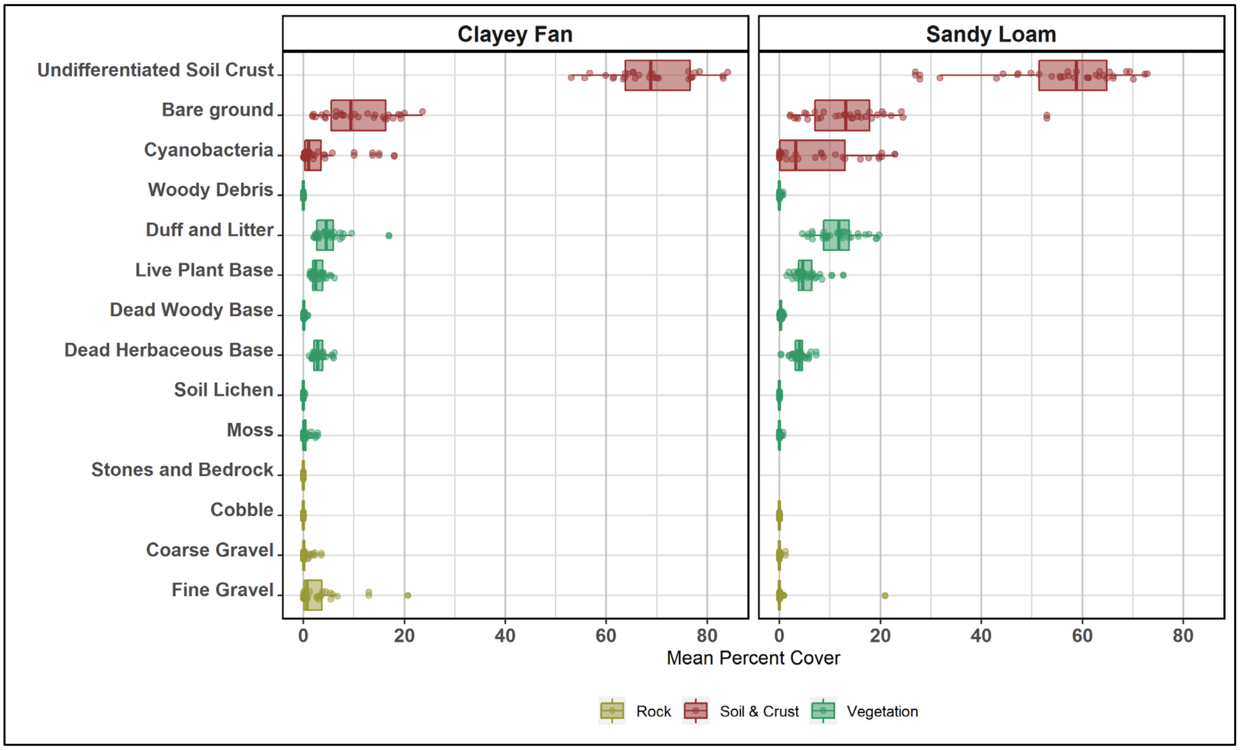

Figure 9. Mean cover of soil surface features in the clayey fan and sandy loam upland ecosites in Petrified Forest NP, 2007-2018, based on cover class midpoints. Boxplots indicate median and range of values for each soil surface category observed. Dots indicate plot-level means.

Table 2. Mean soil stability rating class for the clayey fan and sandy loamy upland ecosites at Petrified Forest NP, 200-2018. 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 Class	min	max
Clayey fan	Overall	3.43	1	6
	Vegetated	4.00	1	6
	Bare	3.10	1	6
Sandy loam upland	Overall	3.16	1	6
	Vegetated	3.61	1	6
	Bare	2.54	1	6

Vegetation overview

Plots in the sandy loam upland ecosite were generally more vegetated than clayey fan plots (Table 3). Shrub cover was a small component of total vegetation in both ecosites but was generally greater in sandy loam upland plots. Percent cover of forbs was very similar across both ecosites, while cover of annual grasses was higher in the clayey fan sites. Cactus and yucca cover were minimal, especially in clayey fan plots.

Table 3. Average percent cover of life form for the sandy loam upland and clayey fan ecosites in Petrified Forest NP, 2007-2018, based on cover class midpoints. Min and Max represent minimum and maximum plot mean observed during the monitoring period.

Ecosite	Lifeform	Mean % Cover	Min	Max
Sandy loam upland	Total live foliar	20.29	6.44	32.67
	Perennial grass	14.65	0.68	30.67
	Shrub	4.63	0.55	12.07
	Forb	1.22	0.00	6.18
	Annual grass	0.20	0.00	6.05
	Cactus and succulents	0.12	0.00	0.56
Clayey fan	Total live foliar	13.84	2.78	43.50
	Perennial grass	9.81	0.18	27.83
	Shrub	1.73	0.12	8.77
	Forb	1.12	0.00	15.37
	Annual grass	1.18	0.00	23.17
	Cactus and succulents	0.07	0.00	0.71

Cover by life form differed between plots within ecosites (Figure 10). Shrub cover was greater in the sandy loam ecosite, but also more variable across plots. Perennial grass cover also varied between plots within each ecosite. Annual grass cover was uniformly low when averaged over the monitoring years, but several plots in the clayey fan averaged higher values. Plot S11 in the sandy loam ecosite is notable for having particularly low cover of perennial grass.

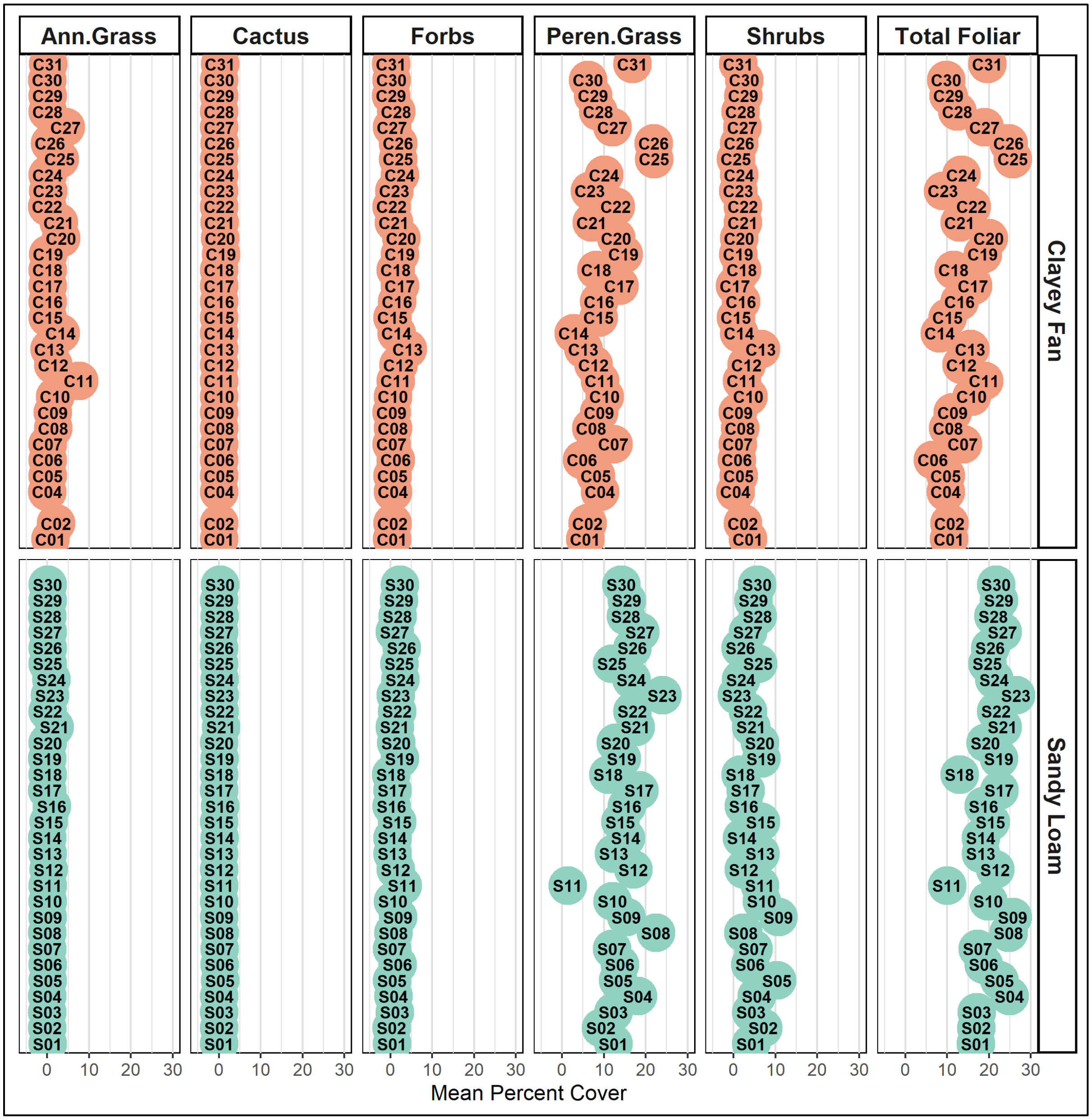

Figure 10. Cover patterns by life form in the clayey fan and sandy loam upland ecosites monitored at Petrified Forest NP. Plot means were calculated for each year, then averaged across all years. Perennial grass and total foliar cover were higher in the sandy loam upland ecosite. Shrub cover is higher and varies more across plots in sandy loam plots. Annual grass cover is higher in clayey fan plots.

We identified 165 plant species at PEFO between 2007 and 2018: 142 species in the clayey fan and 133 in the sandy loam upland ecosite. Both ecosites were dominated by warm season grasses, including blue grama (*Bouteloua gracilis*), galleta grass (*Hilaria jamesii*) and dropseeds *Sporobolus spp*. (Figure 11). Dropseed composition is primarily *S. airoides* in the clayey fan ecosite, but also includes *S. contractus*, *S. cryptandrus*, and *S. flexuous* in the sandy loam upland ecosite. Shrubs were less common, but still occurred in about half the plots sampled in both ecosites, although typically with low foliar cover. Native annual grass species were frequently encountered in the clayey fan ecosite, where more clayey soils result in areas of standing water that support quick growth of these diminutive grasses. Six-weeks grama grass (*Bouteloua barbata)* and Madagascar dropseed (*Sporobolus coromandelianus*) were found in over a quarter of the quadrats sampled in the clayey fan ecosite type during the monitoring period. Frequency of detection of the 10 most common species in both ecosites is provided in Table 4. Appendix A contains a list of all species.

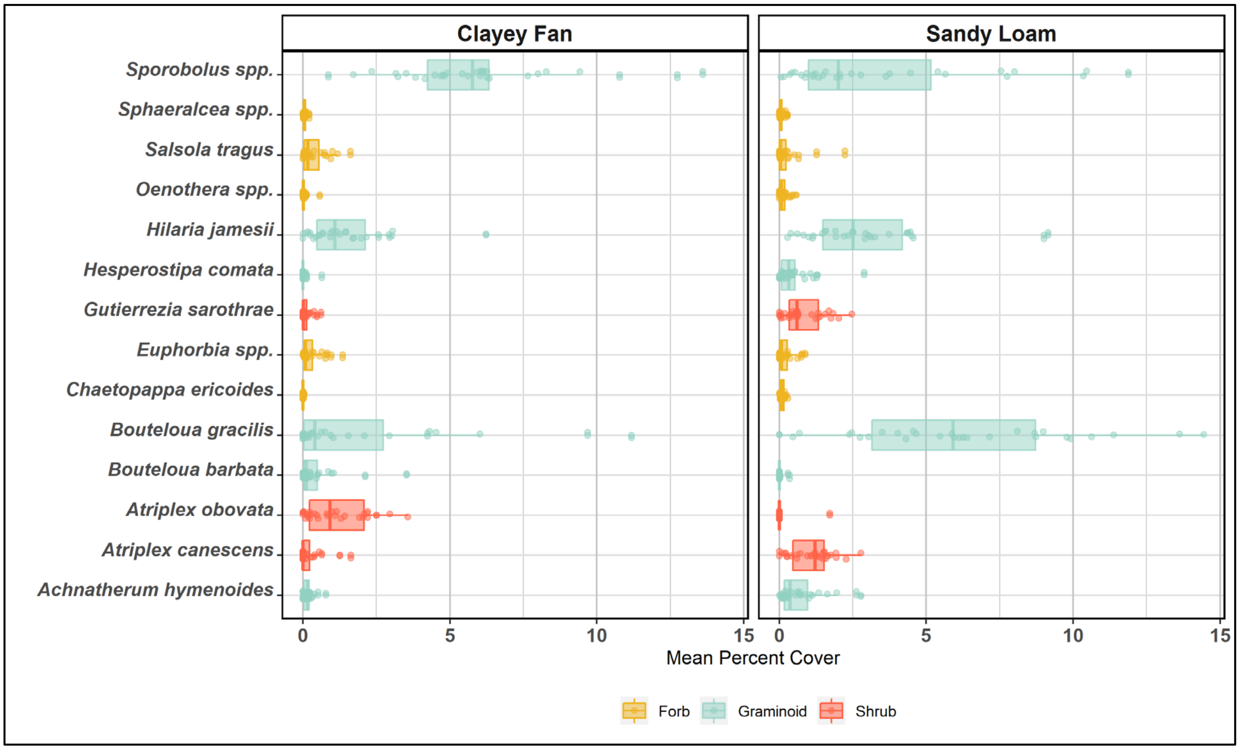

Figure 11. Mean percent cover of the 12 most frequently sampled species, based on cover class midpoints, at the clayey fan and sandy loam upland ecosites in Petrified Forest NP, 2007-2018. Boxplots indicate median and range of values for each soil surface category observed. Dots indicate plot-level means and color represents lifeform.

Species of dropseed (primarily alkali sacaton) dominate the clayey fan ecosite, occurring in nearly every quadrat sampled (frequency of 0.96, Table 4), while in the sandy loam upland system, galleta grass shares dominance with blue grama and dropseeds. Shrub composition also differs between ecosites; mound saltbush, *Atriplex obovata* is commonly found in clayey fan plots, while the larger four-wing saltbush (*Atriplex canescens*), along with snakeweed (*Gutierrezia sarothrae*), occur most often in sandy loam plots. Forbs are a small component of the vegetation cover but comprise much of the diversity. Tiny perennial rose heath (*Chaetopappa ericoides*) was detected in about one-third of all sandy loam plots and annual sandmats (*Euphorbia* spp., formerly in the genus *Chamaesyce*), and the nonnative Russian thistle were the most commonly detected forbs in the clayey fan ecosite. Except for a few dominants, most plant species in these ecosites occur infrequently and at low cover (Figure 12). In fact, 90% of species detected during the monitoring period average less than 2% cover and occur in fewer than 20% of the total quadrats sampled.

Table 4. Plant species with the greatest absolute quadrat frequency at Petrified Forest NP over the sampling period (2007–2018) summarized for the clayey fan and sandy loam upland ecosites. Common name, lifeform, duration and nativity 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.

Ecosite	Scientific Name	Common Name	Lifeform	Duration	Nativity	Quadrat Frequency
Sandy loam upland	*Hilaria jamesii* (C4)	galleta grass	grass	perennial	native	79%
	Bouteloua gracilis (C4)	blue grama	grass	perennial	native	73%
	Sporobolus spp. (C4)	dropseed	grass	perennial	native	69%
	Achnatherum hymenoides (C3)	Indian ricegrass	grass	perennial	native	54%
	Gutierrezia sarothrae	snakeweed	shrub	perennial	native	49%
	Atriplex canescens	four-wing saltbush	shrub	perennial	native	42%
	Chaetopappa ericoides	rose heath	forb	perennial	native	36%
	Hesperostipa comata (C3)	needle and thread	grass	perennial	native	29%
	Sphaeralcea spp.	mallow	forb	perennial	native	27%
	Oenothera spp.	evening primrose	forb	biennial	native	25%
Clayey fan	*Sporobolus* spp. (C4)	dropseed	grass	perennial	native	96%
	Atriplex obovata	saltbush	shrub	perennial	native	57%
	Hilaria jamesii (C4)	galleta grass	grass	perennial	native	55%
	Bouteloua gracilis (C4)	blue grama	grass	perennial	native	44%
	Euphorbia spp.	annual sandmats	forb	annual	native	39%
	Salsola tragus	Russian thistle	forb	annual	nonnative	37%
	Achnatherum hymenoides (C3)	Indian ricegrass	grass	perennial	native	33%
	Sphaeralcea spp.	mallow	forb	perennial	native	33%
	Bouteloua barbata (C4)	six-week grama	grass	annual	native	32%
	Sporobolus coromandelianus (C4)	Madagascar dropseed	grass	annual	native	26%

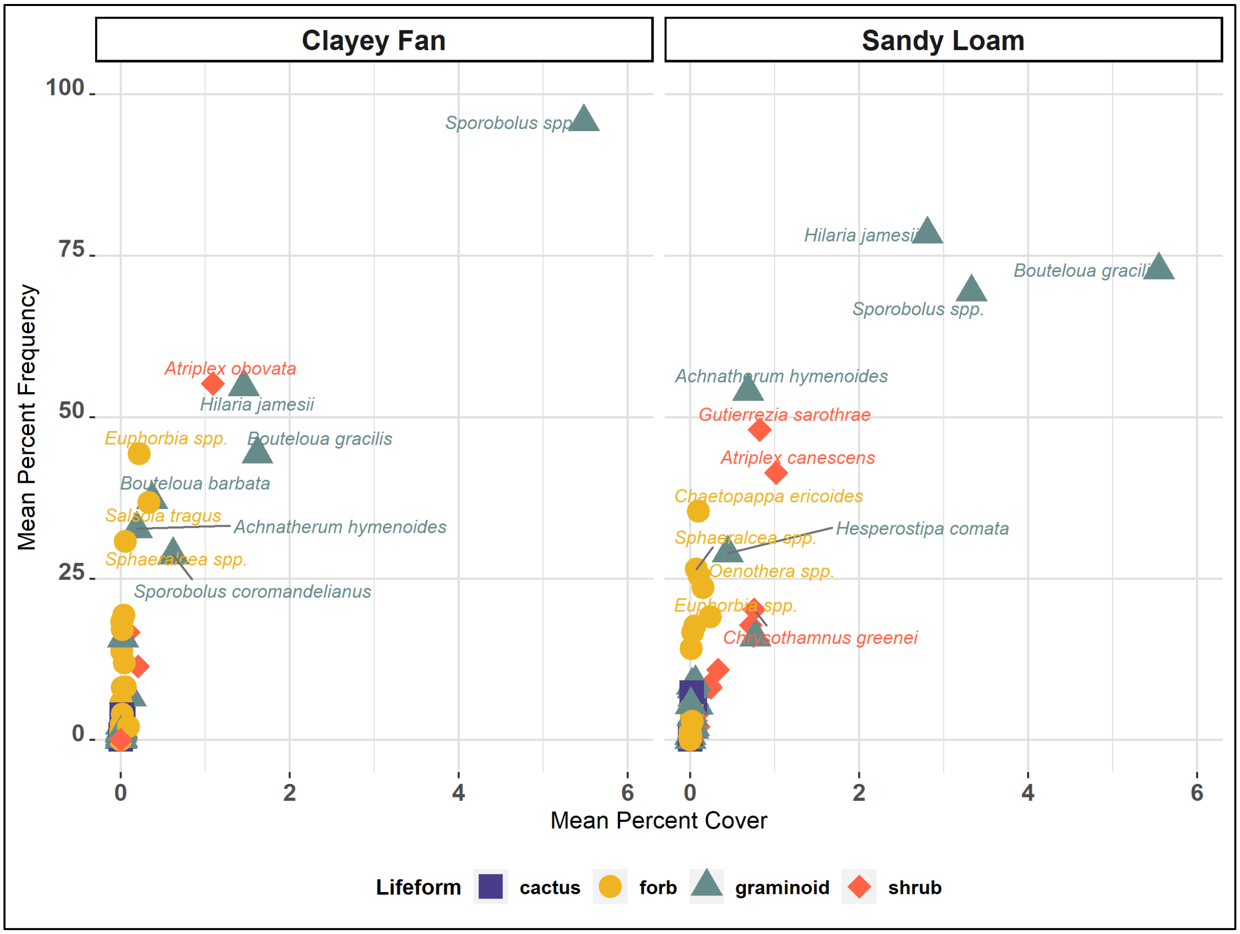

Figure 12. Typical abundance and distribution for dominant plant species in the clayey fan and sandy loam ecosites at Petrified Forest NP (2007–2018). Grass species are the most frequently detected (y-axis) and have the highest cover values (x-axis). The majority of species that occur in both ecosites have low frequency *and* cover. Species that occur in less than 20% of quadrats are not labelled.

We assessed species richness at the 10 m^2 scale by taking the mean of all quadrats within a plot prior to taking means across plots and years. Species richness was highly variable across the plots in each ecosite. The lowest richness encountered in a quadrat was a single species (15 of these single-species quadrats were encountered in clayey fan, and 14 in sandy loam plots). The highest was 24 species (in plot C16 in 2018). Both ecosites displayed this extremely wide range of richness among plots, which reflects the patchy nature of species in these grasslands. Many ephemeral washes run through the clayey fan ecosystem, and often higher diversity is found here. In the sandy loam upland ecosite, areas of deep sand typically support higher numbers of species. Beta diversity (the ratio between regional diversity and local diversity, defined here as the ecosite richness/average plot richness across all years) was 4.0 for the clayey fan ecosite and 3.25 for the sandy loam upland.

Twelve non-native species were encountered during the monitoring period (7% of all species detected). Of these, only two are currently listed as noxious weeds in the state of Arizona, *Halogeton glomeratus* and *Portulaca oleracea* (https://agriculture.az.gov/pests-pest-control/agriculture-pests/noxious-weeds accessed 07/10/2019). Cheatgrass (*Bromus tectorum*) and Russian thistle

(*Salsola tragus*) were the most commonly detected nonnative species, and the only two that occurred in greater than 10% of the sampled quadrats in a given year. See Table 5 for the percent quadrat frequency of these two species over the monitoring period.

We detected seven new species for the park during monitoring. Four were detected in 2010, which was an extremely strong monsoon season at PEFO. Three of these species, threadstem carpetweed (*Mollugo cerviana*), and kiss me quick (*Portulaca pilosa*), slender Russian thistle (*Salsola collina*) are nonnative species. The others, salt heliotrope (*Heliotropium curassavicum*), sunbright (*Phemeranthus parviflorus*), Coulter's horseweed (*Laennecia coulteri*), and manyflower false threadleaf (*Schkuhria multiflora*) are native. We initially identified a tiny cactus as the rare species, *Pediocactus peeblesianus*, however that was a misidentification and we later confirmed it to be Whipple's fish-hook cactus (*Sclerocactus whipplei*). See Appendix A for a complete list of all species found during the monitoring period.

Table 5. Quadrat frequency (%) of the two most common nonnative species in plots sampled in the clayey fan and sandy loam upland ecosites during Southern Colorado Plateau Network monitoring at Petrified Forest NP (2007–2018). NS indicates that the ecosite was not sampled in that year according to our revisit design. Note: each year represents different groupings of sampled plots, and may represent different numbers of plots sampled as shown in Appendix B.

Ecosite	Scientific Name	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Clayey fan	*Bromus tectorum*	5.2	2.2	0.0	2.0	0.7	1. 7	NS	0.3	NS	5.0	NS	2.7
	Salsola tragus	61.5	57.0	34.1	61.3	48.2	34.0	NS	21.7	NS	11.3	NS	31.3
Sandy loam upland	*Bromus tectorum*	23.5	10.0	2.7	0.5	3.3	NS	0.0	NS	0.3	NS	3.7	NS
	Salsola tragus	27.1	26.7	15.3	36.4	44.7	NS	15.0	NS	5.3	NS	4.3	NS

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 the purpose of this report, trend is defined as a directional change over time that is not explained by short-term changes in mechanistic driver variables.

Significant change in vegetation communities commonly occurs over decades or centuries. However, measured responses like plant cover and frequency typically exhibit high variability from year to year in response to mechanistic driver variables, such as rainfall and temperature. Therefore, assessing trend with relatively short interval data sets, such as the 11-year monitoring period at PEFO, has many limitations.

Non-directional, year-to-year variation can have an outsized effect on perceived linear trends, especially if years with extreme highs or lows are, by chance, located at the start or end of the monitoring period. Annual variation in weather can be accounted for by adding predictor variables (covariates) which can minimize this effect, but all covariates are imperfect predictors, especially when looking across different sites, different plant life forms and species, and different observers and sampling conditions. Additionally, climate change is now influencing precipitation patterns and driving temperatures consistently higher every year on a global scale, confounding the effect of time and climate. These trend results present our best assessment based on our current toolset, however, a critical next step will be better linking change in response variables to system drivers so we can further refine our models and begin to make predictions about future responses of these systems to anticipated shifts in climate over time.

Covariates

Final covariates and model specifications for models are shown in Appendix C. Of the covariates we tested, seasonal precipitation totals performed similarly to derived variables, such as SPEI, so we chose to use them since their interpretation is simpler. 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 (including all life form metrics in both ecosites), we found our models had the lowest posterior predictive loss (PPL) when we included all four in an additive model. Figure 13 displays the temporal patterns of the covariates we included in 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.

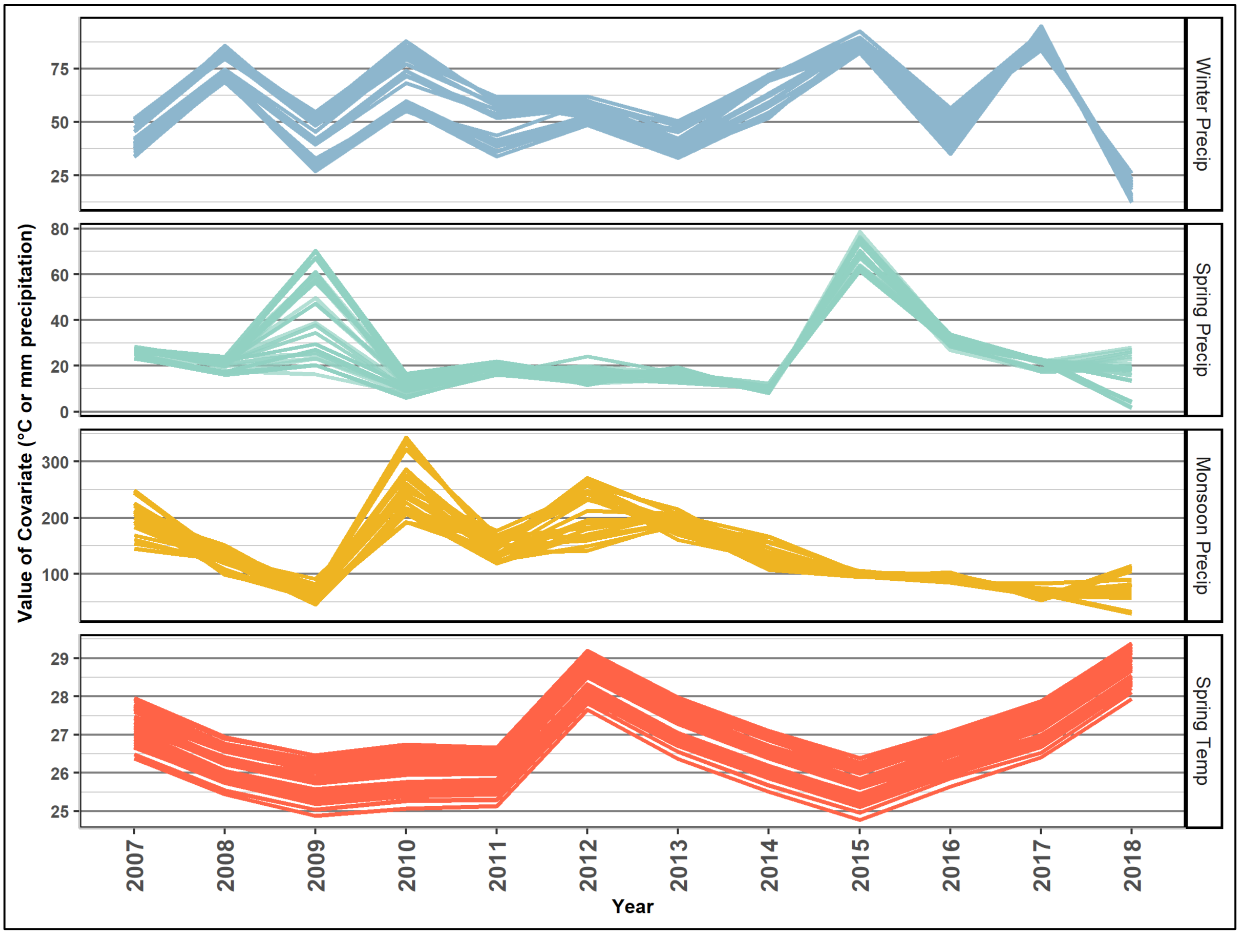

Figure 13. Annual patterns of climate covariates included in trend models for monitored plots in the clayey fan and sandy loam upland ecosites at Petrified Forest NP (2007–2018). Seasonal precipitation totals for winter (November–March) spring (April–June), monsoon (July–September) was obtained from the United States Stage IV Quantitative Precipitation Archive (Lin and Mitchell, 2005). Note: scale of y-axis varies in scale and units.

Trend in species richness

Species richness is a count of how many distinct species are detected in a plot. It is the most basic measure of diversity. Research indicates that reduction in species richness is linked to impairment in ecosystem function (Maestre et al. 2012). We assessed species richness at the 10 m^2 quadrat-level across the monitoring period to determine if the number of species detected per quadrat was increasing or decreasing over time in either ecosite.

Clayey Fan

Species richness fluctuated considerably from year to year in the clayey fan ecosite (Figure 14). The model for this response included spring temperature and all three seasonal precipitation covariates. Conditional on the model, wetter monsoon seasons led to a greater number of species detected in the field. The effect of other variables was neutral. The greatest monsoon precipitation during our monitoring period occurred in 2010, which has the highest model-predicted richness.

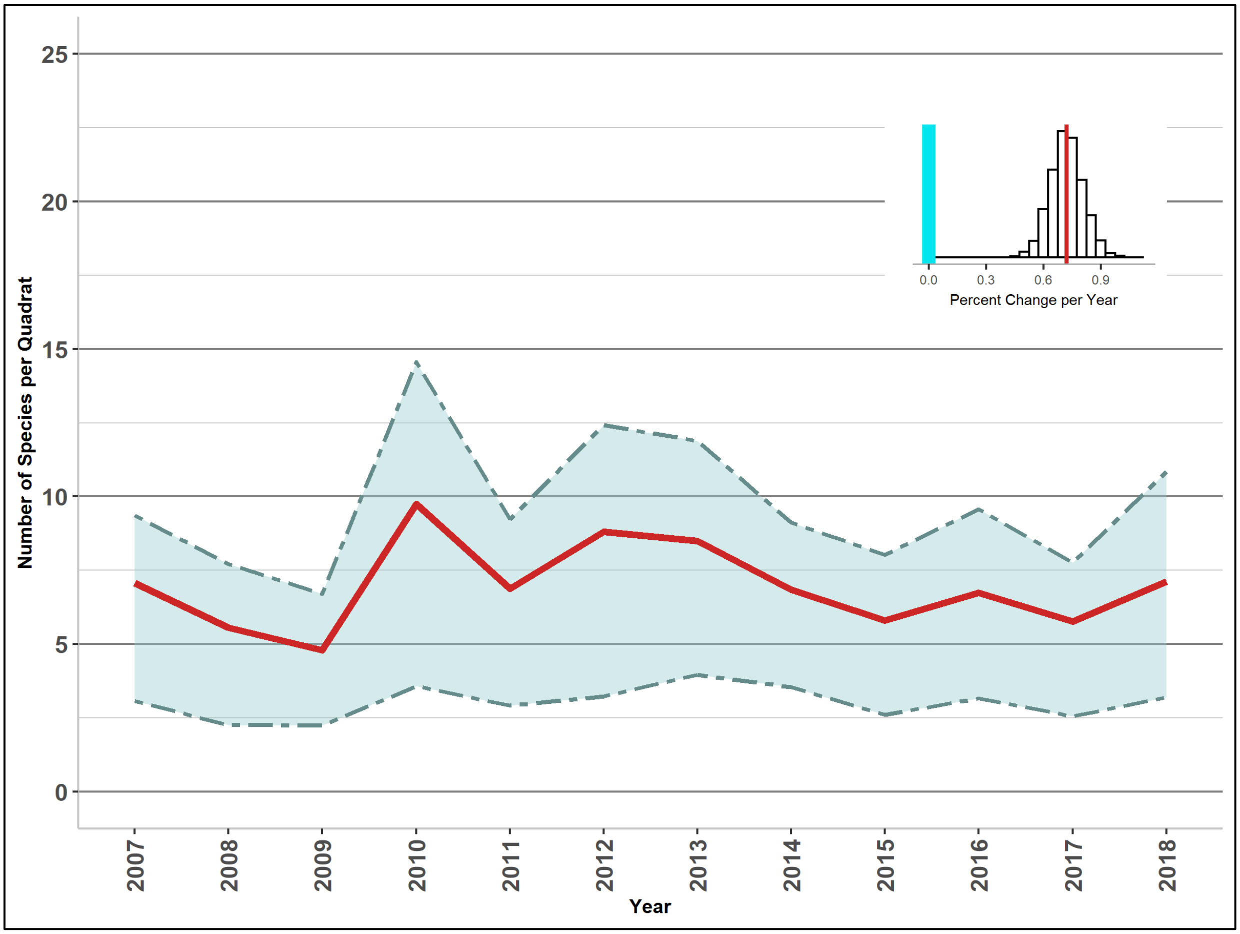

Figure 14. Change over time in mean model-predicted quadrat-level species richness (2007–2018) at sampled plots in the clayey fan ecosite at Petrified Forest NP as a function of seasonal precipitation and spring temperature. Mean richness increased with increasing monsoon season precipitation. The solid line indicates the mean at sampled plots, and the shaded area represents the 95% credible intervals. Inset shows posterior distribution of change over time is centered above 0% indicating an increasing trend. There is evidence that species richness is increasing through time in a way that is not explained by yearly fluctuations in precipitation and spring temperature.

When we controlled for variation in weather variables on species richness (by holding their values at their mean for the monitoring period), we saw a slight positive trend in model-predicted species richness. This slight increase represents directional change in species richness during the monitoring period that is not explained by the variables we included in the model. This increase could be a result of increased skill of the field crew leading to higher detection of new species or could be related to other factors that are important for species richness that we have not accounted for in the model. Variation in species richness in this ecosite are primarily the result of changes in annual forb and grass species presence that, because of their short life-span, may exhibit highly species-specific responses to precipitation and temperature, complicating how we explain this response.

Sandy loam upland

Species richness showed similar change over time in the sandy loam upland ecosite. We modeled species richness including spring temperature and winter, spring and monsoon season precipitation as covariates.

Conditional on the model, both winter and monsoon precipitation had a positive effect on species richness, i.e., more precipitation in those seasons led to higher numbers of species detected when we sampled in October. Increasing spring temperatures and increased spring precipitation had a weaker, but negative effect on species richness. This model predicts high richness in 2010, which is the season we encountered several new species (Figure 15).

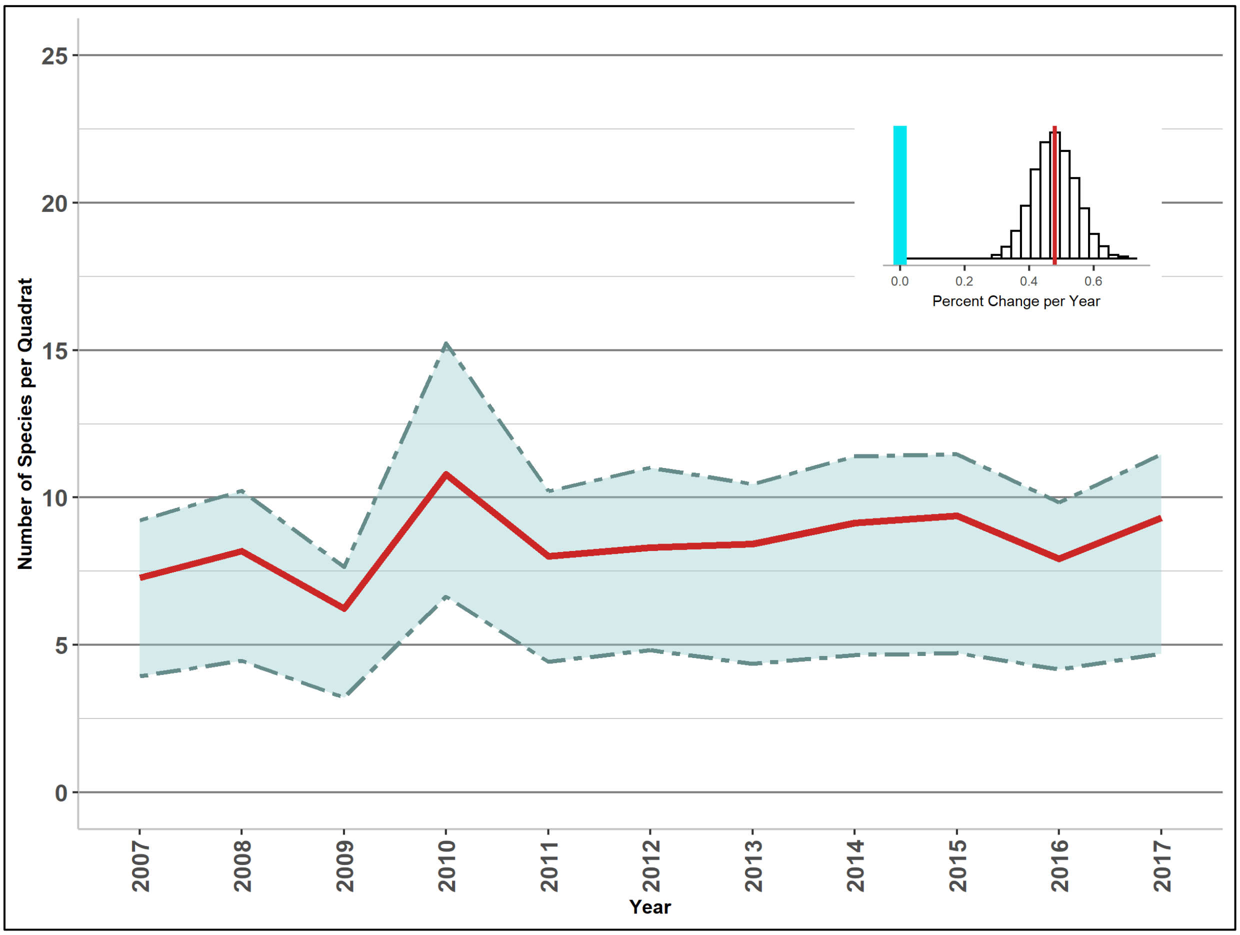

Figure 15. Change over time in mean model-predicted quadrat-level species richness as a function of seasonal precipitation and spring temperature at plots sampled in the sandy loam upland ecosite at Petrified Forest NP, 2007–2018. The solid line indicates the predicted mean at sampled plots, and the shaded area represents the 95% credible intervals. Mean richness increases with wetter winter and monsoon seasons and decreases with warmer spring temperatures and increased spring precipitation. Inset shows posterior distribution of change over time is centered above 0% indicating an increasing trend. There is evidence that species richness is increasing through time in a way that is not explained by yearly fluctuations in precipitation and spring temperature.

When we looked at trend by controlling for variation in weather variables, the posterior distribution for percent change per year was slightly positive (Figure 15, inset graph). The increasing trend in species richness, seen here as well as in the clayey fan site, indicate that our covariates are not adequately explaining the change in species richness over time. One possible explanation is that during the first three years of sampling (2007–2009) we sampled the same 10 plots in each ecosite, reducing the number of species we encountered overall. This may be causing the model to under-predict richness for all plots in those initial years, resulting in an increasing trend. It is also possible that our included covariates are not adequately explaining changes in species richness. Continuing to refine our predictor variables will be a focus of future work.

Trend in total foliar cover

Changes in total foliar cover can be hard to interpret because this group represents the aggregated total of all grass, forb and shrub cover in a plot. The various lifeform and traits of the individual components may respond differently to the same conditions. Large year-to-year changes in total foliar cover are more likely to be driven by more transient species of annual grass or shrubs, while cover of things like perennial grasses, shrubs and cactus tend to be more stable through time. We were interested in whether total live foliar cover was increasing or decreasing over time in these ecosites.

Clayey Fan

All four weather variables were included in this model. There was some evidence of lack of fit in the variance term (p=0.99), however, the results are conservative as the model was over predicting error, so we present them here. Conditional on the model, spring temperature had a negative effect on total foliar cover in this ecosite, indicating that higher spring temperatures result in lower total foliar cover. All three included precipitation variables had positive effects on cover. The strongest effect was monsoon precipitation. In 2012 and 2018, PEFO experienced high spring temperatures following a relatively dry winter and model-predicted cover were at their lowest (Figure 16). This is concerning, since future climate predictions indicate that warmer, drier springs will become more common at PEFO in the near future (Andrews et al. 2019a). Wet winter conditions and cool spring temperatures resulted in predicted mean cover at its highest level in 2015 (a year we didn't sample in this ecosite). When we removed the effect of changes in the weather variables from the model, the distribution centered slightly above 0%, indicating a slight increasing trend over the monitoring period (Figure 16, inset graph).

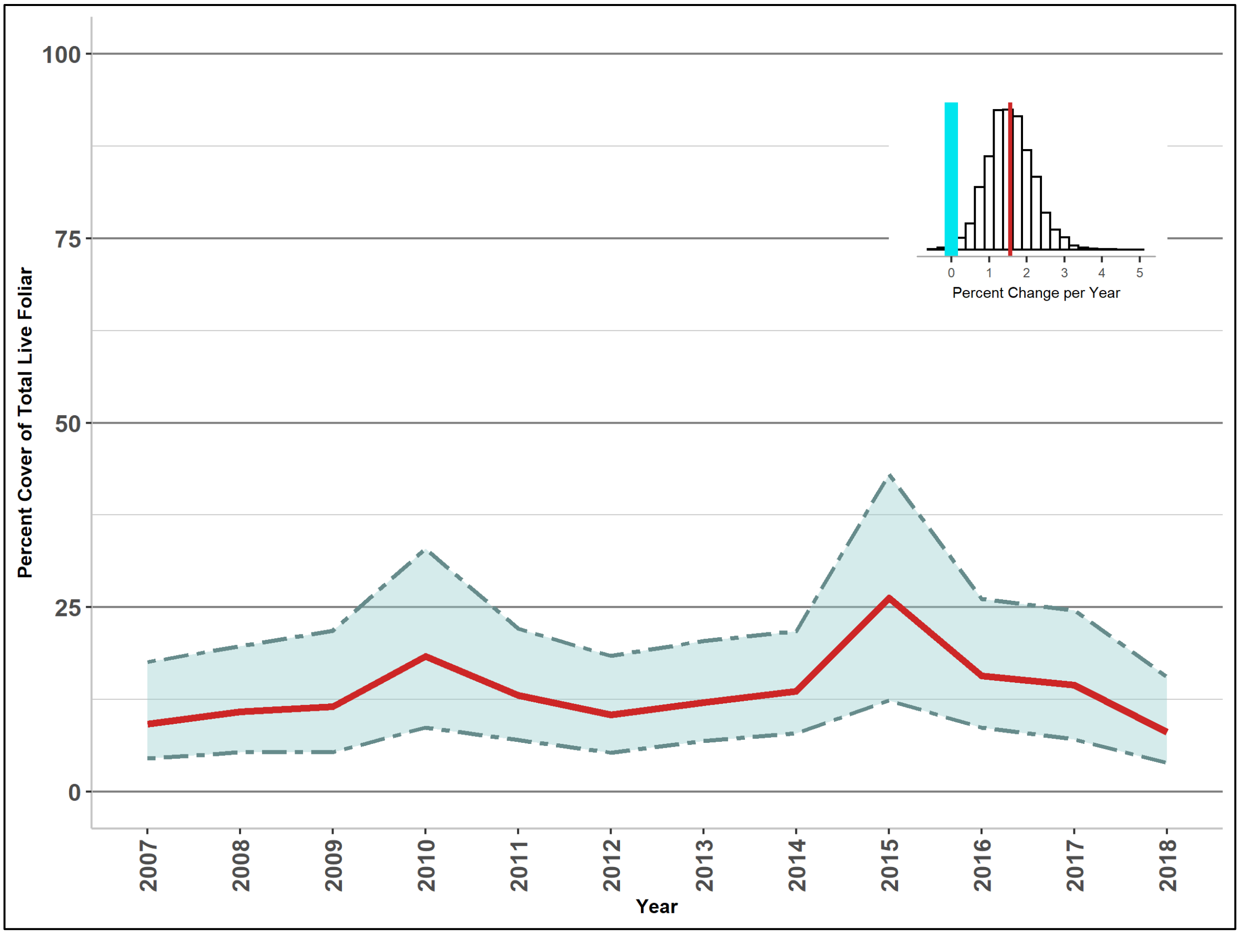

Figure 16. Model-based prediction of the change over time in mean total foliar cover (2007–2018) as a function of spring temperature and seasonal precipitation at plots sampled in the clayey fan ecosite at Petrified Forest NP. The solid line indicates the predicted mean at sampled plots, and the shaded area represents the 95% credible intervals. Mean cover increases with increased seasonal precipitation (monsoon, winter and spring) and cooler spring temperatures. Inset shows posterior distribution of change over time is centered above 0% indicating some evidence of a positive trend. There is some evidence that total foliar cover is increasing slightly through time in a way that is not explained by yearly fluctuations in precipitation and spring temperature.

Sandy loam upland

In the sandy loam ecosite, modeled total foliar cover showed less interannual variation. Here, cover responded positively to all four included covariates, including spring temperature. However, monsoon precipitation had the strongest effect, conditional on the model. The only year during our sampling period with relatively wet seasons for both winter and monsoon season precipitation was 2010, when it caused a slight increase in total foliar cover in this ecosite (Figure 17). When we looked at trend by controlling for the covariates, the posterior distribution for percent change per year centered around 0%, indicating no trend (Figure 17, inset graph).

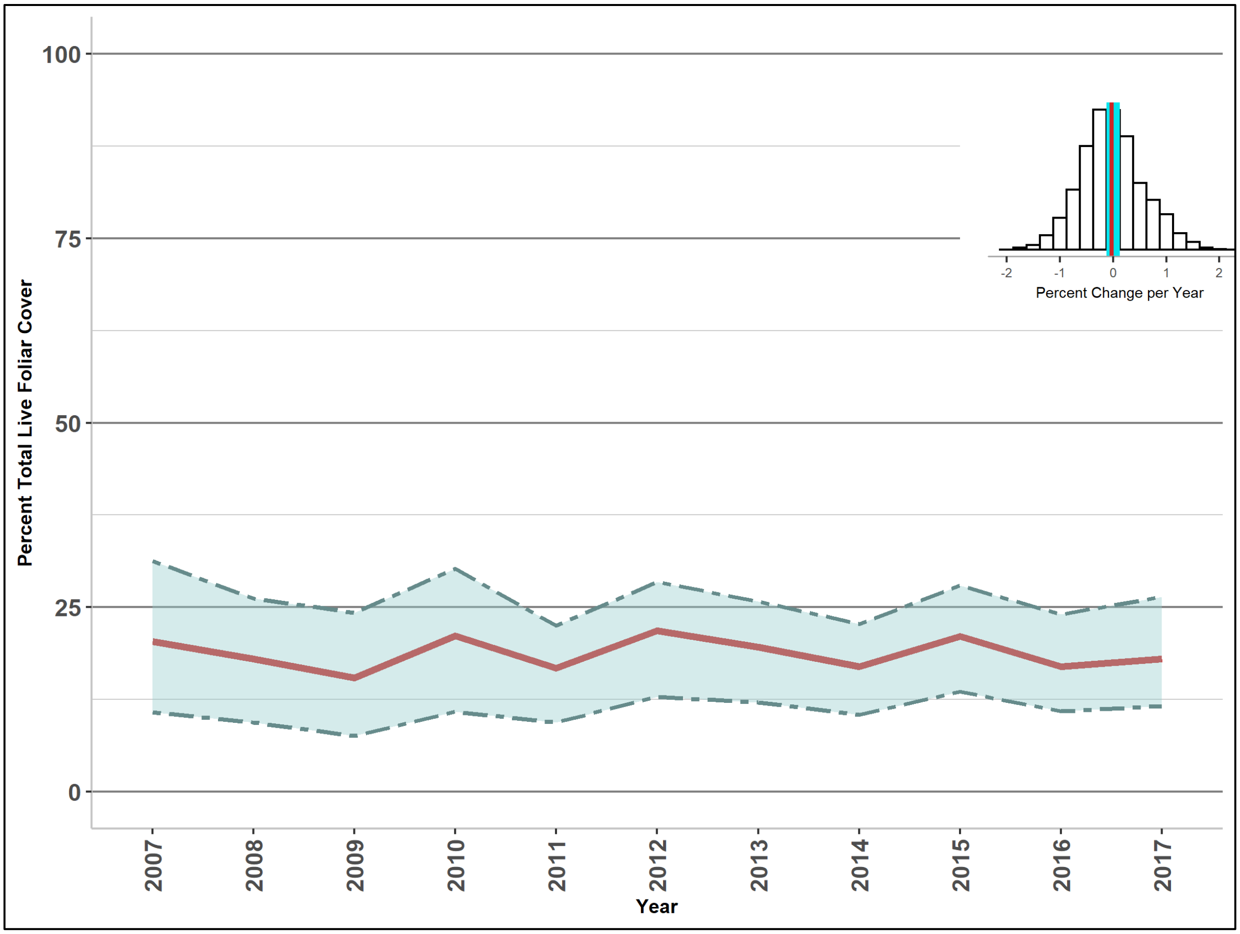

Figure 17. Model-based prediction of the change over time in mean total foliar cover (2007–2018) as a function of spring temperature and seasonal precipitation at plots sampled in the sandy loam upland ecosite at Petrified Forest NP. The solid line indicates the predicted mean at sampled plots, and the shaded area represents the 95% credible intervals. Mean cover increases with increased seasonal precipitation and spring temperatures. Inset shows posterior distribution of change over time is centered around 0% indicating no evidence of trend.

Trend in perennial grass cover

Perennial grasses comprise close to 75% of the total vegetative cover in both ecosites monitored at PEFO, however they differ in the component species. Given the dominance of this lifeform, large changes in cover through time would have an outsized effect on the overall functioning of these ecosites. We were interested in whether there had been significant directional change in the cover of perennial grass species over the monitoring period in either ecosite (2007–2018).

Clayey fan

Patterns of change in perennial grass cover in the clayey fan ecosite were very similar to that of total foliar cover (Figure 18). Conditional on the model, spring temperature had a negative effect on grass cover, while the included seasonal precipitation variables had positive effects of roughly the same magnitude. Warmer spring temperatures led to decreased cover of perennial grass, while more winter, spring, and monsoon precipitation increased grass cover. Despite a pattern of warming spring temperatures and decreasing precipitation overall at PEFO since 2015, model-predicted perennial grass cover was high in 2015 and 2017 due to above-average winter precipitation received at the park (Figure 18). In 2015, the wet winter was followed by a cool and wet spring, resulting in a peak in model-predicted grass cover.

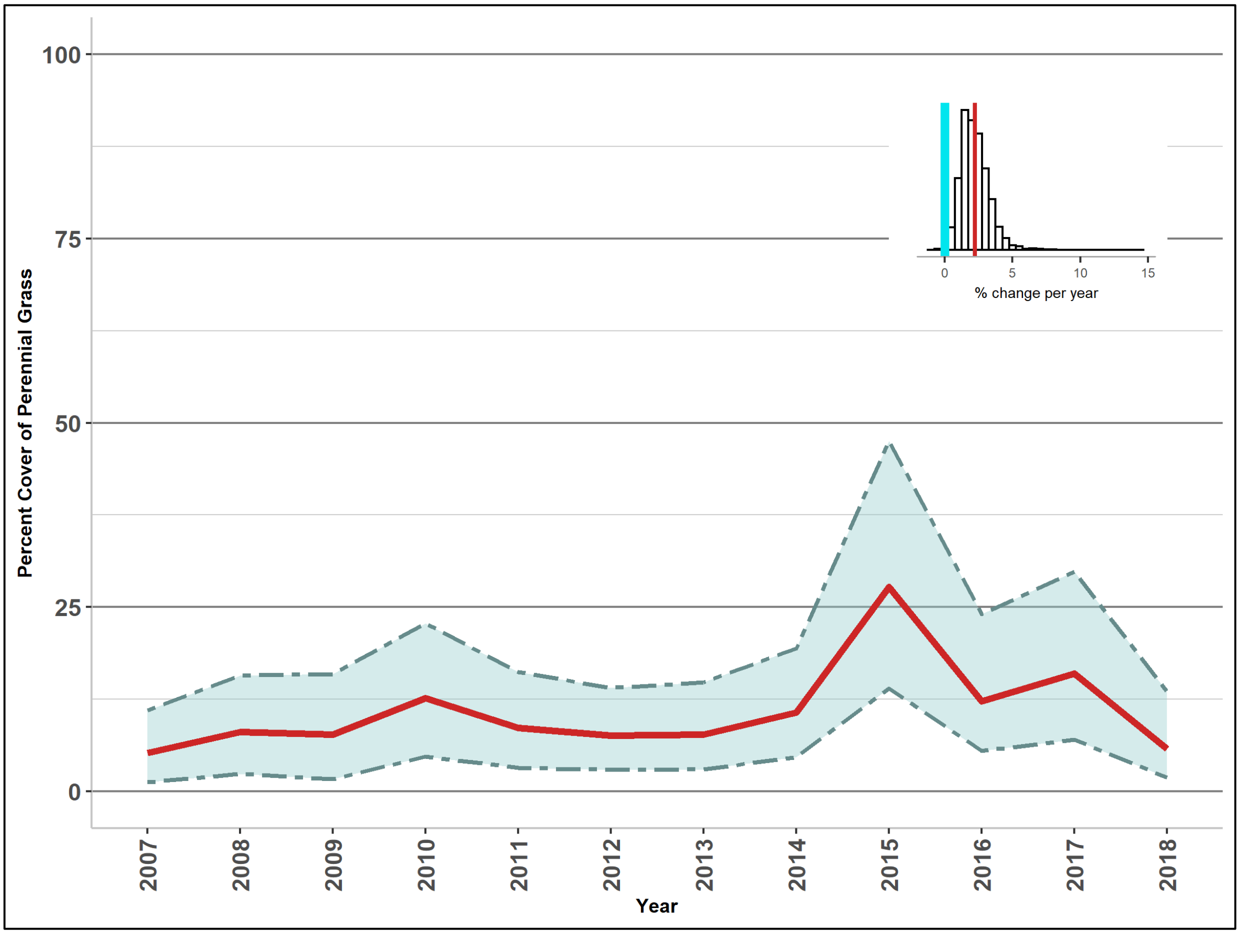

Figure 18. Model-based prediction of the change over time in mean perennial grass cover (2007–2018) as a function of spring temperature and seasonal precipitation at plots sampled in the clayey fan ecosite at Petrified Forest NP. The solid line indicates the predicted mean at sampled plots, and the shaded area represents the 95% credible intervals. Mean cover increases with increased precipitation and decreases with higher spring temperature. Inset shows posterior distribution of change over time is centered above 0% indicating some evidence of a slight increasing trend. This effect is not strong since the distribution still overlaps 0%.

When we controlled for the effect of annual variation in spring temperature and monsoon precipitation by holding them constant at their mean over the monitoring period, there was evidence of a slight increasing trend in perennial grass cover in this ecosite (Figure 18, inset).

Sandy loam upland

Model-predicted perennial grass cover showed little annual variability over the monitoring period (Figure 19). The 95% credible intervals are wide, which reflects relatively high plot-to-plot variability in perennial grass cover, particularly the very low perennial grass cover at plot S11 compared to other sandy loam plots (Figure 19).

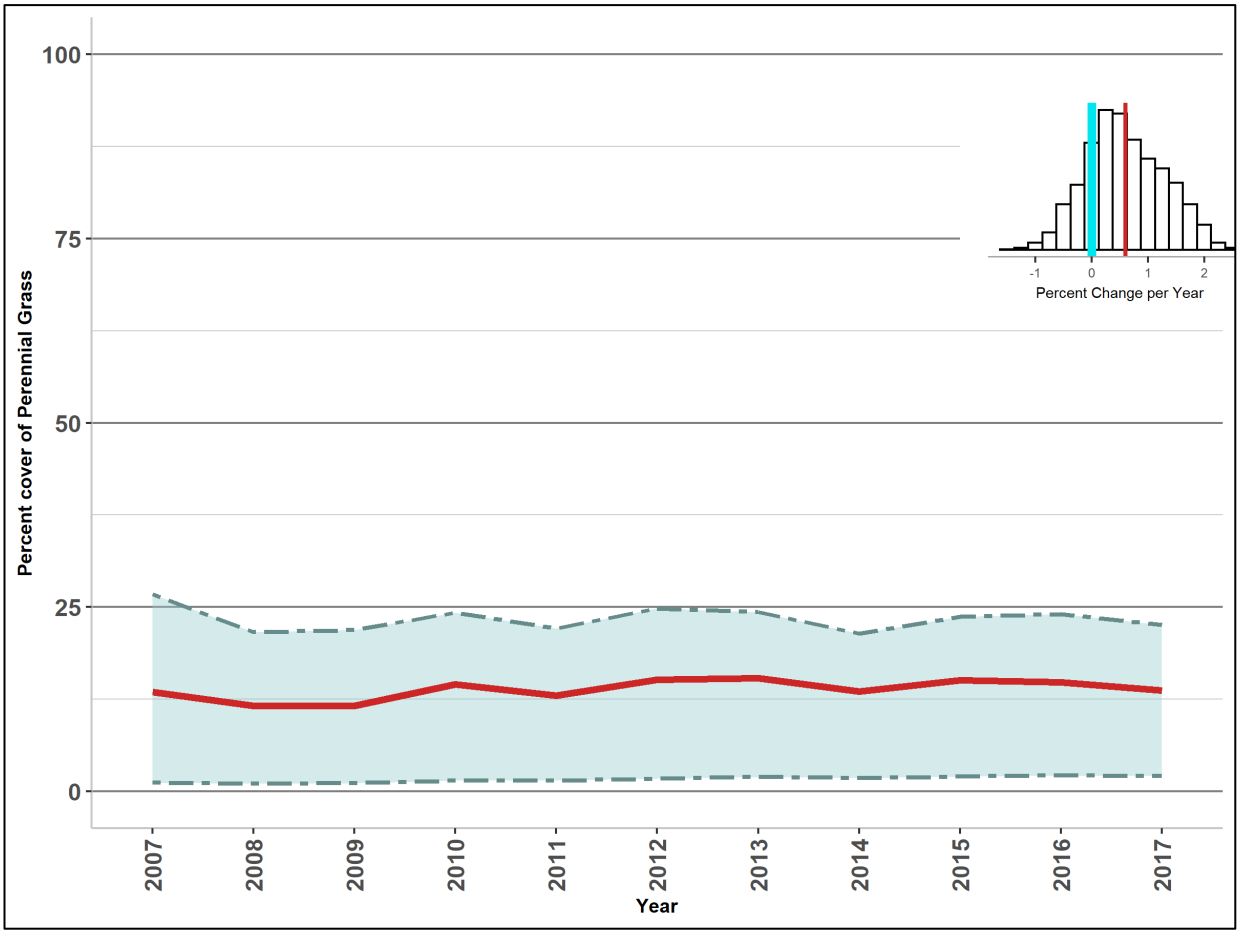

Figure 19. Model-based prediction of the change over time in mean perennial grass cover (2007–2018) as a function of spring temperature and seasonal precipitation at plots sampled in the sandy loam upland ecosite at Petrified Forest NP. The solid line indicates the predicted mean at sampled plots, and the shaded area represents the 95% credible intervals. Mean cover increases with increased spring and monsoon season precipitation and is less affected by winter precipitation and spring temperature. Inset shows posterior distribution of change over time strongly overlaps 0% indicating little evidence for trend.

Monsoon precipitation, and to a lesser extent spring precipitation, had a positive effect on sandy loam grass cover. Winter precipitation and spring temperatures had slightly negative and neutral effects respectively, conditional on the model. Previous studies have suggested the importance of warm season precipitation to C4 grasses, and blue grama, in particular, has been shown to be adept at utilizing even small precipitation events during summer to increase growth (Sala and Lauenroth 1982). The negative effect of winter precipitation is unexpected, however, and warrants more study. It is possible it could be an artifact of weather patterns during the monitoring period. Wet winters are often followed by dry monsoons seasons and vice versa (Figure 13). Other research has indicated that arid grassland species might respond more to a single large precipitation event than to an equal amount of precipitation derived from a series of small rainfall events, a factor we did not investigate in our covariate selection (Sala et al. 1992). When we removed the effect of the covariates, the model showed little evidence of trend (Figure 19, inset).

Trend in shrub cover

Although shrub cover is a relatively small component of the total vegetation in these ecosites, it provides important habitat structure for birds and small mammals. Additionally, shrub cover tends to be more stable over time than herbaceous cover, and reductions in cover generally represent dieback or mortality. Increasing shrub cover is often associated with disturbed states in grasslands, including drought and overgrazing (Rondeau et al. 2013). We were interested in whether cover of shrubs in either ecosite had changed over the monitoring period.

Clayey fan

Shrubs at the clayey fan ecosite did not respond strongly to any of the included weather variables and remained relatively stable during the monitoring period (Figure 20). Conditional on this model, there was a slightly negative effect of higher spring temperature, while increased monsoon precipitation increased shrub cover. When we removed the effect of the covariates, there was no evidence of trend (Figure 20, inset).

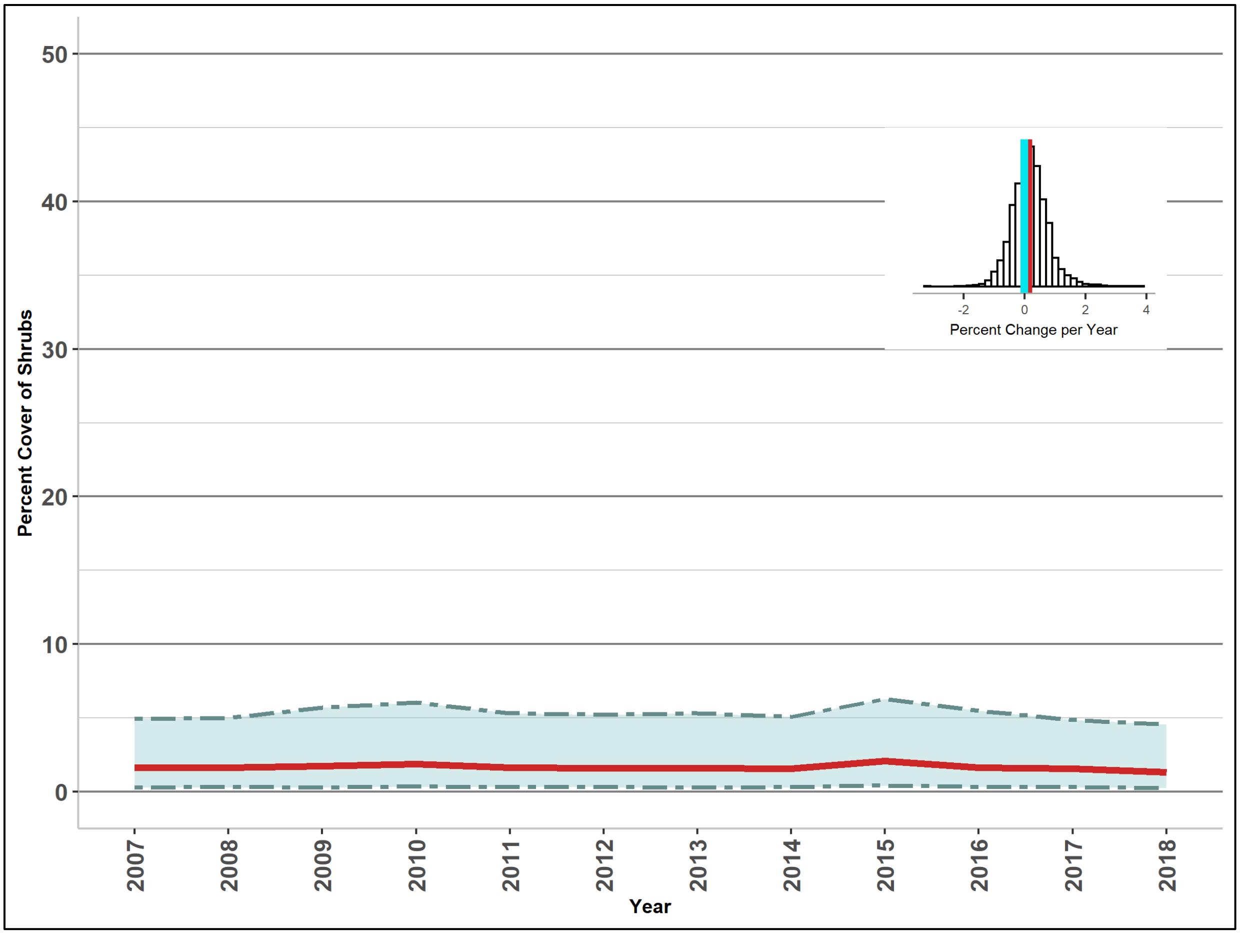

Figure 20. Model-based prediction of the change over time in shrub cover (2007–2018) as a function of spring temperature and seasonal precipitation at plots sampled in the clayey fan ecosite at Petrified Forest NP. The solid line indicates the predicted mean at sampled plots, and the shaded area represents the 95% credible intervals. Mean cover was not strongly affected by changes in precipitation but decreased slightly with higher spring temperature. Inset shows posterior distribution of change over time is centered around 0% indicating no evidence of trend.

Sandy loam upland

Mean model-predicted shrub cover in the sandy loam ecosite increased in response to higher amounts of winter and spring precipitation. Spring temperature also had a positive effect. Similar to shrub cover in the clayey fan site, year-to-year variability was relatively small (Figure 21). When we remove the effect of the covariates, there was no evidence of trend (Figure 21, inset).

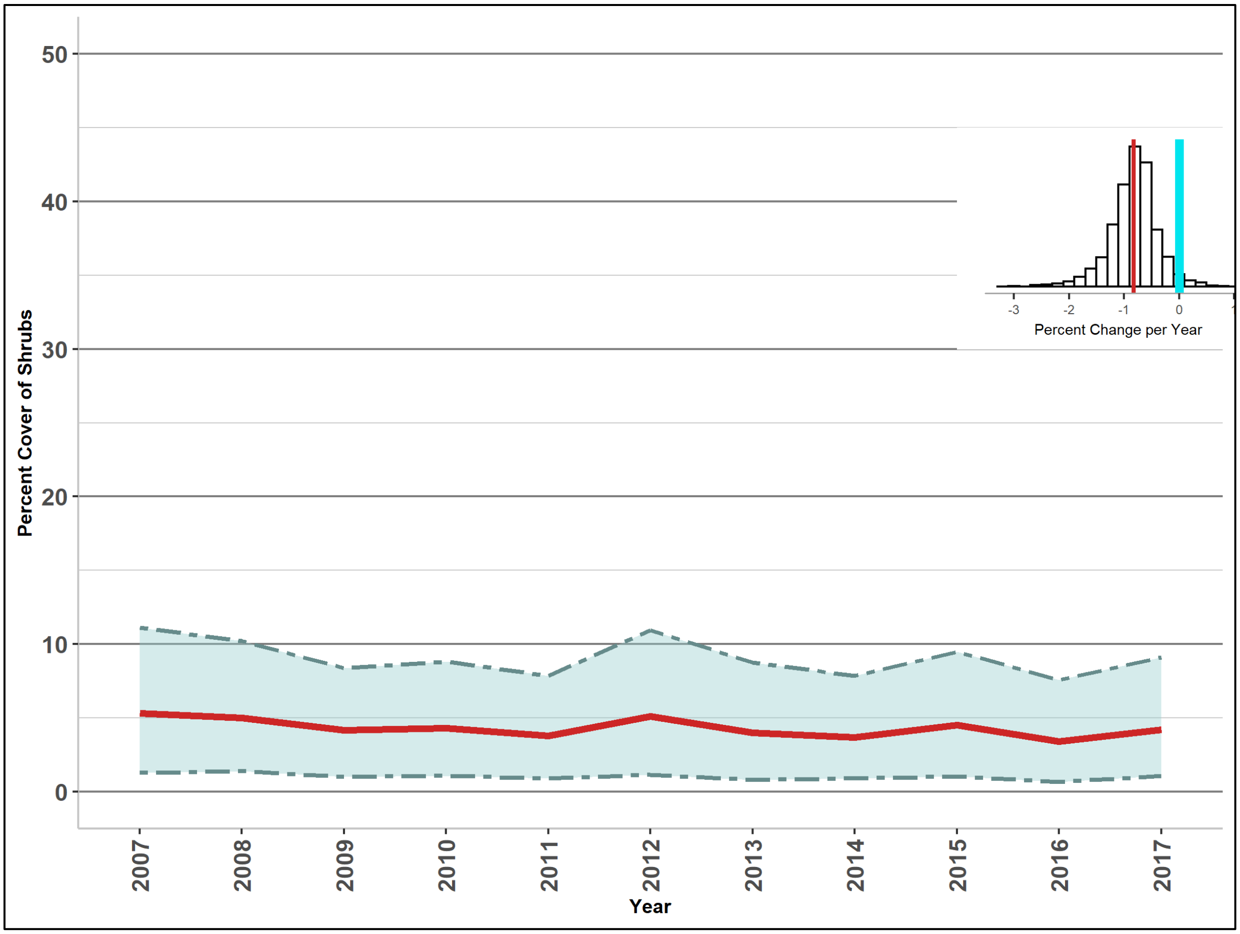

Figure 21. Model-based prediction of the change over time in shrub cover (2007-2018) as a function of spring temperature and seasonal precipitation at plots sampled in the sandy loam upland ecosite at Petrified Forest NP. The solid line indicates the predicted mean at sampled plots, and the shaded area represents the 95% credible intervals. Mean cover increased in response to increased winter and spring precipitation and higher spring temperatures. Inset shows posterior distribution of change over time. Based on the model, there is some evidence that shrub cover has decreased over time in a way that is not explained by yearly fluctuations in precipitation and spring temperature. This effect is not strong since the distribution still overlaps 0%.

Trend in Soil Stability

Clayey fan

Winter precipitation and monsoon precipitation were included in this model. Conditional on the model, increasing monsoon precipitation had a negative effect on soil stability ratings, as did increasing winter precipitation, although this effect was less strong. The model-predicted mean of soil stability was highest in 2009, which had a weak monsoon and dry winter. Although monsoon precipitation has been decreasing since 2015, several wet winters resulted in decreasing soil stability in the model.

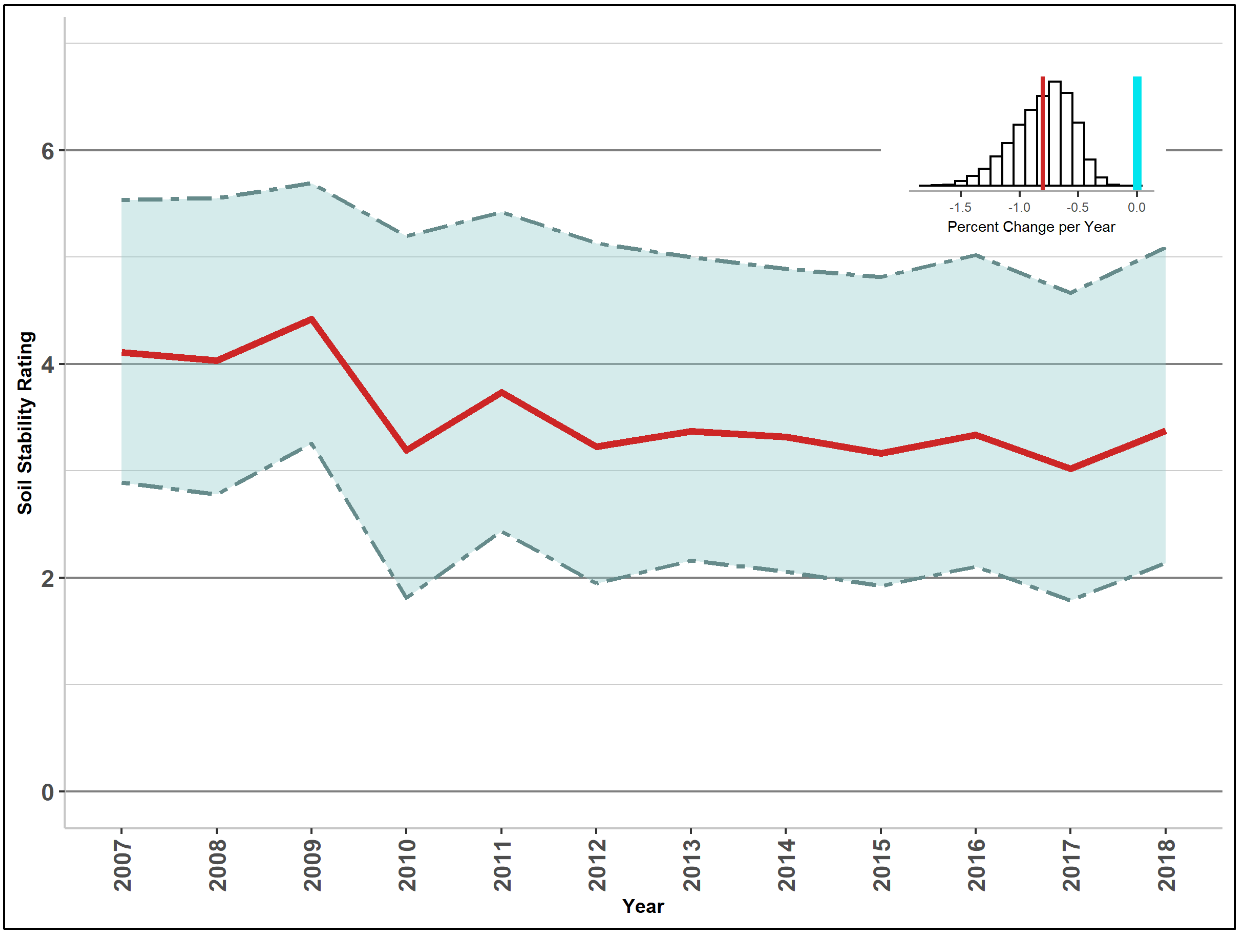

Figure 22. Model-based prediction of the change over time in soil stability (2007–2018) as a function of seasonal winter and monsoon precipitation at plots sampled in the clayey fan ecosite at Petrified Forest NP. The solid line indicates the predicted mean at sampled plots, and the shaded area represents the 95% credible intervals. Soil stability decreased with increasing monsoon and winter precipitation. Inset shows posterior distribution of change over time is centered below 0%, indicating some evidence of a negative trend. Based on the model, there is evidence that soil stability has decreased over time in a way that is not explained by yearly fluctuations in monsoon or winter precipitation.

Sandy loam upland

For the sandy loam upland ecosite, we included all four covariates in the model: winter precipitation, spring temperature, spring precipitation and monsoon precipitation. Spring precipitation had the strongest effect of the four variables, and the direction was positive for all variables except monsoon precipitation, which had a slight negative effect conditional on this model. There is some evidence for a positive trend of increasing soil stability in this ecosite, since the posterior distribution of percent change per year only slightly overlaps zero (Figure 23, inset).

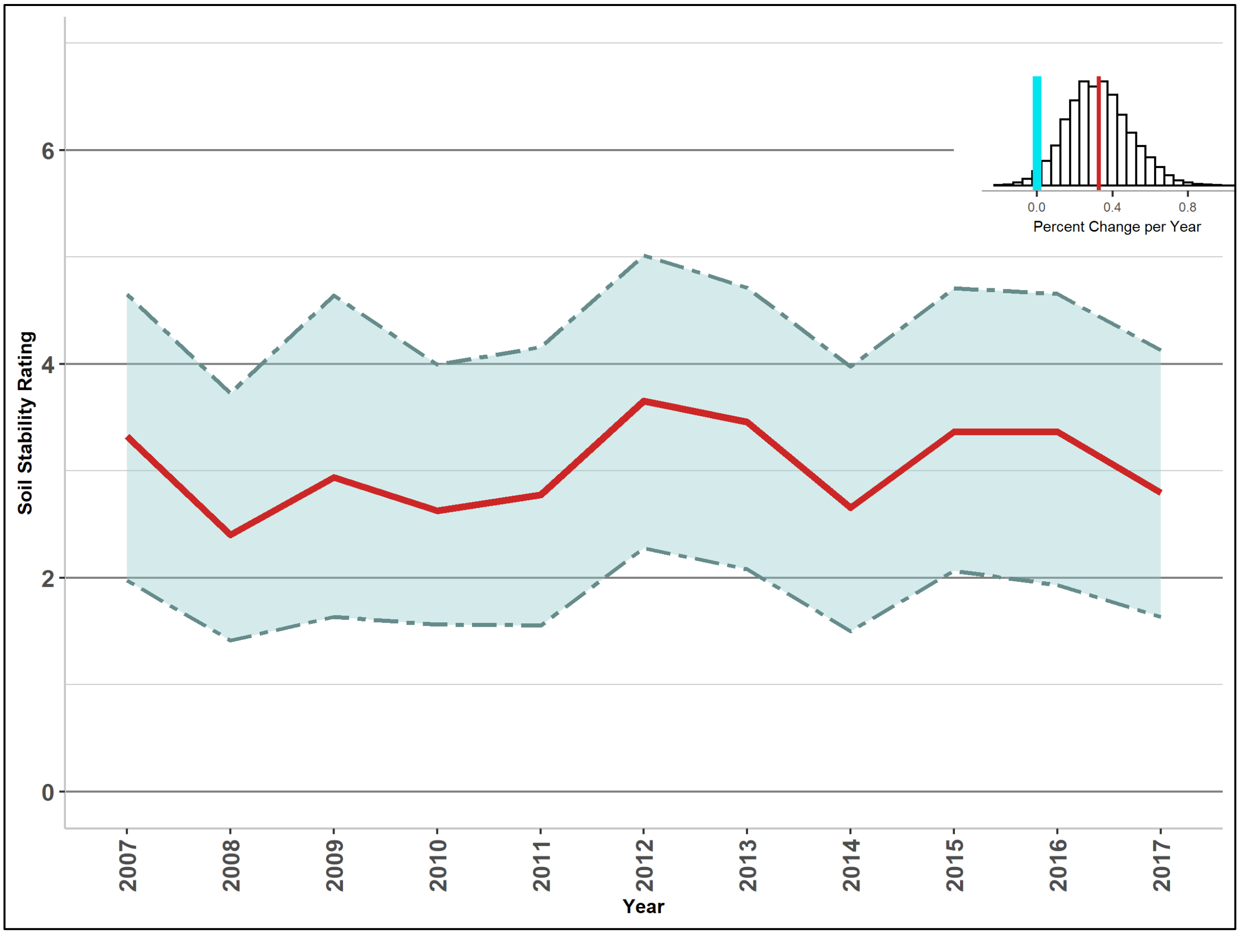

Figure 23. Model-based prediction of the change over time in soil stability (2007-2018) as a function of seasonal precipitation and spring temperature at plots sampled in the sandy loam upland ecosite at Petrified Forest NP. The solid line indicates the predicted mean rating at sampled plots, and the shaded area represents the 95% credible intervals. Soil stability increased with increasing spring precipitation. Inset shows posterior distribution of change over time is centered above 0%, indicating some evidence of a positive trend. Based on the model, there is evidence that soil stability has increased over time in a way that is not explained by yearly fluctuations in the included covariates, but this effect is not strong since the distribution does still overlap zero.

Conclusions

This report presents the results of vegetation and soil monitoring at Petrified Forest National Park (PEFO) by the Southern Colorado Plateau Inventory and Monitoring Network from 2007–2018. We sampled 60 plots, 30 in each of two grassland ecosites predominant in the park—sandy loam upland and clayey fan. We summarized data collected over the monitoring period to better characterize the ecosites, 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 clayey fan and sandy loam upland ecosites at PEFO during the monitoring period (2007–2018)?

The ecosites are generally similar. Soils were deeper and contained less clay in the sandy loam upland ecosite. Undifferentiated crust was the largest component of ground cover in both ecosites. Soil aggregate stability was in the mid-range for both ecosites when averaged over the sampling period and was higher in the clayey fan site. Soil stability in both ecosites was higher under vegetation than when samples were taken from areas with no vegetation canopy.

Total vegetation cover was higher in plots sampled in the sandy loam upland ecosite than in clayey fan plots. Perennial grass was the largest component of vegetation cover in both ecosites, comprising roughly two-thirds of total cover of vegetation. Shrub cover was higher at plots in the sandy loam ecosite while annual grasses were more common in the clayey fan site. Forb and cactus cover were low in both ecosites.

We identified 165 unique plant species. The dominant species in the clayey fan ecosite was dropseed (*Sporobolus* spp.). Sandy loam upland plots were co-dominated by three grass species: blue grama (*Bouteloua gracilis*), galleta grass (*Hilaria jamesii*) and dropseed (*Sporobolus* spp.). We found 12 nonnative species in our plots, but only cheatgrass (*Bromus tectorum*) and Russian thistle (*Salsola tragus*) occurred in more than 10% of the quadrats sampled in any year. Seven new species (two native and five nonnative) were detected during sampling and added to the park's species list.

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 and spring temperature on mean plant cover. Shrub cover remained relatively stable during the monitoring period and responded little to the included climate covariates. Total foliar cover responded most strongly to changes in monsoon precipitation in both ecosites, and this effect was positive. Increasing seasonal precipitation had a net positive effect on perennial grass cover in both ecosites, except for a slight negative effect of winter precipitation in the sandy loam upland ecosite.

Increased monsoon precipitation had a positive effect on species richness in the clayey fan ecosite while monsoon and winter precipitation increased richness in the sandy loam ecosite. Monsoon precipitation had a negative effect on soil stability in both ecosites, while precipitation during other seasons tended to increase stability in the sandy loam upland ecosite.

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

No response we 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. There were slight increasing trends in species richness for both ecosites, indicating that the number of species we identified per quadrat has increased over time. Total cover of live vegetation and cover of perennial grass showed increasing trends in the clayey fan ecosite, but these were slight. Soil aggregate stability showed slight but opposite trends over time in the two ecosites, decreasing slightly in the clayey fan ecosite and slightly increasing in the sandy loam upland ecosite when we controlled for the included climate variables.

Overall, based on the metrics of vegetation cover, species richness and soil stability we examined, the two ecosites at Petrified Forest NP appear to be in good condition. While we provide evidence of considerable interannual change over time in monitored metrics, there were few trends in the indicators we modeled and most were slight and/or positive, i.e., increasing species richness. Although we did not examine trend in nonnative species, they are generally infrequent in both ecosystems and comprise a small component of the vegetation.

SCPN will continue upland vegetation and soils monitoring at PEFO in the coming decades. Annual data summaries will be provided to the park each year in the spring following fieldwork. Additional trend reports will be produced following each complete revisit cycle, with the next expected following the 2023 field season.

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Appendix A: All vascular plant species detected at Petrified Forest National Park (2007–2018)

Table A1. This table lists all species detected during Southern Colorado Plateau Network upland monitoring in Petrified Forest National Park, 2007–2018. Nativity, lifeform and duration were derived from USDA Plants database (https://plants.sc.egov.usda.gov/java). "Eco" indicates in which ecosite a given species occurs (C represents clayey fan and "S" sandy loam upland).

Family	Scientific Name	Common Name	Nativity	Duration	Eco
Amaranthaceae	*Amaranthus acanthochiton*	greenstripe	native	annual	S
Amaranthaceae	*Amaranthus* spp.	amaranth	–	–	C S
Amaranthaceae	*Atriplex canescens*	fourwing saltbush	native	perennial	C S
Amaranthaceae	*Atriplex confertifolia*	shadscale saltbush	native	perennial	C S
Amaranthaceae	*Atriplex obovata*	mound saltbush	native	perennial	C S
Amaranthaceae	*Atriplex saccaria*	sack saltbush	native	annual	C S
Amaranthaceae	*Chenopodium leptophyllum*	narrowleaf goosefoot	native	annual	C S
Amaranthaceae	*Chenopodium* spp.	goosefoot	–	–	C S
Amaranthaceae	*Corispermum americanum*	American bugseed	native	annual	C
Amaranthaceae	*Halogeton glomeratus*	saltlover	nonnative	annual	C
Amaranthaceae	*Kochia scoparia*	burningbush	nonnative	annual	S
Amaranthaceae	*Krascheninnikovia lanata*	winterfat	native	perennial	C S
Amaranthaceae	*Salsola collina*	slender Russian thistle	nonnative	annual	C S
Amaranthaceae	*Salsola tragus*	prickly Russian thistle	nonnative	annual	C S
Amaranthaceae	*Suaeda nigra*	bush seepweed	native	annual	C
Amaranthaceae	*Zuckia brandegeei*	siltbush	native	perennial	C
Amaryllidaceae	*Allium macropetalum*	largeflower onion	native	perennial	C
Apiaceae	*Cymopterus* spp.	springparsley	native	perennial	S
Apocynaceae	*Asclepias involucrata*	dwarf milkweed	native	perennial	S
Apocynaceae	*Asclepias subverticillata*	horsetail milkweed	native	perennial	S
Asparagaceae	*Yucca angustissima*	narrowleaf yucca	native	perennial	C S
Asparagaceae	*Yucca baccata*	banana yucca	native	perennial	C S
Asteraceae	*Ambrosia* spp.	ragweed	–	–	C
Asteraceae	*Artemisia bigelovii*	Bigelow sage	native	perennial	C S
Asteraceae	*Artemisia filifolia*	sand sagebrush	native	perennial	C S

Family	Scientific Name	Common Name	Nativity	Duration	Eco
Asteraceae	*Artemisia ludoviciana*	white sagebrush	native	perennial	C
Asteraceae	*Chaenactis stevioides*	Esteve's pincushion	native	annual	S
Asteraceae	*Chaetopappa ericoides*	rose heath	native	perennial	C S
Asteraceae	*Chrysothamnus greenei*	Greene's rabbitbrush	native	perennial	C S
Asteraceae	*Conyza canadensis*	Canadian horseweed	native	annual	C
Asteraceae	*Dieteria canescens*	hoary tansyaster	native	annual	S
Asteraceae	*Dieteria* spp.	tansyaster	–	–	C
Asteraceae	*Ericameria nauseosa*	rubber rabbitbrush	native	perennial	C S
Asteraceae	*Erigeron concinnus*	Navajo fleabane	native	perennial	C S
Asteraceae	*Erigeron divergens*	spreading fleabane	native	biennial	C S
Asteraceae	*Erigeron* spp.	fleabane	–	–	C S
Asteraceae	*Gaillardia pinnatifida*	red dome blanketflower	native	perennial	C S
Asteraceae	*Gutierrezia sarothrae*	broom snakeweed	native	perennial	C S
Asteraceae	*Helianthus annuus*	common sunflower	native	annual	C
Asteraceae	*Heliomeris multiflora*	showy goldeneye	native	perennial	C
Asteraceae	*Hymenopappus filifolius*	fineleaf hymenopappus	native	perennial	C S
Asteraceae	*Hymenopappus flavescens*	collegeflower	native	biennial	C S
Asteraceae	*Hymenoxys richardsonii*	pingue rubberweed	native	perennial	C
Asteraceae	*Isocoma rusbyi*	Rusby's goldenbush	native	perennial	C S
Asteraceae	*Laennecia coulteri*	Coulter's horseweed	native	annual	C S
Asteraceae	*Pectis angustifolia*	lemonscent	native	annual	C S
Asteraceae	*Psilostrophe sparsiflora*	greenstem paperflower	native	perennial	C
Asteraceae	*Psilostrophe tagetina*	woolly paperflower	native	biennial	C
Asteraceae	*Sanvitalia abertii*	Abert's creeping zinnia	native	annual	C S
Asteraceae	*Schkuhria multiflora*	manyflower false threadleaf	native	annual	C S
Asteraceae	*Senecio flaccidus*	threadleaf ragwort	native	perennial	C S
Asteraceae	*Senecio spartioides*	broom-like ragwort	native	perennial	C
Asteraceae	*Stephanomeria* spp.	wirelettuce	native	–	C S
Asteraceae	*Taraxacum officinale*	common dandelion	nonnative	perennial	C
Asteraceae	*Thelesperma megapotamicum*	Hopi tea greenthread	native	perennial	C S
Asteraceae	*Townsendia annua*	annual Townsend daisy	native	annual	C S

Family	Scientific Name	Common Name	Nativity	Duration	Eco
Asteraceae	*Tragopogon dubius*	yellow salsify	nonnative	biennial	C S
Asteraceae	*Verbesina encelioides*	golden crownbeard	native	annual	C
Asteraceae	*Xanthisma gracile*	slender goldenweed	native	annual	S
Asteraceae	*Xanthisma spinulosum*	cut-leaf ironplant	native	perennial	S
Asteraceae	*Xanthium strumarium*	rough cocklebur	native	annual	C
Asteraceae	*Zinnia grandiflora*	Rocky Mountain zinnia	native	perennial	S
Boraginaceae	*Cryptantha flava*	Brenda's yellow cryptantha	native	perennial	C
Boraginaceae	*Cryptantha* spp.	cryptantha	–	–	C S
Boraginaceae	*Lappula occidentalis*	flatspine stickseed	native	annual	C S
Boraginaceae	*Nama dichotoma*	wishbone fiddleleaf	native	annual	S
Boraginaceae	*Nama hispida*	bristly nama	native	annual	C S
Boraginaceae	*Phacelia integrifolia*	gypsum phacelia	native	annual	S
Boraginaceae	*Phacelia ivesiana*	Ives' phacelia	native	annual	S
Boraginaceae	*Phacelia* spp.	phacelia	–	–	C S
Brassicaceae	*Descurainia pinnata*	western tansymustard	native	annual	C S
Brassicaceae	*Dimorphocarpa wislizeni*	touristplant	native	annual	C S
Brassicaceae	*Draba cuneifolia*	wedgeleaf draba	native	annual	C
Brassicaceae	*Erysimum capitatum*	sanddune wallflower	native	biennial	C S
Brassicaceae	*Physaria intermedia*	mid bladderpod	native	perennial	S
Brassicaceae	*Sisymbrium altissimum*	tall tumblemustard	nonnative	annual	S
Cactaceae	*Cylindropuntia whipplei*	Whipple cholla	native	perennial	C S
Cactaceae	*Echinocereus* spp.	hedgehog cactus	native	perennial	S
Cactaceae	*Echinocereus triglochidiatus*	kingcup cactus	native	perennial	C S
Cactaceae	*Escobaria vivipara*	spinystar	native	perennial	C S
Cactaceae	*Opuntia* spp.	opuntia	native	perennial	C S
Cactaceae	*Sclerocactus whipplei*	Whipple's fishhook cactus	native	perennial	C
Convolvulaceae	*Evolvulus nuttallianus*	shaggy dwarf morning-glory	native	perennial	C S
Ephedraceae	*Ephedra cutleri*	Cutler's jointfir	native	perennial	C S
Ephedraceae	*Ephedra torreyana*	Torrey's jointfir	native	perennial	C S
Ephedraceae	*Ephedra viridis*	Mormon tea	native	perennial	C S
Euphorbiaceae	*Euphorbia albomarginata*	whitemargin sandmat	native	perennial	C

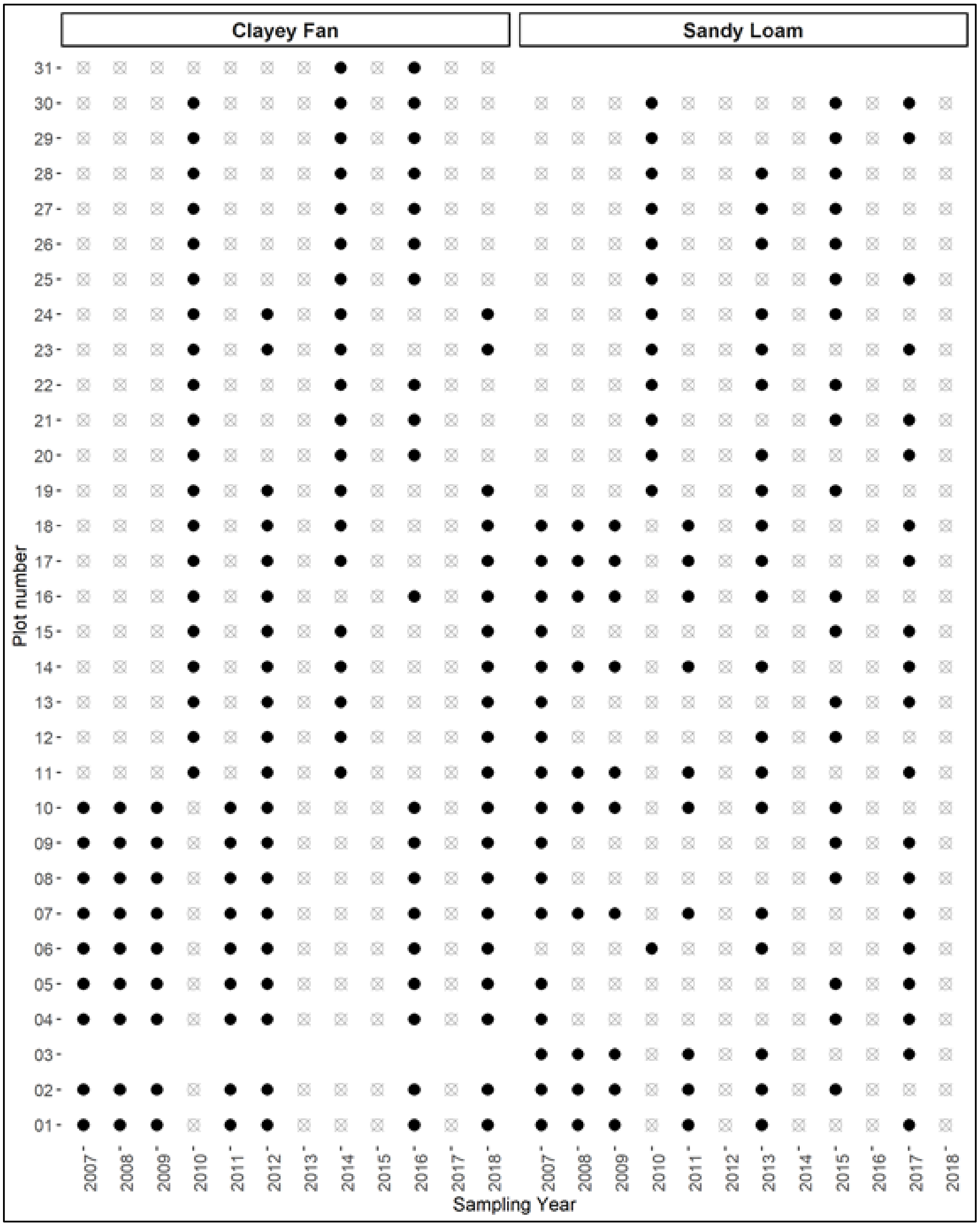
Family	Scientific Name	Common Name	Nativity	Duration	Eco
Euphorbiaceae	*Euphorbia fendleri*	Fendler's sandmat	native	perennial	C S
Euphorbiaceae	*Euphorbia* spp.	sandmat	native	annual	C S
Fabaceae	*Astragalus amphioxys*	Crescent milkvetch	native	perennial	C S
Fabaceae	*Astragalus ceramicus*	painted milkvetch	native	perennial	C S
Fabaceae	*Astragalus lentiginosus*	freckled milkvetch	native	annual	S
Fabaceae	*Astragalus mollissimus*	woolly locoweed	native	perennial	C S
Fabaceae	*Astragalus* spp.	milkvetch	native	perennial	C S
Fabaceae	*Dalea candida*	white prairie clover	native	perennial	C S
Fabaceae	*Dalea lanata*	woolly prairie clover	native	perennial	C S
Fabaceae	*Lupinus* spp.	lupine	native	–	S
Fabaceae	*Parryella filifolia*	common dunebroom	native	perennial	C S
Fabaceae	*Pomaria jamesii*	James' holdback	native	perennial	C S
Geraniaceae	*Erodium cicutarium*	redstem stork's bill	nonnative	annual	C
Helioptropaceae	*Heliotropium curassavicum*	salt heliotrope	native	annual	C
Liliaceae	*Calochortus aureus*	golden mariposa lily	native	perennial	C S
Linaceae	*Linum aristatum*	bristle flax	native	annual	C S
Linaceae	*Linum lewisii*	Lewis flax	native	perennial	C S
Linaceae	*Linum* spp.	flax	native	–	C
Loasaceae	*Mentzelia albicaulis*	whitestem blazingstar	native	annual	C S
Loasaceae	*Mentzelia multiflora*	Adonis blazingstar	native	perennial	C S
Loasaceae	*Mentzelia* spp.	blazingstar	native	–	C S
Malvaceae	*Sphaeralcea* spp.	globemallow	native	perennial	C S
Molluginaceae	*Mollugo cerviana*	threadstem carpetweed	nonnative	annual	C S
Montiaceae	*Phemeranthus parviflorus*	sunbright	native	perennial	C
Nyctaginaceae	*Boerhavia spicata*	creeping spiderling	native	annual	S
Oleaceae	*Menodora scabra*	rough menodora	native	perennial	C S
Onagraceae	*Oenothera* spp.	evening primrose	native	–	C S
Orobanchaceae	*Cordylanthus wrightii*	Wright's bird's beak	native	annual	C S
Orobanchaceae	*Orobanche ludoviciana*	Louisiana broomrape	native	annual	S
Plantaginaceae	*Plantago patagonica*	woolly plantain	native	annual	C S
Poaceae	*Achnatherum hymenoides*	Indian ricegrass	native	perennial	C S

Family	Scientific Name	Common Name	Nativity	Duration	Eco
Poaceae	*Aristida adscensionis*	sixweeks threeawn	native	annual	C S
Poaceae	*Aristida purpurea*	purple threeawn	native	perennial	C S
Poaceae	*Bouteloua barbata*	sixweeks grama	native	annual	C S
Poaceae	*Bouteloua eriopoda*	black grama	native	perennial	C S
Poaceae	*Bouteloua gracilis*	blue grama	native	perennial	C S
Poaceae	*Bromus tectorum*	cheatgrass	nonnative	annual	C S
Poaceae	*Dasyochloa pulchella*	low woollygrass	native	perennial	S
Poaceae	*Elymus elymoides*	squirreltail	native	perennial	C S
Poaceae	*Enneapogon desvauxii*	nineawn pappusgrass	native	perennial	C S
Poaceae	*Eragrostis pectinacea*	tufted lovegrass	native	annual	C S
Poaceae	*Hesperostipa comata*	needle and thread	native	perennial	C S
Poaceae	*Hesperostipa neomexicana*	New Mexico feathergrass	native	perennial	C
Poaceae	*Hilaria jamesii*	galleta grass	native	perennial	C S
Poaceae	*Muhlenbergia pungens*	sandhill muhly	native	perennial	C S
Poaceae	*Muhlenbergia torreyi*	ring muhly	native	perennial	S
Poaceae	*Munroa squarrosa*	false buffalograss	native	annual	C S
Poaceae	*Panicum hirticaule*	Mexican panicgrass	native	annual	C
Poaceae	*Pascopyrum smithii*	western wheatgrass	native	perennial	C
Poaceae	*Sporobolus coromandelianus*	Madagascar dropseed	native	annual	C S
Poaceae	*Sporobolus* spp.	dropseed	native	perennial	C S
Poaceae	*Thinopyrum ponticum*	tall wheatgrass	nonnative	perennial	C
Poaceae	*Vulpia octoflora*	sixweeks fescue	native	annual	C S
Polemoniaceae	*Eriastrum diffusum*	miniature woollystar	native	annual	C
Polemoniaceae	*Gilia* spp.	gilia	native	–	S
Polemoniaceae	*Ipomopsis gunnisonii*	sanddune ipomopsis	native	annual	C
Polemoniaceae	*Ipomopsis longiflora*	flaxflowered ipomopsis	native	annual	C S
Polemoniaceae	*Ipomopsis multiflora*	manyflowered ipomopsis	native	perennial	C S
Polemoniaceae	*Ipomopsis pumila*	dwarf ipomopsis	native	annual	S
Polygonaceae	*Eriogonum corymbosum*	crispleaf buckwheat	native	perennial	S
Polygonaceae	*Eriogonum deflexum*	flatcrown buckwheat	native	annual	C S
Polygonaceae	*Eriogonum divaricatum*	divergent buckwheat	native	annual	C S

Family	Scientific Name	Common Name	Nativity	Duration	Eco
Polygonaceae	*Eriogonum jamesii*	James' buckwheat	native	perennial	S
Polygonaceae	*Eriogonum leptocladon*	sand buckwheat	native	perennial	C S
Polygonaceae	*Eriogonum pulchrum*	Yavapai County buckwheat	native	perennial	S
Polygonaceae	*Eriogonum* spp.	buckwheat	–	–	S
Polygonaceae	*Polygonum aviculare*	prostrate knotweed	nonnative	annual	S
Polygonaceae	*Polygonum sawatchense*	knotweed	native	annual	S
Portulacaceae	*Portulaca* spp.	portulaca	–	annual	C S
Santalaceae	*Comandra umbellata*	bastard toadflax	native	perennial	C S
Sarcobataceae	*Sarcobatus vermiculatus*	greasewood	native	perennial	C
Solanaceae	*Chamaesaracha coronopus*	greenleaf five eyes	native	perennial	C S
Solanaceae	*Lycium pallidum*	pale desert-thorn	native	perennial	S
Solanaceae	*Quincula lobata*	Chinese lantern	native	perennial	C
Solanaceae	*Solanum jamesii*	wild potato	native	perennial	S
Verbenaceae	*Verbena bracteata*	bigbract verbena	native	annual	C S
Zygophyllaceae	*Kallstroemia parviflora*	warty caltrop	native	annual	C S

Appendix B: Plot sampling history

Complete history of sampling events for each plot included in this report. Black dot indicates that plot was sampled during that year. Rotating panel design was implemented in 2012 and based on this design, two-thirds of plots in each ecosystem are sampled every other year. Maximum number of revisits to a single plot is six and minimum is two.



Appendix C: Bayesian models

Table C-1. Model specifications for all responses present in this report. Model indicates the type of deterministic model used. Model type indicates whether slope only (b0) or slope and intercepts (b1) were allowed to vary 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 means that each site has its own independent variance. Hierarchical site means that 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. P_{mean} is the Bayesian p-value for the mean and is used to indicate lack of fit. P_{sd} is the same for the variance. ppl is posterior predictive loss, models with lowest posterior predictive loss where selected. The Gelman diagnostic (Gel) is an indicator of convergence and should be close to one. See Hobbs et al. in prep for more detail.

Response	Ecosite	Model	Model type	Variance level and type	Likelihood	Covariates	P_{mean}	P_{sd}	ppl	Gel
Richness	Clayey fan	linear	b0	site, fixed	poisson	Winter precipitation, spring temperature, spring precipitation, monsoon precipitation	0.51	0.59	27899	1.01
	Sandy loam upland	linear	b0	stratum, fixed	poisson	Winter precipitation, spring temperature, spring precipitation, monsoon precipitation	0.5	0.69	23228	1
Total live foliar cover	Clayey fan	Inverse logit	b0-b1, g0-g1	site, fixed	hurdle-ordinal-latent-beta	Winter precipitation, spring temperature, spring precipitation, monsoon precipitation	0.73	0.99	6505	1.06
	Sandy loam	Inverse logit	b0-b1, g0	site, fixed	hurdle-ordinal-latent-beta	Winter precipitation, spring temperature, spring precipitation, monsoon precipitation	0.5	0.87	2413	1.01
Perennial grass cover	Clayey fan	Inverse logit	b0-b1, g0-g1	site, fixed	hurdle-ordinal-latent-beta	Winter precipitation, spring temperature, spring precipitation, monsoon precipitation	0.79	0.62	9070	1.03
	Sandy loam upland	Inverse logit	b0-b1, g0	site, fixed	hurdle-ordinal-latent-beta	Winter precipitation, spring temperature, spring precipitation, monsoon precipitation	0.56	0.6	3318	1.01

Response	Ecosite	Model	Model type	Variance level and type	Likelihood	Covariates	P_{mean}	P_{sd}	ppl	Gel
Shrub cover	Clayey fan	Inverse logit	b0-b1, g0-g1	site, fixed	hurdle-ordinal-latent-beta	Winter precipitation, spring temperature, spring precipitation, monsoon precipitation	0.59	0.65	5185	1.07
	Sandy loam upland	Inverse logit	b0-b1, go	site, fixed	hurdle-ordinal-latent-beta	Winter precipitation, spring temperature, spring precipitation, monsoon precipitation	0.5	0.62	6954	1.07
Soil stability	Clayey fan	linear	b0	site, hierarchical	ordinal-latent-normal	Winter precipitation, monsoon precipitation	0.43	0.5	11054	1.01
	Sandy loam upland	linear	b0	site, hierarchical	ordinal-latent-normal	Winter precipitation, spring temperature, spring precipitation, monsoon precipitation	0.47	0.56	7711	1.02

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