



Vegetation Trends in Pinyon-Juniper Woodlands in Southern Colorado Plateau Network Parks



Pinyon-juniper woodlands at Mesa Verde National Park.
NPS

Vegetation trends in pinyon-juniper woodlands in Southern Colorado Plateau Network parks

Science Report NPS/SR—2025/307

Megan Swan ¹

¹ National Park Service
Southern Colorado Plateau Inventory and Monitoring Network
930 N Switzer Canyon Dr., Suite 200
Flagstaff, AZ 86001

Christopher Calvo¹, editor

Please cite this publication as:

Swan, M. 2025. Vegetation trends in pinyon-juniper woodlands in Southern Colorado Plateau Network parks. Science Report NPS/SR—2025/307. National Park Service, Fort Collins, Colorado.
<https://doi.org/10.36967/2312771>

The National Park Service Science Report Series disseminates information, analysis, and results of scientific studies and related topics concerning resources and lands managed by the National Park Service. The series supports the advancement of science, informed decisions, and the achievement of the National Park Service mission.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible and technically accurate.

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

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

This report is available in digital format from the [National Park Service DataStore](#) and the [Natural Resource Publications Management website](#). If you have difficulty accessing information in this publication, particularly if using assistive technology, please email irma@nps.gov.

Contents

	Page
Figures.....	v
Tables.....	viii
Appendices.....	ix
Abstract.....	x
List of Acronyms	xii
Executive Summary	xiv
Introduction.....	1
Methods.....	3
Study area	3
Monitoring site selection	4
Selected monitoring sites.....	5
Sampling design	5
Soil profile and surface features	6
Soil stability.....	7
Herbaceous and shrub vegetation	7
Trees	8
Seedlings	8
Saplings	8
Overstory trees	9
Canopy cover.....	9
Data management and analysis methods.....	9
Status estimates	9
Trend estimates.....	10
Covariates	12
Results and Discussion	15
Status	15
Sampling overview.....	15
Climate overview.....	15

Contents (continued)

	Page
Soil overview.....	16
Understory vegetation overview.....	20
Overstory vegetation overview.....	25
Trend	29
Assessing trend.....	29
Climate	30
Change over time in soil stability.....	33
Change over time in understory vegetation.....	34
Change over time in overstory trees.....	50
Summary: temporal trends	55
Summary: covariate effects	59
Conclusions.....	63
Management Implications.....	64
Literature Cited	65

Figures

	Page
Figure 1. Overview map of the sampling frames and plot locations for the three NPS units included in this report.....	3
Figure 2. Pinyon-juniper vegetation surrounding an archeological site in the woodlands at Mesa Verde National Park	4
Figure 3. Diagram of a Southern Colorado Plateau Network upland monitoring plot.	6
Figure 4. Seasonal precipitation patterns based on 30-year normal (1991–2021) at four ecosites in three National Parks (BAND, GRCA, MEVE).....	15
Figure 5. Median annual precipitation (left) and maximum temperature (right) based on 30-year normal (1991–2020) for four ecological sites in three National Parks (BAND, GRCA, MEVE).....	16
Figure 6. Maximum auger depth of soil profile samples collected during plot establishment at four ecosites in three National Parks (BAND, GRCA, MEVE).	17
Figure 7. Texture of soil profile samples collected during plot establishment at four ecosites in three National Parks (BAND, GRCA, MEVE).....	18
Figure 8. Mean percent cover of soil surface features at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008–2022.	19
Figure 9. While not comprising much of the overall vegetative cover at most sites, perennial forbs represent a large component of species richness in PJ woodlands.	22
Figure 10. Treemaps of dominant species.....	23
Figure 11. Overstory tree basal area and status for junipers and pinyons (overstory trees are all individuals ≥ 15 cm in diameter) at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008–2022.	26
Figure 12. Mean tally of saplings by size class for junipers and pinyons at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008–2022.	27
Figure 13. Mean tally of seedlings by species and size class for junipers and pinyons at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008–2022.....	28
Figure 14. Mean percent canopy cover at four ecological sites in three National Parks (BAND, GRCA, MEVE) during 2008–2022.....	29
Figure 15. Percent of normal precipitation received at each monitored plot in four ecosites in three National Parks (BAND, GRCA and MEVE).	31
Figure 16. Median accumulated seasonal and annual precipitation totals at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022.....	32

Figures (continued)

	Page
Figure 17. Annual median maximum temperature (Tmax, red triangles) and minimum temperature (Tmin, inverted green triangles) across plots at four ecosites in three National Parks (BAND, GRCA and MEVE) from 2008 to 2022.	33
Figure 18. Model-based prediction of change over time in aggregate soil stability at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022.	34
Figure 19. Model-based prediction of change over time in total live perennial grass cover at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022.	35
Figure 20. Model-based prediction of change over time in total live muttongrass cover at four ecosites in two National Parks (GRCA, MEVE) from 2008 to 2022.	36
Figure 21. Model-based prediction of change over time in total live blue grama cover at four ecosites in two National Parks (BAND, GRCA) from 2008 to 2022.	37
Figure 22. Model-based prediction of change over time in total live squirreltail cover at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022.	38
Figure 23. Model-based prediction of change over time in total live shrub cover at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022.	39
Figure 24. Model-based prediction of change over time in total live mountain mahogany cover at Mesa Verde National Park from 2008 to 2022.	40
Figure 25. Model-based prediction of change over time in total live antelope bitterbrush cover at Mesa Verde National Park from 2008 to 2022.	41
Figure 26. Model-based prediction of change over time in total live snakeweed cover at two national parks (BAND and GRCA) from 2008 to 2022.	42
Figure 27. Model-based prediction of change over time in total live cactus and succulent cover at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022.	43
Figure 28. Model-based prediction of change over time in total live prickly pear cover at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022.	44
Figure 29. Model-based prediction of change over time in total live forb cover at one ecosite in Bandelier National Monument (BAND) from 2008 to 2022.	45
Figure 30. Model-based prediction of change over time in ragleaf bahia presence at one ecosite in Bandelier National Monument (BAND) from 2008 to 2022.	46
Figure 31. Model-based prediction of change over time in cheatgrass presence at two ecosites in two National Parks (BAND, GRCA) from 2008 to 2022.	47

Figures (continued)

	Page
Figure 32. Model-based prediction of change over time in total live toadflax penstemon cover at two ecosites in Mesa Verde National Park (MEVE) from 2008 to 2022.....	48
Figure 33. Model-based prediction of change over time in quadrat-scale species richness at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022.	50
Figure 34. Model-based prediction of change over time in juniper seedling density at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022.	51
Figure 35. Model-based prediction of change over time in pinyon seedling density at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022.	52
Figure 36. Model-based prediction of change over time in juniper sapling density at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022.	53
Figure 37. Model-based prediction of change over time in pinyon sapling density at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022.	54
Figure 38. Summary of direction of year effects (trend) for modeled responses.....	56
Figure 39. Cumulative annual (a) climatic water deficit (mm) and (b) soil water (mm) for each water year (Oct–Sept) at four ecosites in three National Parks (BAND, GRCA, MEVE).....	57
Figure 40. Summary of direction of covariate effects on modeled responses.	60
Figure 41. Plot sampling history at four ecosites in three National Parks (BAND, GRCA, MEVE).....	73
Figure 42. Plot sampling intervals at four ecosites in three National Parks (BAND, GRCA, MEVE).....	74

Tables

	Page
Table 1. Names and characteristics of the four ecological sites included in this report.....	5
Table 2. Cover classes used by the Southern Colorado Plateau Network for estimating ocular cover during upland monitoring.....	7
Table 3. Seedling size classes used by the Southern Colorado Plateau Network for tallying tree seedlings during upland monitoring.	8
Table 4. Sapling size classes used by the Southern Colorado Plateau Network for tallying tree saplings during upland monitoring.	9
Table 5. Crown health codes for overstory trees.....	9
Table 6. Summary of response variables assessed in this report.....	11
Table 7. Details on climate and physical variables that were included as covariates in at least one model.	14
Table 8. Mean soil stability rating class and standard error (SE) for three ecosites in three National Parks (BAND, GRCA, MEVE) during 2009–2022.	20
Table 9. Average percent cover (and range) by lifeform in four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008–2022.....	21
Table 10. Average quadrat (10 m ²) and plot-scale (1500 m ²) richness estimates and range (lowest and highest values) for five grassland ecological sites in three National Parks during 2008–2022 (BAND, GRCA, MEVE).....	24
Table 11. Overall percent quadrat frequency of the 18 nonnative species encountered during sampling in four ecosites at three National Parks during 2008 to 2022 (BAND, GRCA, MEVE).....	25
Table 12. Average tree mortality by ecological site and species for three park units.....	55
Table 13. List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022.	75
Table 14. Median percent cover of dominant plants at four ecosites in three National Parks (BAND, GRCA, MEVE).	89
Table 15. Model specifications for all responses presented in this report.....	92
Table 16. Summary of direction of year effects (trend) for modeled responses.	96
Table 17. Summary of direction of covariate effects on modeled responses.....	97
Table 18. Plot sampling history at four ecosites in three National Parks (BAND, GRCA, MEVE).....	98

Appendices

	Page
Appendix A: Plot Sampling History	73
Appendix B: Vascular Plant Species Detected at Pinyon Juniper Ecological Sites (2008–2022)	75
Appendix C: Cover class midpoint medians of dominant species	89
Appendix D: Bayesian Models	92
Appendix E. Fully Accessible Versions of Figure 38, Figure 40, and Figure 41	96

Abstract

The Southern Colorado Plateau Network has monitored vegetation and soils in pinyon-juniper woodlands at Bandelier National Monument (BAND), Grand Canyon National Park (GRCA), and Mesa Verde National Park (MEVE) since 2007. This report analyzes 15 years of data on site characteristics and changes in selected indicators. Overall, MEVE and GRCA exhibited similar conditions in Pinyon-Juniper woodlands, with sparsely vegetated understories and dense canopies dominated by Utah juniper (*Juniperus osteosperma*) and two-needle pinyon pine (*Pinus edulis*). In contrast, BAND had a more diverse understory with a greater variety of forb and shrub species, and a less dense overstory primarily of one-seed juniper (*Juniperus monosperma*). Seedling and sapling presence was noted at all sites but was least common at BAND. Soils differed in texture, development, and depth across parks. Aggregate stability was generally moderate across all sites. While plant species richness was generally low, it was highest at BAND. Nonnative plants were uncommon except for cheatgrass (*Bromus tectorum*), which had up to 40% cover at some BAND plots. Vegetation analysis revealed a pattern of stability and slight positive changes over the 15-year monitoring period. Species richness increased at all sites, and cover of shrubs and cactus/succulents rose at three out of four locations. However, exotic cheatgrass (*Bromus tectorum*) also increased significantly at BAND—averaging about 2% per year—while it slightly decreased at GRCA (< 1% annually). Climate variables influenced plant trends, with increasing water stress negatively impacting vegetation cover, particularly perennial grasses. Although tree mortality was generally low, it was highest for pinyons at GRCA. Limiting disturbance in pinyon-juniper woodlands to prevent the introduction of invasive grasses is recommended; stand thinning in old-growth woodlands designed to potentially increase drought resilience requires further study and is not recommended.



Diverse canopies within the pinyon-juniper habitat at Grand Canyon National Park.
NPS / MEGAN SWAN

List of Acronyms

AGDD: Accumulated growing degree-days

AET: Actual evapotranspiration

AI: Aridity index

BA: Basal area

BAND: Bandelier National Monument

CWD: Climatic water deficit

DBH: Diameter at breast height

DRC: Diameter at root crown

GRCA: Grand Canyon National Park

Gel: Gelman-Rubin diagnostic

GRTS: Generalized Random Tessellation Stratified

ITIS: Integrated Taxonomic Information System

JAGS: Just Another Gibbs Sampler

MCMC: Markov Chain Monte Carlo

MEVE: Mesa Verde National Park

n: Number in a sample

NPS: National Park Service

NRCS: Natural Resources Conservation Services

PET: Potential evapotranspiration

PJ: Pinyon-juniper

PPL: Posterior predictive loss.

PRISM: Parameter-elevation Regressions on Independent Slopes Model

SCPN: Southern Colorado Plateau Network

SSURGO: Soil Survey Geographic Database

Tmax: Median highest monthly temperature

Tmin: Median lowest temperature

USDA: United States Department of Agriculture

Executive Summary

The Southern Colorado Plateau Network has been monitoring vegetation and soils in pinyon-juniper woodlands at three national park units since 2007 [Bandelier National Monument (BAND), Grand Canyon National Park (GRCA), and Mesa Verde National Park (MEVE)]. This report analyzes 15 years of data and examines both the overall character of the sites as well as change over time in selected indicators.

Overall, pinyon-juniper sites at MEVE and GRCA were generally similar, with sparsely vegetated understories of grass and shrubs and overstories with relatively dense canopy cover dominated by Utah juniper (*Juniperus osteosperma*) and two-needle pinyon pine (*Pinus edulis*). In contrast, the understory at BAND is more vegetated and diverse with greater numbers of forb and shrub species and a less dense overstory dominated by one-seed juniper (*Juniperus monosperma*) with few surviving pinyon and less canopy cover than at MEVE and GRCA. Seedlings and saplings of both tree genera were present at all sites but were least common at BAND.

Soils varied by texture, development, and depth across sites and between plots within sites, particularly at BAND. Soil aggregate stability was moderate across all sites, and duff and litter comprised the majority of the soil surface cover. Species composition of the understory also differed among sites. Species richness was low overall but was highest at BAND. Nonnative plants were not common at most sites, except for cheatgrass (*Bromus tectorum*) at BAND which had up to 40% cover in some plots.

Measured values (or responses) analyzed for trend include: cover and frequency of lifeform groups (graminoid, forb, shrub, cactus or succulents); cover and frequency of dominant plant species; seedling and sapling density; overstory basal area; canopy cover; soil stability; and species richness. There was a general pattern of stability or positive but slight changes in measured variables during the 15-year monitoring period. Most notably, species richness increased at every site and cover of shrubs and cactus/succulents increased at 3 of 4 sites. However, the exotic annual cheatgrass (*Bromus tectorum*) also exhibited an increase in presence on plots at BAND (about 2% per year on average), but slightly decreased in cover at GRCA (< 1% annually).

Climate variables often had significant effects on vegetation responses. Increasing water stress (climatic water deficit or CWD) tended to reduce vegetation cover across all sites except winter CWD which had positive effects on multiple species (grass, forbs, and shrubs). In particular, greater spring (April–June) water stress reduced plant cover and abundance, particularly the cover of perennial grass. Other covariates had mixed or mostly weak effects. The importance of spring water stress is concerning since predicted earlier snowmelt and higher spring temperatures will almost certainly result in drier springs in the coming decades. Semi-arid woodlands are also expected to be highly affected by severe drought driven by robust predictions of increasing temperature (> 2° C by 2059) and decreasing soil moisture availability, especially in the spring season (Gremer et al. 2018, Andrews et al. 2019a, 2019b, 2019c).

Overall, there was little overstory tree mortality during the monitoring period, but mortality was highest in pinyons at GRCA. Seedling and sapling densities showed slight increases at many sites during the monitoring period.

Management implications of the monitoring data include limiting disturbance to PJ woodlands wherever possible, particularly to avoid introducing invasive grasses that can increase the risk of stand-replacing fire. In old-growth, persistent woodlands like those found at GRCA and MEVE, stand thinning is not recommended as it is unclear whether it will increase drought resiliency and risks introducing invasive annual grasses.

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. Pinyon-juniper woodlands (PJ) are a dominant vegetation type in the Western US and comprise much of the vegetation in parks on the Southern Colorado Plateau (Thomas et al. 2006). These vegetation communities are vitally important to the overall character of Southern Colorado Plateau Network (SCPN) parks, forming an integral component of the natural and cultural landscape. SCPN parks contain some of the best examples of old-growth persistent pinyon-juniper woodlands in the region, given their history of protection from fire, anthropogenic use, and domestic grazing (Thomas et al. 2006).

PJ woodlands provide important ecosystem services and are predicted to decline in many places throughout the West due to climate change (Noel et al. 2024). In SCPN parks, PJ ecosystems provide habitat for birds including the vulnerable pinyon jay (*Gymnorhinus cyanocephalus*), mammals, reptiles, and insects (BirdLife International 2020, Thomas et al. 2006). Native vegetation in PJ contributes to park diversity, including rare and endemic species such as the Chapin Mesa milkvetch (*Astragalus schmollii*) and Tusayan fame flower (*Phemeranthus validulus*), and woodlands in some parks contain old growth PJ with individual trees ≥ 750 years old (Floyd 2004). More generally, PJ vegetation shades and stabilizes the soil which, critically, preserves and protects numerous paleontological, and cultural resources which can be damaged by erosion.

SCPN monitors PJ woodlands as part of an initiative to provide long-term, scientifically sound monitoring data to inform park management of natural resource condition and trends. Specifically, field crews collect data on the structure, abundance, species composition and richness of upland understory vegetation, density of seedlings and saplings, canopy cover, density, and basal area of overstory trees, soil surface features, and soil stability (DeCoster et al. 2012).

SCPN staff established sets of long-term monitoring plots in four PJ ecosystem types in three park units: mesa top pinyon-juniper at Bandelier National Monument (BAND); loamy mesa top PJ and shallow loamy mesa top PJ at Mesa Verde National Park (MEVE); and limestone upland PJ at Grand Canyon National Park (GRCA). Sites at MEVE and GRCA represent old-growth pinyon juniper woodlands dominated by Utah juniper (*Juniperus osteosperma*) and two-needle pinyon (*Pinus edulis*) (Floyd 2003, Romme et al. 2009). The site at BAND is a transitional woodland, dominated by younger (< 150 year old) one-seed juniper (*Juniperus monosperma*); pinyons are almost entirely absent at BAND due to a landscape-scale pinyon die-off event prior to the start of monitoring (Breshears et al. 2008). Some monitored areas at BAND were also subjected to a large-scale thinning treatment that occurred near the establishment of monitoring which reduced juniper cover by about 9% on average in treated areas (Romme et al. 2009, Meddens et al. 2016).

Reporting on natural resource status and trend 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 in PJ woodlands in three parks from 2008–2022. In the first section, data collected over

all years are summarized to provide a robust estimate of status for selected indicators. In the second section, Bayesian hierarchical models are employed to look at how selected response variables have changed over 15 years of monitoring.

Methods

Study area

The Southern Colorado Plateau Inventory and Monitoring Network encompasses 19 NPS units on 1,150,335 ha of protected lands in the Four Corners region (northern Arizona, northern New Mexico, southern Colorado, southern Utah), including > 750,000 ha of designated or proposed wilderness (Thomas et al. 2006). Within this area, SCPN has been monitoring upland vegetation in selected areas since 2007.

Pinyon-juniper is a dominant vegetation type in the network, and pinyon and/or juniper exists to some extent in every park within SCPN (Thomas et al. 2006). Three park units prioritized pinyon juniper woodlands for monitoring: Bandelier National Monument (BAND), Grand Canyon National Park (GRCA) and Mesa Verde National Park (MEVE) (Figure 1). The onset of monitoring varied between park units as follows: MEVE in 2007, BAND in 2008, GRCA in 2010, and the second site at MEVE in 2012. In this report, we focus on data collected in 2008–2022.

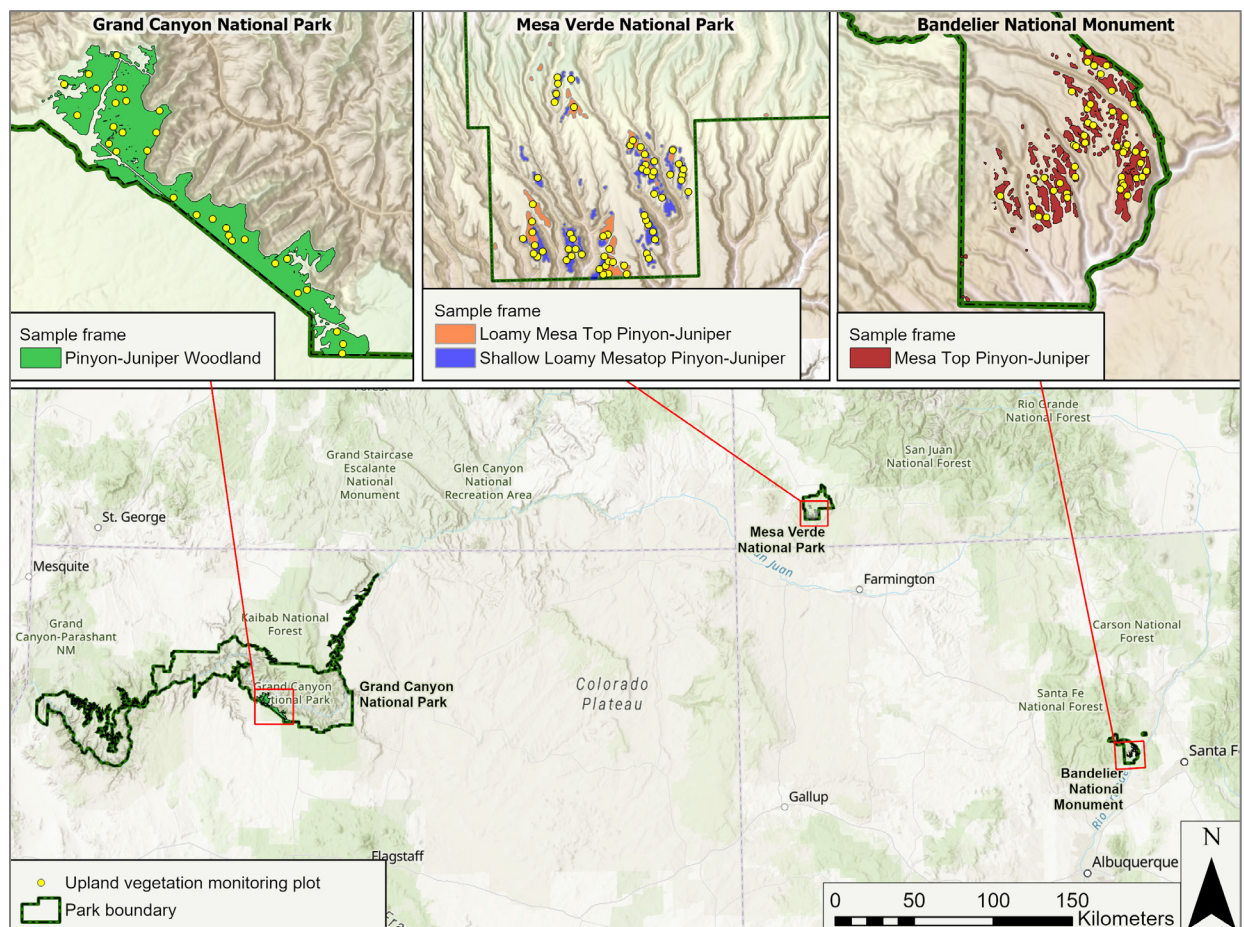


Figure 1. Overview map of the sampling frames and plot locations for the three NPS units included in this report.

NPS / KRISTIN STRAKA

Monitoring site selection

Ecological sites were used to select and define areas for monitoring (DeCoster et al. 2012). An ecological site (or ecosite) represents a unique combination of soils, climate, and topography which result in potential vegetation assemblages that are expected to respond similarly to disturbance and management actions (Caudle et al. 2013; Figure 2). Ecosites with a large, cohesive spatial extent that were highly valued by park staff and regional experts were selected for monitoring (Thomas et al. 2006).



Figure 2. Pinyon-juniper vegetation surrounding an archeological site in the woodlands at Mesa Verde National Park

NPS / MEGAN SWAN

Sampling frames are the target areas from which monitoring plot locations are randomly selected. When developing sampling frames, soil map units containing high percentages of the target ecosite were modified by removing areas considered not appropriate for monitoring, including areas surrounding infrastructure (roads and buildings), heavily disturbed areas, and areas with slopes $> 20\%$ (Soil Survey Staff, NRCS SSURGO dataset, 2012). Although this removes areas that are more likely to be impacted by anthropomorphic disturbance, it achieves a protocol goal of focusing on

intact and undisturbed areas (DeCoster et al. 2012). Generalized Random Tessellation Stratified (GRTS) design (Stevens and Olsen 2004) was used to generate a set of spatially distributed potential sampling points within the final sampling frame and points were then field screened to remove any plots that did not align with soil or ecosite characteristics.

Selected monitoring sites

The PJ monitoring plots comprise four ecological sites in three national parks (Table 1, Figure 1): Ecological sites included limestone upland ecological site at GRCA, and two distinct ecosites at MEVE (loamy mesa top pinyon-juniper and shallow loamy mesa top pinyon-juniper). At BAND, in collaboration with the park, we delineated a sampling frame prior to soil map completion. This “ecological site” represents a broad interpretation of a pinyon-juniper/skunkbush sumac shallow sandy ecological site and therefore isn’t as restricted by soil and vegetation types as the other ecosites.

Table 1. Names and characteristics of the four ecological sites included in this report.

Unit	Ecosite Name	Ecosite Code	Ecosite ID	Elevation (m)	Area (ha)	Total plots
BAND	Mesa top pinyon-juniper	BAND P	F036XB133NM	1967	1315	45
GRCA	Limestone upland pinyon-juniper woodland	GRCA P	F035XF619AZ F035XF611AZ	1980	5598	30
MEVE	Loamy mesa top pinyon-juniper woodland	MEVE L	R036XY142CO	2150	459	30
MEVE	Shallow loamy mesa top pinyon-juniper woodland	MEVE S	R036XY141CO	2148	577	30

Sampling design

This report presents data from 135 permanent monitoring plots: 30 plots at GRCA, 30 plots each in two ecological sites at MEVE, and 45 plots at BAND (Figure 1). Plots were randomly assigned to one of three monitoring panels ($n = 10$ or 15 plots/panel). Two of these panels (20 or 30 plots) were sampled every other year in a rotating design. A complete panel revisit cycle, in which all plots are sampled twice, takes five years (For details on the timing of plot sampling, see Appendix A).

Initially, a subset of 10 plots was established (during 2007 at MEVE and 2010 at GRCA) and these plots were resampled every year for three years to better understand interannual variability at the sites to inform our sampling design. Subsequently, additional plots were added at each site. At BAND, an initial subset of plots was not sampled repeatedly, but instead all plots were established and sampled once between 2008–2010 (DeCoster et al. 2012). A structured panel revisit design was implemented for all sites beginning in 2012. We dropped 2007 data from the analysis because MEVE L was the only ecological site sampled that year.

During the monitoring period (2008–2022), the maximum number of revisits to any single plot was seven and the minimum was two. Several changes were made to panel membership and plots at

BAND due to direct fire impacts and changes to accessibility resulting from fire (the loss of a staging area from which to access backcountry plots). In addition, our revisit schedule was significantly impacted by the onset of the Covid-19 pandemic in 2020. Due to crew health and safety limitations, no sites were sampled in 2020. A complete sampling history for all the plots is provided in the first figure in Appendix A.

Monitoring plots are 50 m × 52 m and consist of three parallel 50 m transects spaced 25 m apart (Figure 3). Within this area, field crews collect data on trees, 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 the same time each year and as close to maximal plant growth as possible given schedule constraints (See dates of sampling in the second figure in Appendix A).

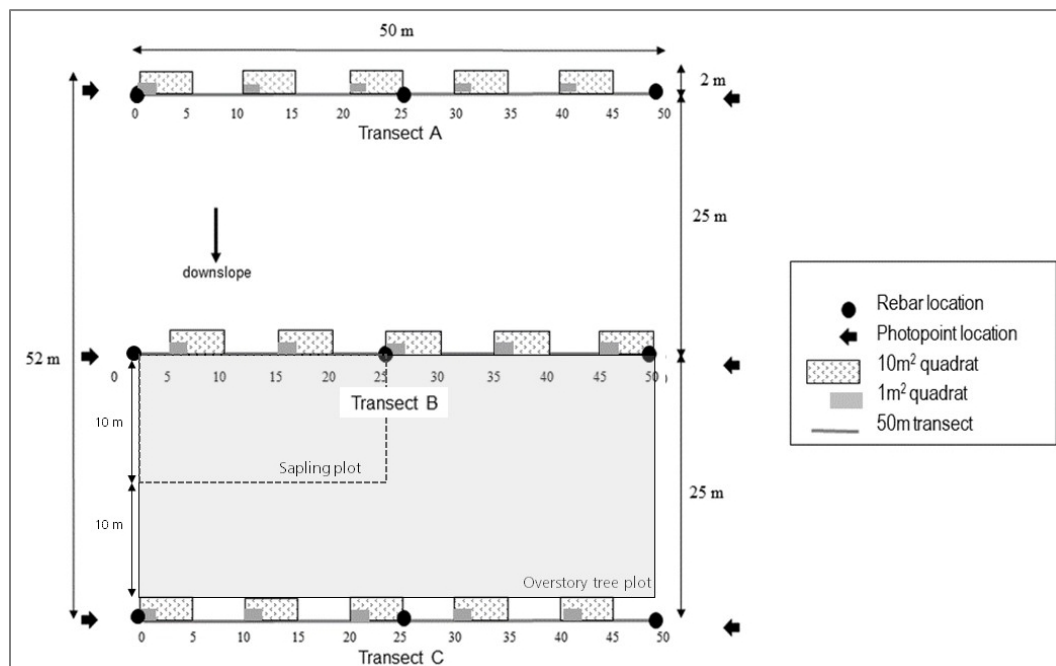


Figure 3. Diagram of a Southern Colorado Plateau Network upland monitoring plot. Seedlings are tallied and shrub and herbaceous cover are measured in 10 square meter (m^2) quadrats, soil surface features in 1 m^2 quadrats. Canopy cover is sampled along each 50 meter (m) transect and soil stability samples are taken from six random locations along each transect. Saplings are tallied in sapling plot, and overstory trees are measured in overstory tree plot.

NPS / MEGAN SWAN

Soil profile and surface features

When establishing each plot, a soil profile sample is collected using a $1\frac{1}{2}$ inch diameter soil auger. Soil is extracted to the maximum depth possible (up to 100 centimeters (cm)) and characterized for color, texture, rock fragment quantity and size and soil effervescence in the field using standard methods for each 10 cm depth increment (Schoeneberger et al. 2012).

When sampling, soil surface features and biological soil crust attributes are assessed in 1 m² quadrats nested within the 10 m² (2 m × 5 m) quadrats and located at 10 m intervals along each transect (Figure 3). Crews make 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 12 cover classes (Table 2).

Table 2. 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%

Soil stability

Soil aggregate stability is sampled 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 rate 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 2008 to 2015, when observers encountered deep litter, surface stones, or exposed bedrock during sampling, they did not sample. As a result, in years prior to 2016, fewer than 18 soil samples were sometimes collected within a plot. In 2016, the protocol was altered to permit observers to select new random locations to sample when the soil surface is obstructed at the original random sampling point.

Herbaceous and shrub vegetation

Within each plot, field crews estimate percent cover of live herbaceous and shrub vegetation in fifteen 10 m² (2 m × 5 m) quadrats (Figure 3). They place five quadrats at 10 m intervals along each transect and identify all live vascular plants observed in each quadrat to species (or the lowest taxonomic level possible). Ocular estimates of absolute cover for each species are made using one of

12 cover class intervals ranging from > 0.1% to 75–100% (Table 2). Plants were considered live if there was evidence that they were living at any point during the current growing season, even if they are dead or senescent during sampling. Plants that have foliar cover within the quadrat but are rooted outside the quadrat are assigned a cover class, but not a frequency.

All live species are then aggregated into lifeform categories (perennial grass, annual grass, forb, shrub, and cacti/succulent) to estimate cover class (Table 2) for each lifeform detected in the quadrat while accounting for layering and overlap. A cover class for the aggregated total of all live cover (total foliar) is also assigned and represents the estimated aggregated total of all live grass, forb and shrub cover in a plot. Lastly, all standing dead herbaceous and standing dead woody vegetation is assigned a cover class within the 10 m² quadrat.

Trees

Seedlings

Seedlings include trees that are < 2.5 cm in diameter at breast height (< 2.5 cm at root crown for *Juniperus* spp.). Within each plot, field crews tally the number of seedlings by species and size class within the fifteen 10 m² (2 m × 5 m) quadrats used for herbaceous vegetation sampling (Figure 3). Three height size classes are used for non-juniper tree species and two diameter size classes are applied to junipers (due to the difference in early growth forms) (Table 3). Only seedlings rooted within the quadrat and alive during sampling are counted. For clonal species, seedlings that are branched below ground level are counted as individuals while only the tallest stem is counted in seedlings branched above the ground.

Table 3. Seedling size classes used by the Southern Colorado Plateau Network for tallying tree seedlings during upland monitoring. Classes 4 and 5 apply to *Juniperus* spp. only.

Seedling Class	Definition
1	≤ 15 cm height
2	15 to < 137 cm height
3	> 137 cm height and < 2.5 cm diameter at breast height (DBH)
4	< 0.5 cm diameter at root crown (DRC)
5	0.5 to < 2.5 cm DRC

Saplings

Trees 2.5–14.9 cm in diameter at breast height (DBH) are classified as saplings and are assessed in a 10 m × 25 m subplot delineated in part by the center transect of the plot. Field crews tally all trees by species and size class within this area (Figure 3). Three size classes based on diameter are used for saplings (Table 4). Juniper saplings of all species are measured at root crown; all other species are measured at breast height (137 cm). Only seedlings rooted within a subplot and alive during sampling were counted. For clonal species, seedlings that are branched below ground level are counted as individuals, while only the largest stem is counted in seedlings branched above the ground.

Table 4. Sapling size classes used by the Southern Colorado Plateau Network for tallying tree saplings during upland monitoring.

Sapling size class	Definition
1	2.5 to < 5.0 cm diameter
2	5.0 to < 10.0 cm diameter
3	10.0 to < 15.0 cm diameter

Overstory trees

Overstory trees (≥ 15 cm DBH) are assessed in a 50 m $\times$ 20 m subplot delineated by the center transect of the plot. Field crews tag and measure all trees within this area and record species, status, and size (Figure 3). Each overstory tree is also assigned a crown health class (Table 5). Only trees > 50% rooted within this subplot are assessed. Junipers are measured at root crown (DRC), and all stems branched below DRC are tagged and measured individually. All other species are measured at breast height (137 cm), and stems branched below breast height are tagged and measured individually. For more details on how tree data is collected see DeCoster (2012).

Table 5. Crown health codes for overstory trees.

Code	Description
1	85 to 100% live foliage
2	50 to < 85% live foliage
3	15 to < 50% live foliage
4	> 0 and < 15% live foliage

Canopy cover

Cover of overstory tree canopy is assessed along three 50 m transects. All live canopy cover of any height that intersects the vertical plane of the transect is recorded and the percent of transect length covered by canopy is calculated.

Data management and analysis methods

Status estimates

Sampling data were entered into Access databases, converted to SQL Server, and analyzed using the R statistical software package (R Core Team 2023, 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 (DeCoster et al. 2012). Scientific names, common names, lifeform (shrub, forb, graminoid), and duration information (annual or perennial) for plant species were obtained from the United States Department of Agriculture 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 the five grassland ecological sites is provided in Appendix B.

Status estimates describe the characteristics of the site over the monitoring period (2008–2022) to provide information on the central tendencies and variability of selected indicators. For status estimates, I summarized data across all years to capture 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 three scales (10 m² quadrat, 50 × 52 m plot, entire ecosite). Since plots were sampled unequal numbers of times, I first averaged all 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. Plot means were averaged across years to provide ecosite averages.

For native plant cover, I used the midpoints of each cover class as a metric value to represent the category and calculated arithmetic means of midpoints (Table 2). For exotic plants, frequency estimates (number of quadrats containing species divided by total number of quadrats sampled) are presented. The 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 (Herpigny and Gosselin 2015). However, this approach is still commonly used in ecology (e.g., Endress et al. 2022, Munson 2011).

Trend estimates

A Bayesian hierarchical modeling approach was used to investigate change over time in plant frequency and cover, quadrat-scale richness and seedling and sapling density. This approach models data despite several significant challenges: data were intentionally missing because of sampling design; sample sizes were not stable across years; cover class estimates represent percent cover as ordinal classes; and responses were generally not normally distributed (Hobbs and Hooten 2015). Model details are provided in Appendix D and summarized below. See Irvine et al. (2016) and Zachmann et al. (2021) for detailed descriptions of this modeling approach.

The basic form is a general linear model with additive covariates, interpreted as the annual change in the prediction of the response variable (e.g., foliar cover of perennial grass). I fit three types of models depending on the response. Cover class data for dominant perennial grass and shrub species (those that occurred in > 30% of plots in at least one ecological site) were modeled using a hurdle at 0 inverse logit deterministic model, and an ordinal latent beta model described by Irvine et al. (2016). 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 cover when present (Irvine et al. 2016). For responses like perennial grass cover which are present in every plot, inference on the presence/absence component of the model was dropped to improve model fit (therefore these model results don't include changes in frequency).

To model the prevalence of species with very low overall percent cover, a binomial or zero inflated binomial model was applied to presence/absence data using the five quadrats on each transect as trials and presence in the 10 m² quadrat as a hit. For species richness, the number of unique species sampled within each quadrat was modeled using a generalized Poisson likelihood. Multi-ecosite models failed to converge adequately, so we modeled species richness separately for each ecological

site, using the same model and covariates. Seedlings and saplings were grouped by species across all size-classes and quadrat, or plot-level counts were modeled using a negative binomial or Poisson model. All responses modeled for trend are listed in Table 6 and final model details are provided in Appendix D.

Table 6. Summary of response variables assessed in this report. “A” indicates response was assessed (also in green) while “X” indicates response was not assessed (also in grey). Status analyses include all ecological sites, but not all responses were assessed for trend in every ecological site so ecological sites in which the responses were modeled for trend are listed in the “Ecological site” column.

Response	Status	Trend	Ecological site
Climate	A	A	BAND P, GRCA P, MEVE L, MEVE S
Soil depth	A	X	BAND P, GRCA P, MEVE L, MEVE S
Soil texture	A	X	BAND P, GRCA P, MEVE L, MEVE S
Soil surface features	A	X	BAND P, GRCA P, MEVE L, MEVE S
Soil stability	A	A	BAND P, GRCA P, MEVE L, MEVE S
Cover by lifeform	A	A	BAND P, GRCA P, MEVE L, MEVE S
Species composition	A	X	BAND P, GRCA P, MEVE L, MEVE S
Quadrat richness	A	A	BAND P, GRCA P, MEVE L, MEVE S
Plot richness	A	X	BAND P, GRCA P, MEVE L, MEVE S
Exotic species	A	X	BAND P, GRCA P, MEVE L, MEVE S
Muttongrass (<i>Poa fendleriana</i>)	X	A	GRCA P, MEVE L, MEVE S
Blue grama (<i>Bouteloua gracilis</i>)	X	A	BAND P, GRCA P
Squirreltail (<i>Elymus elymoides</i>)	X	A	BAND P, GRCA P, MEVE L, MEVE S
Big sagebrush (<i>Artemisia tridentata</i>)	X	A	GRCA P
Cliffrose (<i>Purshia mexicana</i> var. <i>stansburyana</i>)	X	A	GRCA P
Antelope bitterbrush (<i>Purshia tridentata</i>)	X	A	MEVE L, MEVE S
Mountain mahogany (<i>Cercocarpus montanus</i>)	X	A	MEVE L, MEVE S
Snakeweed (<i>Gutierrezia sarothrae</i>)	X	A	BAND P, GRCA P
Cactus	X	A	BAND P, GRCA P, MEVE L, MEVE S
Prickly pear (<i>Opuntia</i> spp.)	X	A	BAND P, GRCA P, MEVE L, MEVE S
Ragleaf bahia (<i>Amauriopsis dissecta</i>)	X	A	BAND
Field wormwood (<i>Artemisia ludoviciana</i>)	X	A	BAND
Spiny phlox (<i>Phlox austromontana</i>)	X	A	MEVE L, MEVE S
Toadflax penstemon (<i>Penstemon linarioides</i>)	X	A	MEVE L, MEVE S
Cheatgrass (<i>Bromus tectorum</i>)	X	A	BAND, GRCA
Canopy cover	A	X	BAND P, GRCA P, MEVE L, MEVE S
Seedling density	A	A	BAND P, GRCA P, MEVE L, MEVE S
Sapling density	A	A	BAND P, GRCA P, MEVE L, MEVE S
Overstory density	A	A	BAND P, GRCA P, MEVE L, MEVE S
Overstory basal area	A	X	BAND P, GRCA P, MEVE L, MEVE S

For each of the models, model fit was assessed using posterior predictive simulation to generate Bayesian p-values. Bayesian p-values < 0.1 and > 0.9 indicate significant lack of fit. All models were checked for convergence using the Gelman-Rubin diagnostic (Gelman-Rubin diagnostic ≤ 1.2 , Gelman and Rubin 1992). In cases where the model didn't adequately converge with the full suite of covariates, less influential covariates were dropped until models achieved convergence. Covariates were considered less influential if they had a comparably smaller effect on the modeled response.

Results represent model-predicted probabilities of average percent cover, average probability of occurrence or average count of species per quadrat. Probabilities are based on distributions of predictions accumulated over many iterations of model runs based on the data we collected. Models predict parameters for each site and year, whether or not the plot was sampled, which minimizes the effect of missing data in our panel sampling design (Zachmann et al. 2021). Plots sampled relatively more often have greater influence on model-predicted parameters than those sampled less. All Bayesian analyses were run in R 4.1.2 (R Core Team 2023) using Just Another Gibbs Sampler (JAGS) (Plummer 2022) as the Markov Chain Monte Carlo (MCMC) sampler.

The trend section (beginning on page 41) presents model outputs in three ways. First, annual estimates of the mean response (i.e., percent cover) are shown. Specifically, figures show the mean of the posterior distribution (i.e., modeled predictions of the mean of the response) for each year and the corresponding 95% credible intervals. This represents our best estimate of actual condition each year, *given the effects of the included covariates* on the response. Second, to determine trend, annual estimates of percent change of a given response *after accounting for change in the covariates* is presented. Again, the mean and 95% credible intervals are shown. Finally, to determine the effect of covariates on a given response, the mean and 95% credible intervals of the distribution of the coefficient of each covariate are provided. Note that the magnitude of covariate coefficients is comparable *within* a model, but not between models.

When interpreting these results, it is important to note that Bayesian inference differs from more usual frequentist inference. Instead of providing test statistics or interpreting confidence intervals, Bayesian credible intervals indicate the probability that the true (unknown) value lies within the given interval, based on the evidence provided by the observed data. For example, if the credible interval for trend (change over time) does not include zero it means that there is $< 5\%$ chance that the response has *not* changed over time.

Site specific precipitation data used in status analyses were obtained from Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group (PRISM Climate Group 2023). All summaries and figures were created using R and ggplot2 (R core team 2017; Wickham 2016). Models were run using R and the rjags package (rjags version 4.9, Plummer 2022).

Covariates

Covariates that were most likely to influence the responses modeled were chosen for inclusion in trend models based on previous work and literature. Water availability is the primary limiting factor to plant growth on the Colorado Plateau (Comstock and Ehleringer 1992). However, the influence of

precipitation on plant growth is often mediated by temperature, soil properties such as water holding capacity, and timing and intensity of rainfall. In many cases, derived water balance covariates such as soil water or climatic water deficit (CWD) may better predict plant response than precipitation alone (Stephenson 1998, Thoma et al. 2020). Water balance covariates incorporate temperature and precipitation into a single covariate, such as climatic water deficit (deficit). Deficit is defined as the difference between potential evapotranspiration (PET) and actual transpiration (AET). It is a measurement of water stress; higher deficit indicates plants need more water than is available.

Cumulative water deficit at the plot level were calculated from Daymet data using a modified Thornthwaite water balance mode (Thornton et al. 2016, Tercek et al. 2021). Seasonality of water availability is important, so CWD was summed into seasonal aggregates; winter (November–March), and spring (April–June) for the current water year, and by water year (October–September) for the previous year and two-years previous (lagged).

To partially account for the effects of variation in winter and spring temperatures on plant growth, accumulated growing degree-days (AGDD, January–June) was also included as a covariate. AGDD was calculated following McMaster and Wilhelm (1997),

$$cumGDD_{monthly} = \sum_1^d \frac{T_{max} + T_{min}}{2} - T_{base}$$

where $cumGDD_{monthly}$ is the cumulative growing degree-days (GDD) over a single month, d is the number of days in a month, T_{max} is the maximum temperature on a given day, T_{min} is the minimum temperature on a given day, and $T_{base} = 4.4^{\circ}\text{C}$, the temperature below which grass physiological activity ceases (Wang 1960). AGDD was calculated from daily plot temperatures sourced from Daymet (Daymet: Daily Surface Weather Data on a 1-kilometer (km) Grid for North America, Version 4 R1 <https://doi.org/10.3334/ORNLDAAAC/2129>, accessed 2022).

A plot-scale topographic covariate, terrain, was also included as a covariate in some models. The terrain covariate incorporates slope and aspect into a single value (calculated as $\sin(\text{slope}) \cdot \cos(\text{aspect})$) to account for differences between plots in topography which could influence vegetation responses. Terrain ranges from -1 to 1 . Steep south-facing slopes trend toward -1 and steep north-facing slopes trend toward 1 . This (and similar calculations) have been widely used to approximate insolation (Stage 1976, McCune and Keon 2002) which can indicate topographically mediated variation in effective soil moisture. In addition, the Global Aridity Index value for each site was obtained. This aridity index provides high resolution annual data based on the FAO Penman-Monteith equation (Zomer et al. 2022). It is important to note that this index somewhat counterintuitively assigns higher values to indicate *lower* aridity.

Slope and aspect surface parameters were calculated from the 1/3 Arc Second resolution 2022 National Elevation Datasets in the native horizontal and vertical datums (GCS NAD83, NAVD88) in ArcPro using the quadratic surface type with the adaptive neighborhood distance (which varies the neighborhood size based on variability in the terrain). The data was then extracted to the upland plot points (projected into GCS NAD83) without using bilinear interpolation. Covariates were checked

for correlation prior to use in models, and covariates with a Pearson's r value ≥ 0.8 or ≤ -0.8 were excluded from use in the same model. All covariates were centered and standardized so that relative effects of coefficients could be directly compared in the models.

Details on covariates included in trend analysis can be found in Table 7.

Table 7. Details on climate and physical variables that were included as covariates in at least one model. See Appendix D for details on which covariates were included in each model.

Covariate Name	Description	Data source	Units
AGDD	Accumulated growing degree days	Calculated from plot-level Daymet daily values	hours
Winter deficit	Nov–Mar sum of monthly climatic water deficit	Calculated from plot-level Daymet daily values	mm
Spring deficit	April–June sum of monthly climatic water deficit	Calculated from plot-level Daymet daily values	mm
Lag year deficit	Oct–Sept sum of monthly climatic water deficit for one-year previous to current year	Calculated from plot-level Daymet daily values	mm
2 year deficit	Oct–Sept sum of monthly climatic water deficit for two-years previous to current year	Calculated from plot-level Daymet daily values	mm
Terrain	Topography variable	2022 National Elevation Datasets	N/A
AI	Aridity index	The Global Aridity Index (Global-Aridity_ET0, Version 2	N/A
Total basal area	Total overstory tree basal area for plot	SCPN plot data	m ² /ha

Results and Discussion

Status

Sampling overview

A total of 135 plots were established in the four ecosites and 562 plot sampling visits were made (first figure in Appendix A). During all years, the start of sampling at each ecosite fell within a 20-day window, although sampling windows were occasionally extended to the end of the field season to complete sampling of all required plots (second figure in Appendix A). Plots were sampled between two and seven times. In some years, due to staffing and weather constraints, not all targeted plots were sampled. No plots were sampled in 2020 due to safety concerns associated with the Covid-19 pandemic.

Climate overview

All four ecological sites show a typical bimodal pattern of seasonal precipitation common to the Colorado Plateau. Most precipitation at all sites is received during the summer as part of the North American monsoon (Figure 4), monsoon precipitation is variable both spatially and temporally (Figures 4 and 5). Winter and spring seasons contribute less annual precipitation and exhibit less spatial and temporal variability (Figure 4). BAND differs from the other sites in having its driest period in winter, rather than early summer (Figure 4).

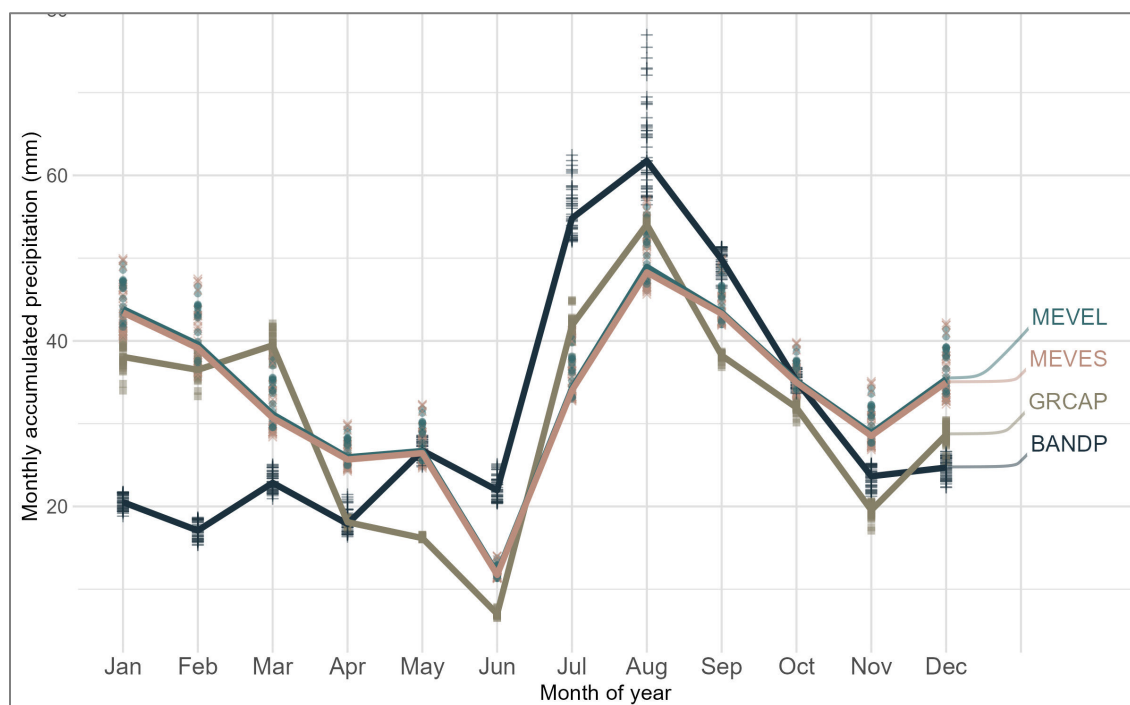


Figure 4. Seasonal precipitation patterns based on 30-year normal (1991–2021) at four ecosites in three National Parks (BAND, GRCA, MEVE). Lines indicate median average accumulated monthly precipitation for each ecological site, dots represent plot-level values (data from PRISM Climate Group, accessed 16 August 2023).

NPS / MEGAN SWAN

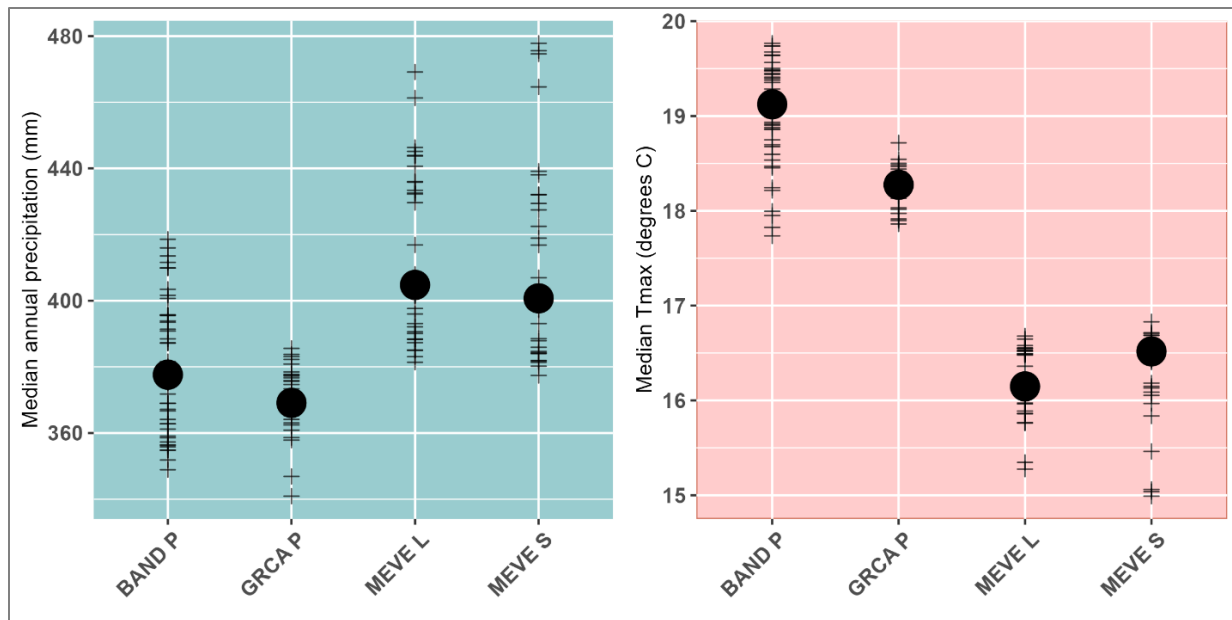


Figure 5. Median annual precipitation (left) and maximum temperature (right) based on 30-year normal (1991–2020) for four ecological sites in three National Parks (BAND, GRCA, MEVE). The dots indicate medians for the ecological sites, and the crosses show plot-level medians to illustrate spatial variability (data from PRISM Climate Group, Oregon State University, <https://prism.oregonstate.edu>, accessed 16 August 2023).

NPS / MEGAN SWAN

Median annual precipitation varied among ecosites, ranging from 369 mm at GRCA P to 404 mm at MEVE L, based on 30-year normal (the average value for each site during the most recent 30-year interval, 1991–2020, Figure 5). BAND P received the most summer (July–September) precipitation of the five sites (Figure 4), but there is notable variation in annual precipitation totals across plots (Figure 5). Median maximum temperature (T_{max}) is coldest at MEVE L (16.1 Celsius (C)) and MEVE S (16.5 C) and warmer at GRCA P (18.3 C) and BAND P (19.1 C) based on the 30-year average (Figure 5).

Soil overview

Soils were nearly uniformly deep across the loamy upland site at MEVE L; 25 of 30 plots were 100 cm deep or deeper. Other ecological sites tended to have shallower soil depth (Figure 6). All plots at MEVE S had soil depth ≤ 60 cm, while over 75% of plots at GRCA P had soil depths of ≤ 50 cm. BAND had a wide range of soil depth, from very shallow to ≥ 100 cm. Since crews used a hand auger to extract soils, they were not able to determine whether the auger depth represented depth to bedrock, or depth to root restricting layers such as large cobbles.

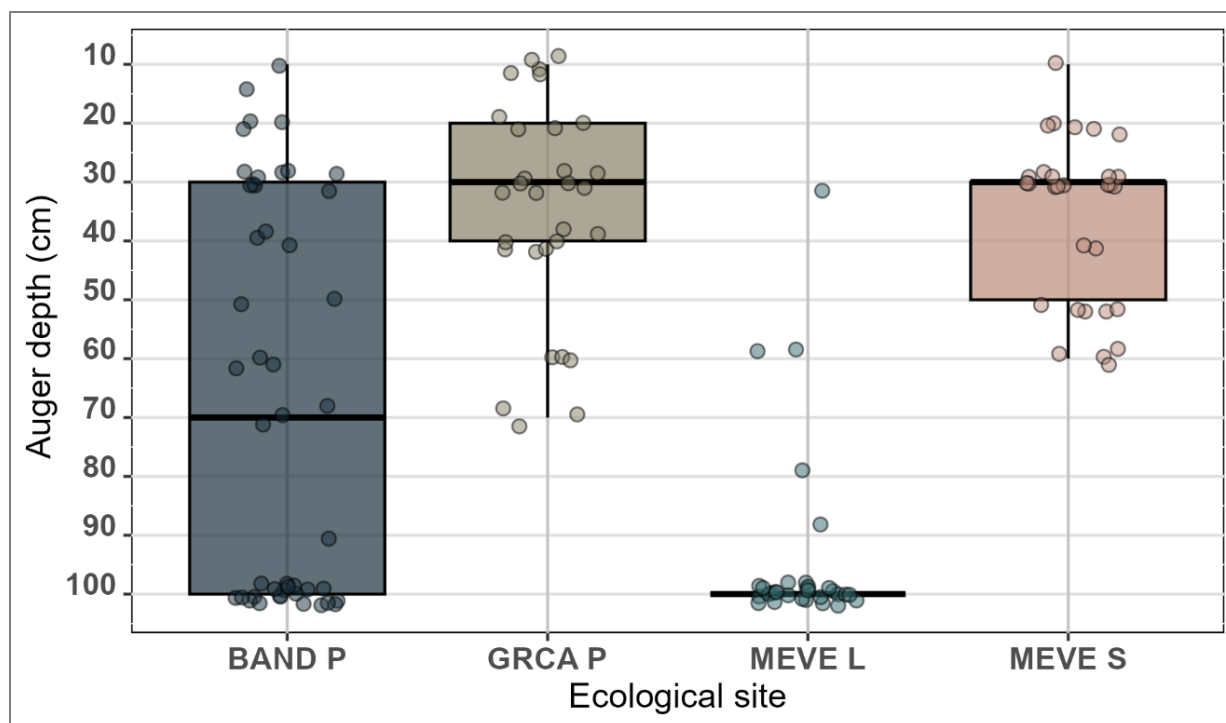


Figure 6. Maximum auger depth of soil profile samples collected during plot establishment at four ecosites in three National Parks (BAND, GRCA, MEVE). Colored boxes indicate the 25% and 75% percentiles of soil depth, and the vertical lines indicate the range of depth (excluding outliers). Horizontal lines indicate the median depth. Colored dots indicate the soil depth for each plot sampled. 100 cm was the maximum depth collected.

NPS / MEGAN SWAN

Soil textures were also somewhat variable between ecosites. Soils at all depths tended to be sandier at BAND than the other 3 sites (Figure 7). GRCA P and MEVE L had more clay-textured soils, especially at deeper depths. Surface sand was prominent at BAND, where some plots are covered by a layer of fine gravel/coarse sand derived from volcanic tuff. This BAND surface layer varies in depth from sparse to several centimeters deep and is not present at all plots.

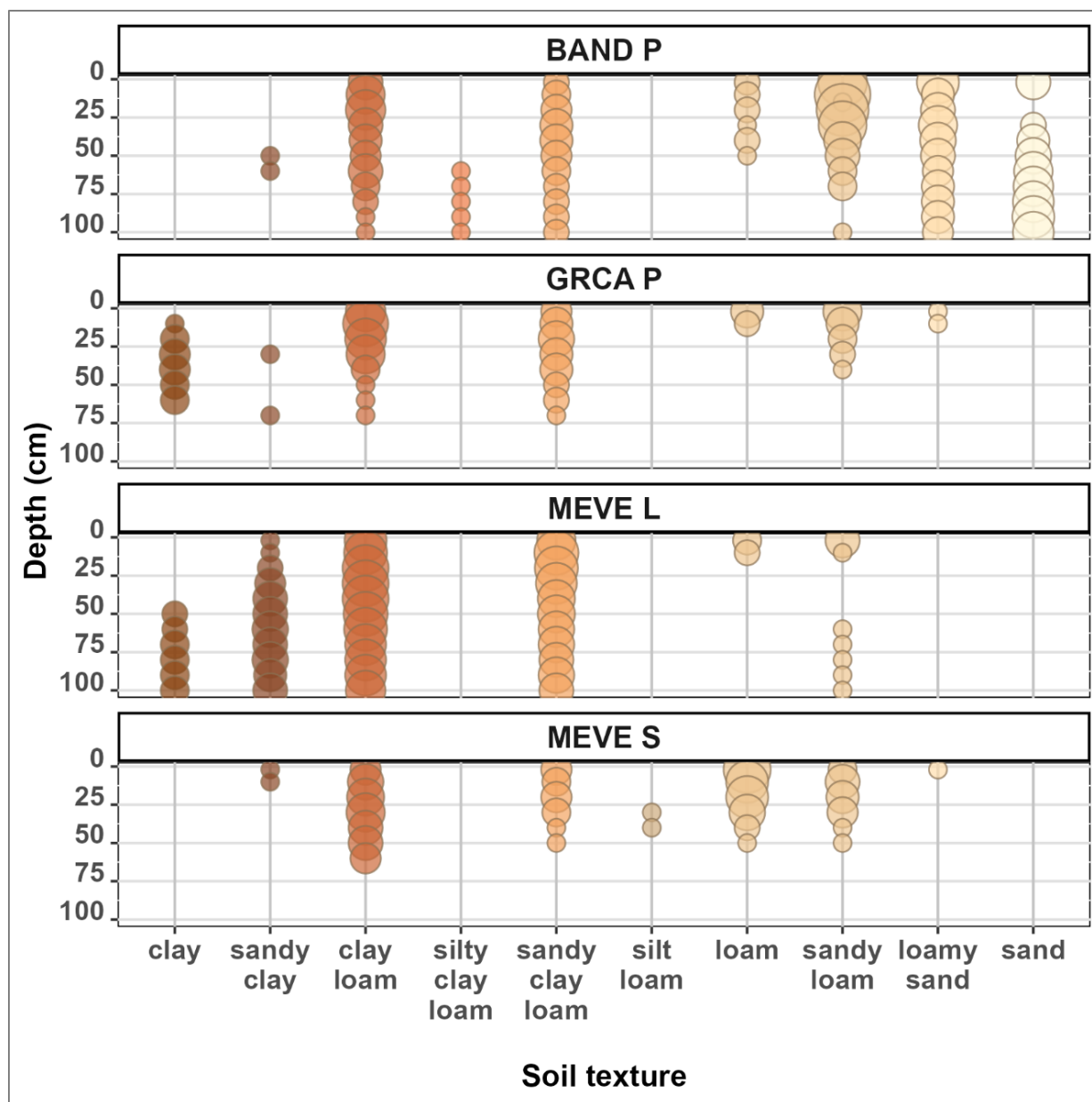


Figure 7. Texture of soil profile samples collected during plot establishment at four ecosites in three National Parks (BAND, GRCA, MEVE). Textures for each depth increment were summarized across all plots in the ecological site. The size of each dot is determined by the how often the texture was present for each depth layer (i.e., larger dots indicate that a given texture was more common at that depth).

NPS / MEGAN SWAN

On the soil surface, duff and litter were the largest component of ground cover in all the plots sampled, except at BAND where fine gravel dominated, as previously described (Figure 8). Undifferentiated crust was also a major component of soil surface cover at all sites. This surface feature includes *both* physical crusts formed from raindrop impact on exposed soil (non-biologic), and cyanobacteria-dominated biologic soil crusts that have not yet developed surface roughness or

distinct coloration; these two crust types can't be distinguished effectively in the field (Belnap et al. 2008). Most soil surface features were highly variable across plots when present (Figure 8).

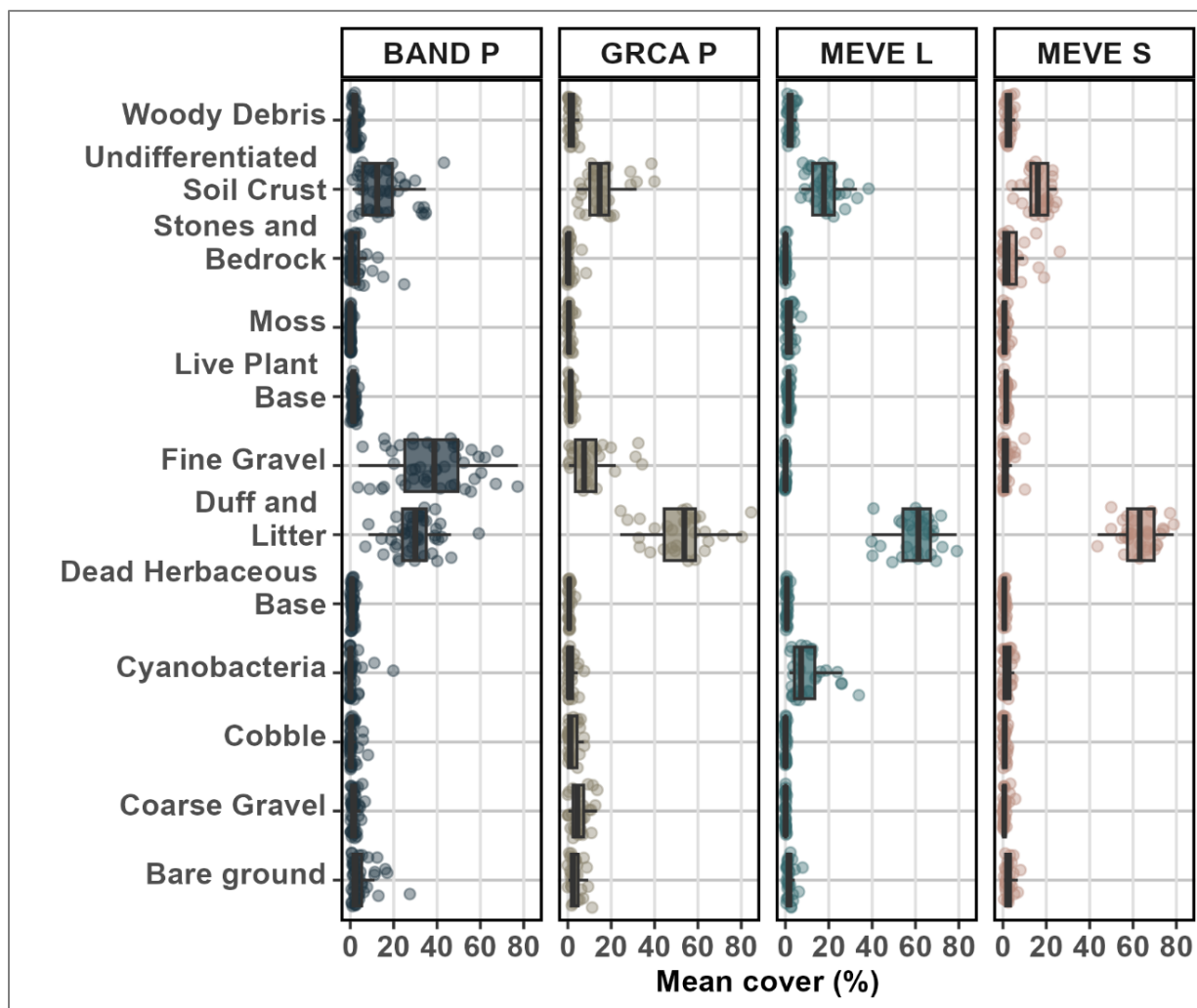


Figure 8. Mean percent cover of soil surface features at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008–2022. Colored boxes indicate the 25 and 75% percentiles, and the horizontal lines indicate the range of percent cover for each surface feature. The vertical line indicates the median percent cover. Colored dots indicate plot-level means. Surface features with less than 1% cover in all ecosites are not shown.

NPS / MEGAN SWAN

Soil aggregate stability sampling was conducted at all four sites (Table 8). Overall soil stability was moderate across the three ecosites and generally higher in samples obtained under perennial vegetative cover compared to samples taken from locations with no cover. Soil stability was highest at MEVE L, which is the site with the greatest amount of cyanobacteria, which indicates more developed biological soil crust (Figure 8, Table 8).

Table 8. Mean soil stability rating class and standard error (SE) for three ecosites in three National Parks (BAND, GRCA, MEVE) during 2009–2022. Soil stability rating class ranges from one (low soil aggregate stability) to six (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 perennial canopy cover.

Ecosite	Canopy Type	Mean Rating Class	SE
BAND P	Overall	3.11	0.02
	Vegetated	3.50	0.02
	Bare	2.72	0.02
GRCA P	Overall	3.95	0.02
	Vegetated	4.28	0.02
	Bare	3.61	0.03
MEVE L	Overall	4.27	0.01
	Vegetated	4.47	0.02
	Bare	4.08	0.02
MEVE S	Overall	3.89	0.02
	Vegetated	4.18	0.04
	Bare	3.60	0.03

Understory vegetation overview

Lifeform groups

Mean percent cover of live vegetation in plots ranged from 8% to 14% but was variable across ecological sites, plots, and years (Table 9). Overall cover of live vegetation was greatest at BAND P, followed by MEVE S. Cover of lifeforms at BAND P was split between perennial grass, shrubs, and forbs, but at all other sites, shrubs and perennial grass comprised the majority of total live cover and forbs were a small component ($\leq 1\%$) (Table 9). Cover of cactus and/or yucca spp. was highest at MEVE. Annual grass was a very minor component of overall cover at all ecosites sampled except BAND, averaging much less than 1%. Annual grass cover at BAND was high but variable, exhibiting a maximum plot cover of nearly 40%.

Table 9. Average percent cover (and range) by lifeform in four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008–2022. Range indicates the lowest and highest plot-level mean for each response.

Lifeform	BAND P	GRCA P	MEVE L	MEVE S
Total live foliar	14.2 (2.44, 48.5)	8.05 (0.66, 58.8)	8.5 (2.1, 21.3)	10.3 (4.2, 31.3)
Perennial grass	3.9 (0.03, 16.9)	3.4 (0.13, 24.7)	3.6 (0.023, 14.9)	2.8 (0.05, 13.7)
Shrub	4.0 (0, 14.6)	3.6 (0.003, 15.1)	2.8 (0.05, 11.4)	5.7 (5.8, 21.02)
Forb	4.21 (0.24, 16.7)	0.57 (0.02, 7.8)	1.0 (0.05, 7.3)	0.6 (0.05, 3.4)
Annual grass	1.8 (0, 39.4)	0.13 (0, 6.8)	0.01 (0, 0.53)	0.01 (0, 0.23)
Cactus and succulents	0.5 (0, 5.4)	0.3 (0, 5.2)	1.2 (0, 5.6)	1.3 (0.006, 5.6)

Species Occurrence

Crews detected 337 unique plant species between 2008 and 2022 across four ecosites (including 34 unknown records and 57 that were grouped at the genus level due to inability to distinguish species reliably in the field (Appendix B). Just 30 of these occurred in all four sites; eighteen of these species were forbs and 6 were perennial graminoids. An additional 30 species occurred in 3 of the 4 sites. Two-hundred species (including unknowns and genus only) occurred in just a single ecosite. Cheatgrass (*Bromus tectorum*) and Russian thistle (*Salsola tragus*) were the only nonnative species common to all four ecological sites.

Muttongrass (*Poa fendleriana*) was by far the most dominant grass in three of the four ecosites, occurring in 90% of plots or more except at BAND, where it occurred in $\leq 18\%$. Squirreltail (*Elymus elymoides*) was also common, appearing in between 11 and 67% of plots depending on ecosite (Appendix B). Blue grama (*Bouteloua gracilis*) was frequent in both GRCA P and BAND P, but this warm-season species did not appear at all at MEVE L and in only a single plot at MEVE S (Appendix B).

Thirty-one shrub species were detected during the monitoring period (Appendix B). Snakeweed (*Gutierrezia sarothrae*) and juniper mistletoe (*Phoradendron juniperinum*) were the only shrub species common to all ecological sites. Despite the lack of commonality in species, Asteraceae and Rosaceae were the most common families, both had seven species represented in the shrub layer. Six cacti were also detected, two of which (*Cylindropuntia whipplei* and *Opuntia* spp.) occurred in all four ecosites (Appendix B).

Most forb species occurred at low frequency and low cover (Table 9; Appendix B, Appendix C), but forbs contributed disproportionately to species richness in these ecosites, accounting for $> 78\%$ of species (219 of 280 when unknowns were excluded) and represented a mix of annual, biennial, and perennial species with varied growth forms (Figure 9, Appendix B). Eighteen forb species were common to all four sites, 33 occurred in 3 of the 4. None of these species were dominant in all ecosites, but several were dominant in a subset, including toadflax penstemon (*Penstemon linarioides*) (which occurred in 79% and 51% of plots at MEVE L and S respectively), and ragleaf bahia (*Amauriopsis dissecta*) (64% of plots in BAND; Appendix B). Most unknown species were

annual forbs, and usually occurred in a single plot and single year and most often in a very early stage of growth.



Figure 9. While not comprising much of the overall vegetative cover at most sites, perennial forbs represent a large component of species richness in PJ woodlands. Desert mountain phlox (*Phlox austromontana*), desert green gentian (*Frasera albomarginata*) and slimleaf plainsmustard (*Schoenocrambe linearifolia*) are examples of perennial forbs that occur in the understory of PJ woodlands.

NPS / MEGAN SWAN

Composition

The following treemaps provide a visual representation of relative proportions of percent cover of dominant species and lifeforms within each ecosite (Figure 10). Dominant species composition differed somewhat between sites. GRCA P had few forbs relative to the other PJ ecological sites. BAND had a larger forb component (Figure 10), and relatively higher species richness compared to other sites (Table 10). The cactus/succulent component was relatively larger in the two MEVE ecosites compared to the other two parks. Across sites, shrubs comprised ~25–50% of total vegetation cover and were the dominant vegetative cover at MEVE S and GRCA P (Figure 10).



Figure 10. Treemaps of dominant species. Treemaps are presented for the a) GRCA P (top) and BAND P (bottom), and b) MEVE L (top) and MEVE S (bottom) ecological sites. Box color indicates lifeform group and box size indicates relative dominance of species by percent cover. Species with less than 0.05% cover are not shown. Data for this figure are available in Appendix C.

NPS / MEGAN SWAN

Table 10. Average quadrat (10 m²) and plot-scale (1500 m²) richness estimates and range (lowest and highest values) for five grassland ecological sites in three National Parks during 2008–2022 (BAND, GRCA, MEVE).

Ecosite	Median quadrat richness (range)	Median plot richness (range)
BAND P	9 (0, 25)	33 (15, 54)
GRCA P	7 (1, 21)	27 (8, 45)
MEVE L	6 (1, 16)	18 (9, 34)
MEVE S	6 (0, 16)	21 (9, 36)

Composition of grass species varied among ecosites (Figure 10). A warm season (C₄) species, blue grama, dominated at BAND, while the cool season (C₃) muttongrass was the most dominant grass species at MEVE. GRCA was co-dominated by both species. Cheatgrass comprised a large component of the graminoid cover at BAND.

Species Richness

Species richness was highly variable across sites at the quadrat and plot scales (Table 10). At the smallest scale (quadrat: 10 m²), richness ranged from 0–25 species. Highest richness was found at BAND P with a median of 9 species per quadrat, and lowest quadrat richness was found at MEVE where both ecosites had a median of 6 species per quadrat (Table 10).

At the plot scale (1500 m²), the lowest richness encountered during sampling was eight species (at GRCA P) and the highest was 54 species (BAND P). Median number of species ranged from 18–33 (Table 10). BAND had the greatest plot-scale richness, and MEVE L had the lowest. The wide range of richness at these scales reflects the patchy distribution of species in these pinyon juniper woodlands.

Nonnative Species

In total, 21 nonnative species were detected across the four ecosites. Three species, namely cheatgrass (*Bromus tectorum*), Russian thistle (*Salsola tragus*), and kiss-me-quick (*Portulaca oleracea*), occurred in all four ecosites. However, the nativity of kiss-me-quick is uncertain (Byrne and McAndrews 1975). Nine nonnative species occurred in just a single ecosite. Only 5 of the 21 nonnative species are considered noxious species in the states in which they were found (Table 11).

The highest number of nonnative species were found in BAND P (14) and MEVE L (13) ecological sites; MEVE S had ten nonnatives and just five were detected at GRCA P. All but two nonnative species were forbs (90%), five of which are biennial or perennial.

Table 11. Overall percent quadrat frequency of the 18 nonnative species encountered during sampling in four ecosites at three National Parks during 2008 to 2022 (BAND, GRCA, MEVE). Scientific and common names and duration from www.ITIS.gov, accessed January 5, 2024. NP (Not Present) indicates species did not occur in ecological site.

Scientific Name	Common name	Duration	BAND P	GRCA P	MEVE L	MEVE S
<i>Alyssum desertorum</i>	desert madwort	annual	NP	NP	NP	0.16
<i>Alyssum simplex</i>	alyssum	annual	NP	NP	NP	0.16
<i>Bromus japonicus</i>	Japanese brome	annual	0.59	NP	NP	NP
<i>Bromus tectorum</i> ^A	cheatgrass	annual	35.19	11.52	2.27	4.86
<i>Carduus nutans</i> ^A	nodding plumeless thistle	perennial	NP	NP	0.88	0.31
<i>Centaurea diffusa</i>	diffuse knapweed	annual	0.04	NP	NP	NP
<i>Chenopodium album</i>	lambsquarters	annual	NP	NP	1.20	0.16
<i>Descurainia sophia</i>	herb sophia	annual	NP	NP	0.88	NP
<i>Erodium cicutarium</i>	redstem stork's bill	annual	0.39	2.53	0.05	NP
<i>Kochia scoparia</i> ^B	burningbush	annual	0.28	NP	NP	NP
<i>Lactuca serriola</i> ^A	prickly lettuce	annual	2.33	NP	4.31	0.08
<i>Lepidium latifolium</i> ^A	broadleaved pepperweed	perennial	NP	NP	0.23	NP
<i>Melilotus officinalis</i>	yellow sweetclover	annual	0.16	NP	NP	0.08
<i>Portulaca oleracea</i>	kiss-me-quick	annual	12.78	7.60	0.09	0.08
<i>Ranunculus testiculatus</i>	curveseed butterwort	annual	NP	0.94	1.39	NP
<i>Salsola collina</i>	slender Russian thistle	annual	0.99	NP	NP	NP
<i>Salsola tragus</i>	Russian thistle	annual	0.55	0.06	0.46	0.08
<i>Sisymbrium altissimum</i>	tall tumble-mustard	perennial	3.39	NP	0.93	0.24
<i>Taraxacum officinale</i>	dandelion	annual	0.12	NP	0.09	NP
<i>Tragopogon dubius</i>	yellow salsify	annual	3.31	NP	0.28	NP
<i>Verbascum thapsus</i> ^A	common mullein	biennial	18.62	NP	NP	NP

^A Species included on the noxious weed list in Arizona, Colorado, and New Mexico.

^B Species included on the noxious weed list in Arizona.

Overstory vegetation overview

Trees

A total of 5666 overstory trees were sampled in plots across the four ecological sites. Species composition of juniper varied by site. The PJ woodlands at MEVE and GRCA are dominated by Utah juniper (*Juniperus osteosperma*) while BAND P overstory is comprised of one-seed juniper (*Juniperus monosperma*) (Figure 11). In addition to the dominant species of juniper, field crews recorded the presence of one rocky mountain juniper (*Juniper scopulorum*) at MEVE S and eight alligator juniper (*Juniperus deppeana*) at two plots in BAND. Pinyon pine (*Pinus edulis*) was present at all ecosites, however, just two live overstory pinyon pine were found in plots at BAND following the widespread pinyon die-off event that occurred in the region in the early 2000s (Breshears et al. 2008). MEVE also experienced extensive die-off of mature pinyon pine (Floyd et al. 2009).

Basal area of live junipers exceeded the basal area of snags and dead and down trees at all sites. Basal area of live Utah junipers was similar at the two ecosites at MEVE, averaging around 30 m² per hectare, and lower at GRCA P (around 12 m² per hectare) (Figure 11). Basal area of one-seed juniper at BAND P averaged less than 10 m² per hectare overall. Basal area of live two-needle pinyon was lower than juniper at all sites. Basal area of pinyon was greatest at GRCA P, and lowest at BAND P. At MEVE, basal area of live pinyon was similar to basal area of dead standing pinyon, while at GRCA, basal area of live pinyon exceeded dead.

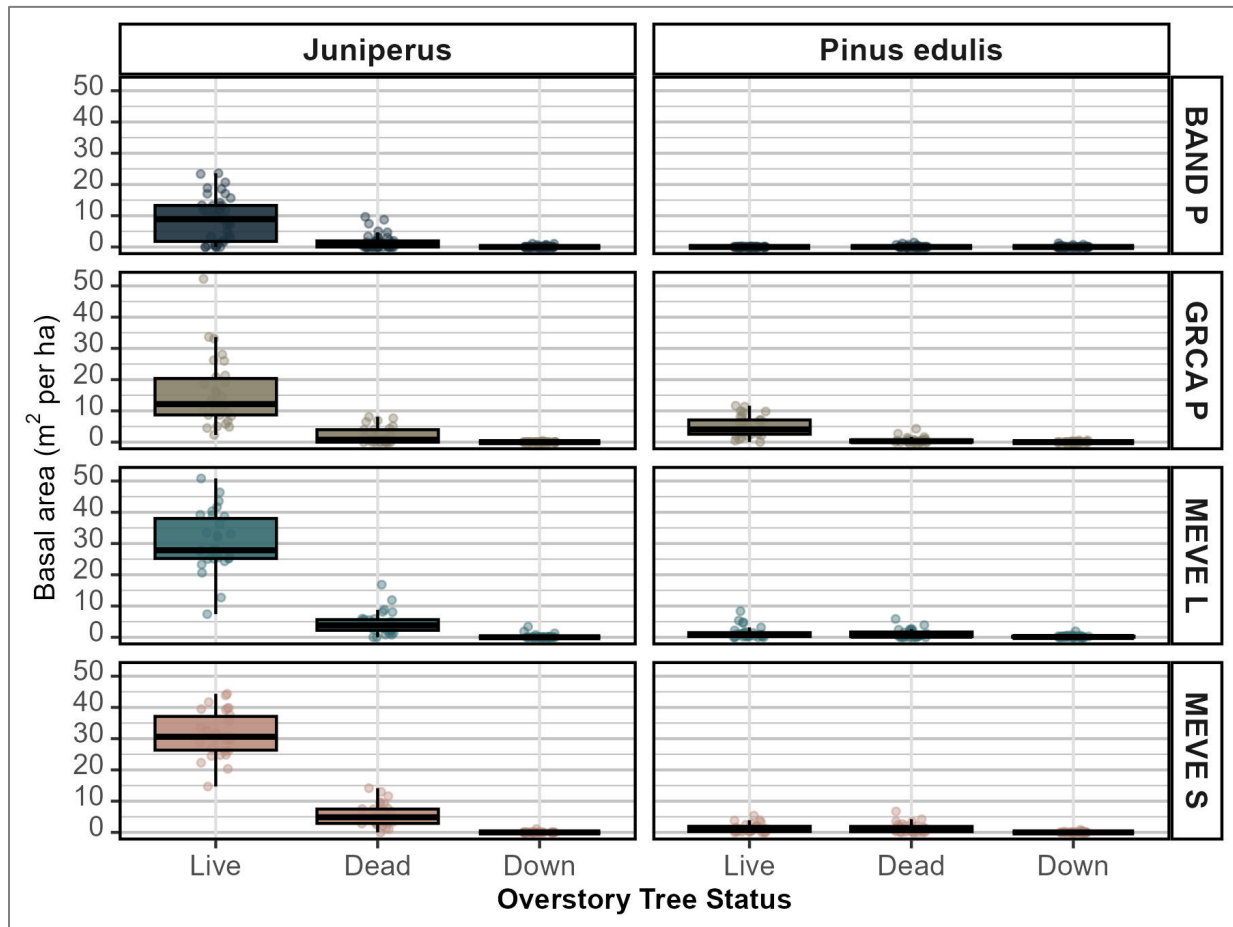


Figure 11. Overstory tree basal area and status for junipers and pinyons (overstory trees are all individuals ≥ 15 cm in diameter) at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008–2022. Colored boxes indicate the 25 and 75% percentiles, and the vertical lines indicate the range of plot basal area (excluding outliers) for each site. The horizontal line indicates the median basal area. Colored dots show plot-level basal area.

NPS / MEGAN SWAN

Saplings

Saplings density varied between ecological sites and varied widely across plots. Pinyon seedlings were more common than junipers at all sites but BAND (Figure 12). MEVE plots had the most saplings per meter (Figure 12). Most plots had live saplings of both species, however, 36 of 45 plots at BAND had no pinyon saplings.

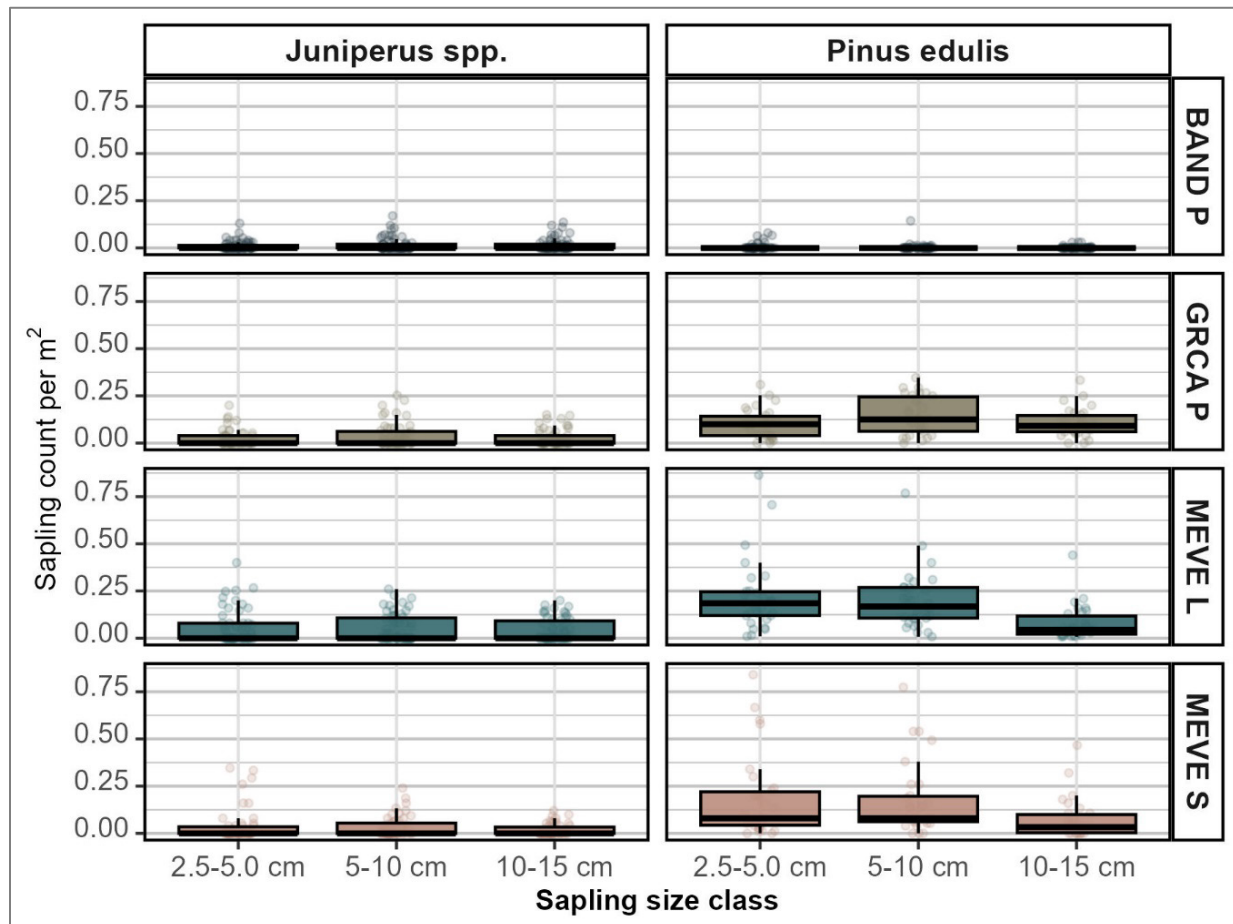


Figure 12. Mean tally of saplings by size class for junipers and pinyons at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008–2022. Colored boxes indicate the 25 and 75% percentiles, and the vertical lines indicate the range of counts (excluding outliers) for each plot. The horizontal line indicates the median plot tally. Colored dots show plot-level means.

NPS / MEGAN SWAN

Seedlings

Seedling counts also varied across ecological sites and plots (Figure 13). Pinyon seedlings at MEVE and GRCA were more frequently encountered than juniper seedlings. At GRCA P, two-needle pinyon seedlings in the small size class (< 15 cm in height) were most frequent, with one plot (GRCA P12) having an exceptionally high count (25 per m²) in one year (2021). Pinyon seedlings in the middle size class were most frequent at MEVE. BAND had the fewest seedlings; 11 of the 45 plots had no seedlings of any species or size class, and eight additional plots had no pinyon seedlings.

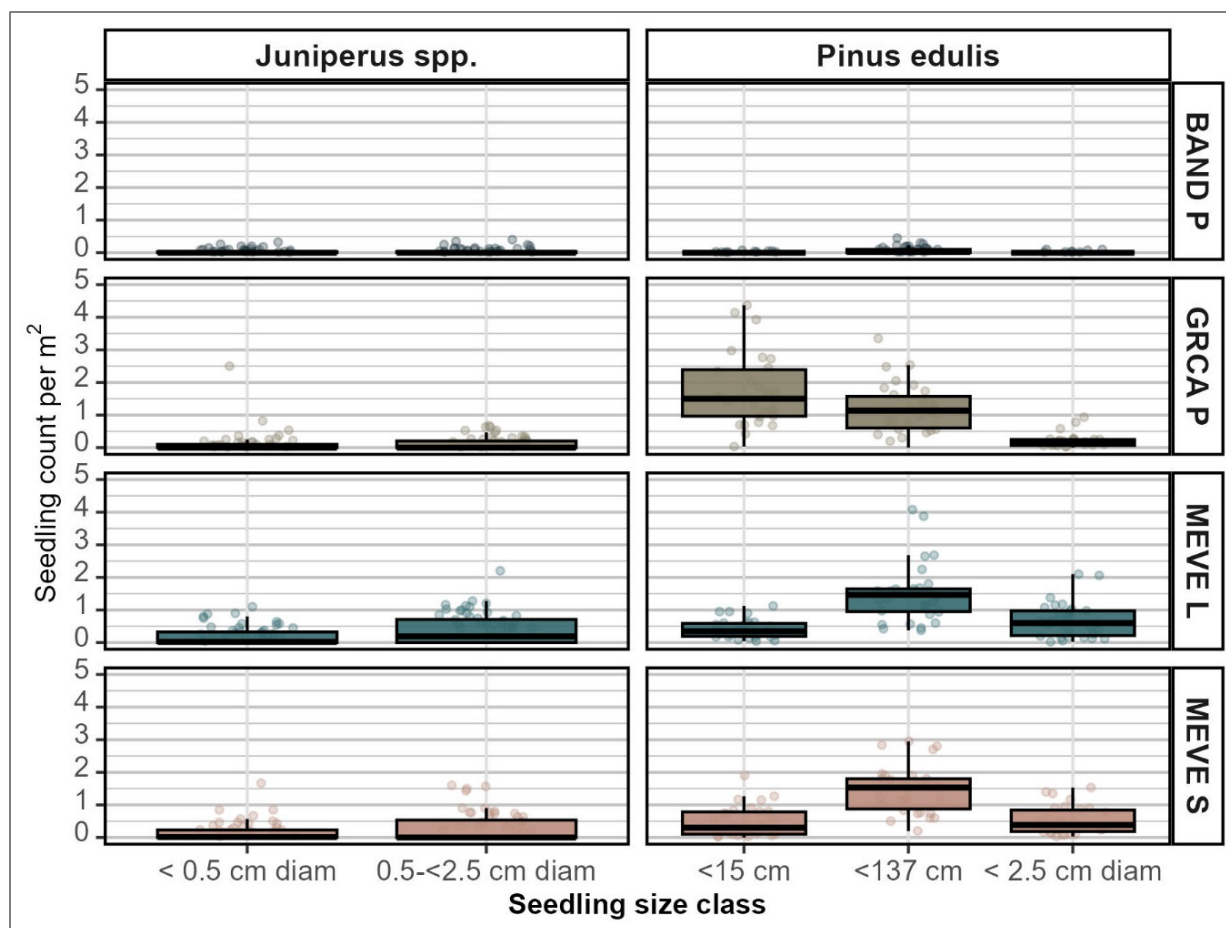


Figure 13. Mean tally of seedlings by species and size class for junipers and pinyons at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008–2022. Colored boxes indicate the 25 and 75% percentiles, and the vertical lines indicate the range of percent cover (excluding outliers) for each surface feature. The horizontal line indicates the median percent cover. Colored dots show plot-level means.

NPS / MEGAN SWAN

Canopy cover

Total canopy cover was lowest at BAND P (Figure 14). Canopy cover at the other three sites was similar. There was considerable variation between plots, especially at BAND where canopy cover ranged from near zero to > 40%. Similarly, one plot at GRCA had much lower canopy cover (< 10%) relative to the other plots in the ecological site while another was much greater (< 60%).

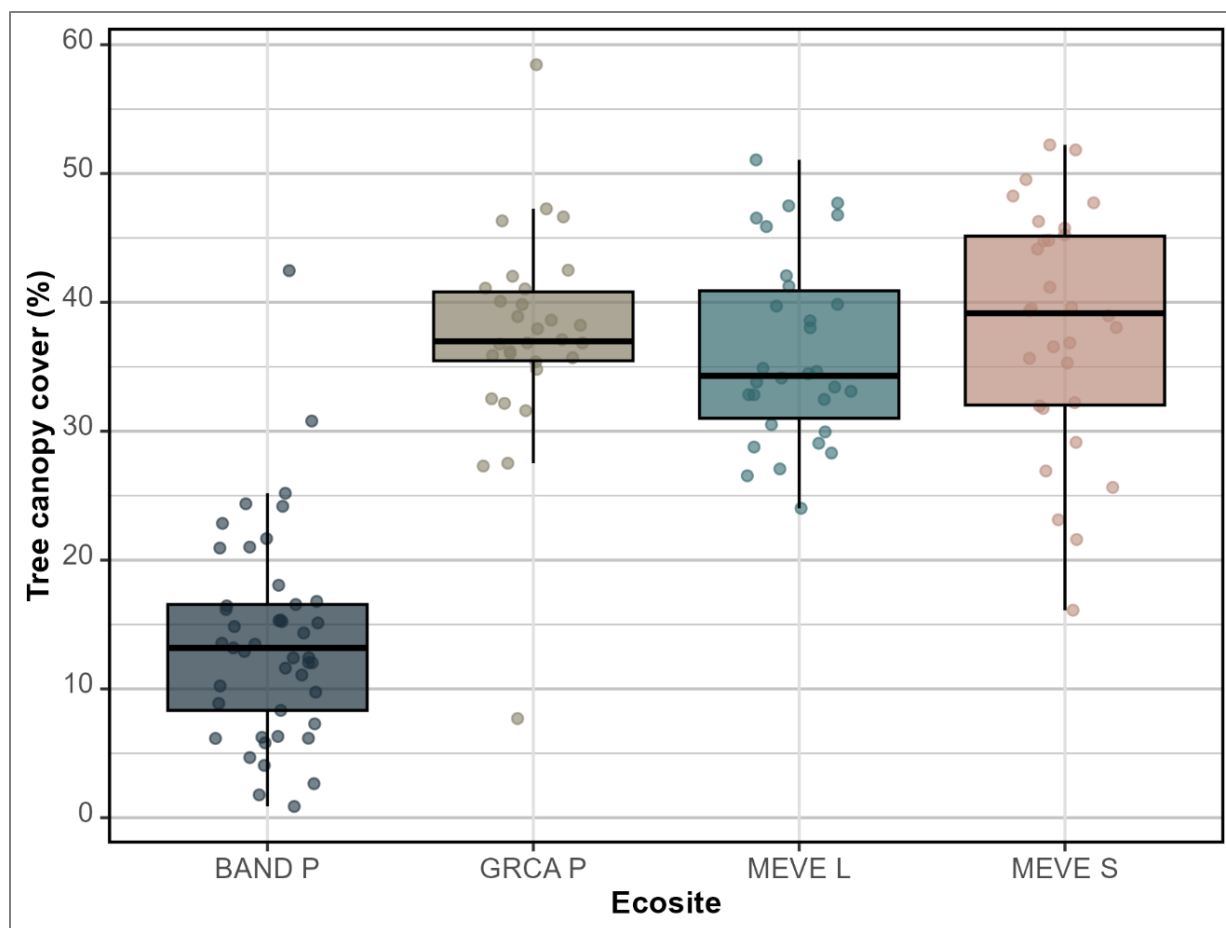


Figure 14. Mean percent canopy cover at four ecological sites in three National Parks (BAND, GRCA, MEVE) during 2008–2022. Colored boxes indicate the 25 and 75% percentiles, and the horizontal lines indicate the range of percent canopy cover. The vertical line indicates the median percent canopy cover. Colored dots indicate plot-level means.

NPS / MEGAN SWAN

Trend

Assessing trend

Inventory and monitoring networks are tasked with reporting on status and trend of selected natural resources. 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 15-year monitoring period of this program, 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. Annual variation in weather was partially accounted for by adding predictor variables (covariates) to

our models. However, climate change is now influencing precipitation patterns and driving temperatures consistently higher on a global scale (IPCC 2022). The results presented here indicate our best assessment based on the current toolset.

Climate

During the monitoring period (2008–2022) the Southwest United States has been in a period of historic drought. The period from 2000–2021 was the driest period of this duration since at least 800 CE, and possibly longer (Williams et al. 2022). Despite this, annual precipitation totals have varied, both spatially (between plots) and temporally (between years) (Figure 15). The driest conditions relative to normal for all ecosites were experienced in 2018 when the two MEVE ecosites received on average < 50% of normal precipitation for the year while BAND and GRCA were slightly less dry, relative to normal (Figure 15). The wettest conditions varied by ecosite. 2019 was the wettest year at MEVE, driven by wetter than normal winter and spring conditions. The wettest conditions overall at BAND were 2010 and 2015, although the park experienced an extremely strong monsoon season in 2013. At GRCA, a multi-year wet period extended from 2014–2016.

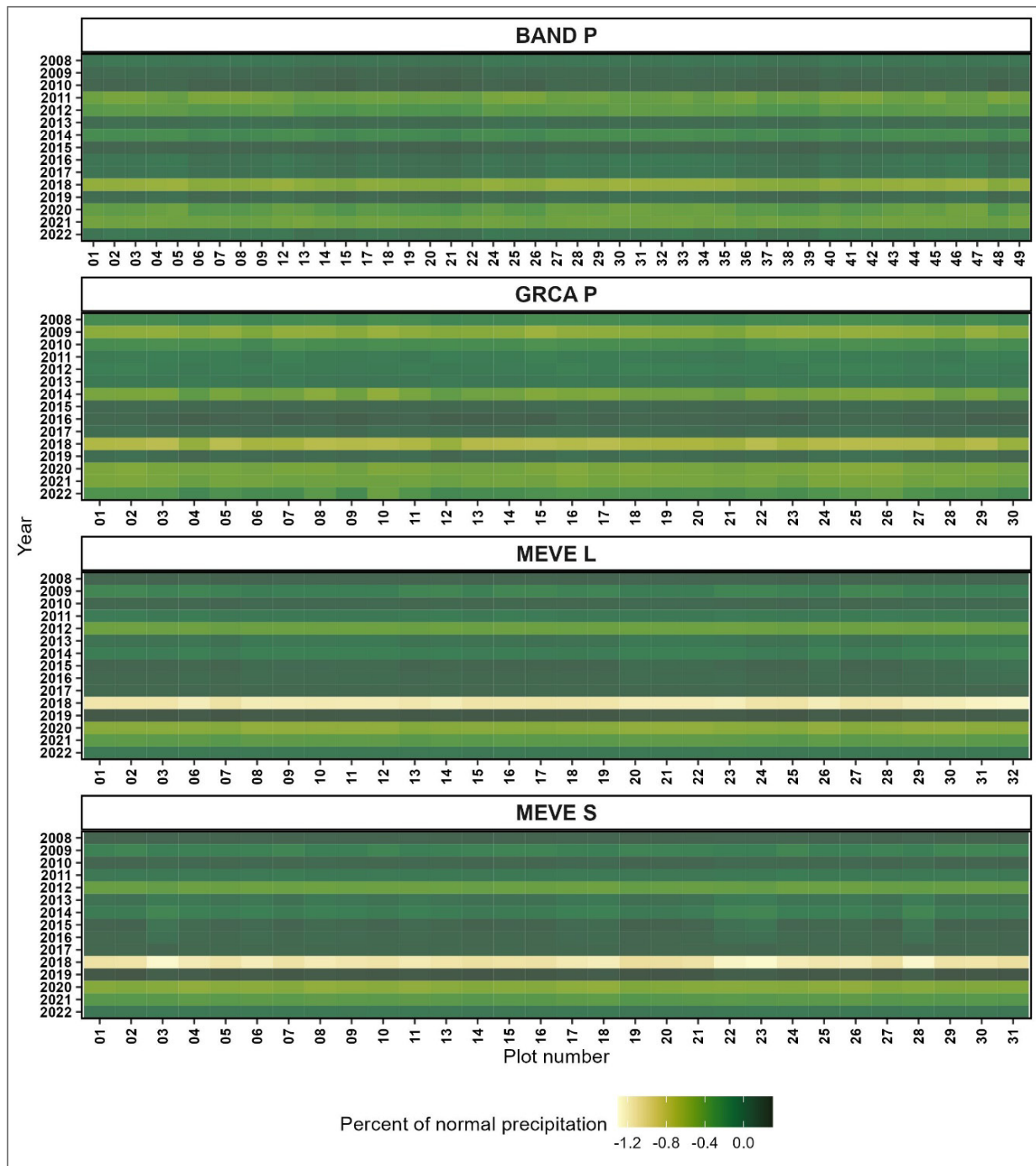


Figure 15. Percent of normal precipitation received at each monitored plot in four ecosystems in three National Parks (BAND, GRCA and MEVE). Note the large amount of variation between years and less variation among plots (30-year normal (1991–2020) from PRISM Climate Group, Oregon State University, <https://prism.oregonstate.edu>, accessed 16 August 2023).

NPS / MEGAN SWAN

The seasonal timing of annual precipitation was also variable by year. Winter (November–March) precipitation totals at BAND and GRCA have been almost uniformly drier than normal during the

monitoring period. Spring seasons (April–June) and summer (July–September) rainfall have been more variable, but precipitation during these seasons exceeded long-term normals in less than half of years for all ecological sites monitored (Figure 16). On the Southern Colorado Plateau, summer precipitation is largely the result of the North American monsoon, which tends to have greater variability than the other seasons, both spatially and temporally (Adams and Comrie 1997). There is also less certainty about the response of monsoon precipitation to climate change (Bhattacharya 2022), whereas the predicted reduction in future spring precipitation is more certain (Bradford et al. 2021).

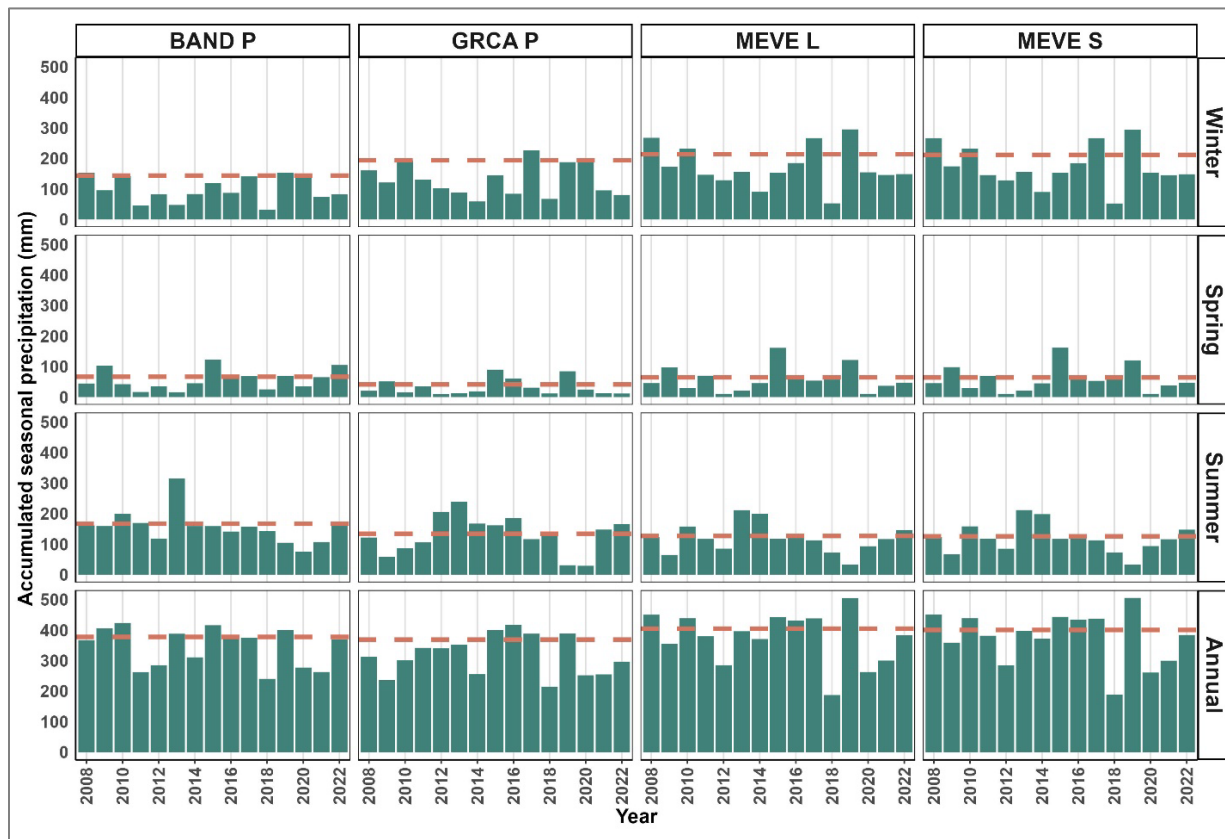


Figure 16. Median accumulated seasonal and annual precipitation totals at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022. Horizontal red line indicates the 30-year normal (1991–2020) (data from PRISM Climate Group, Oregon State University, accessed 16 August 2023).

NPS / MEGAN SWAN

Air temperature trended warmer over the monitoring period for most sites (Figure 17). The median highest monthly temperature (T_{max}) exceeded the long-term average (1991–2021) for 14 of the 15 years at BAND P and 12 of 15 for GRCA P, but only for 3 of 15 years for MEVE S (Figure 17). The lowest monthly temperature (T_{min}) exceeded long-term average for ≥ 9 years at all sites. A broader analysis of temperature across the Southwest indicates a 0.91°C increase in temperature from long term averages (Williams et al. 2022). Andrews (2019) predicts a $> 2^{\circ}\text{C}$ increase in overall temperature in all these sites in the near-term future.

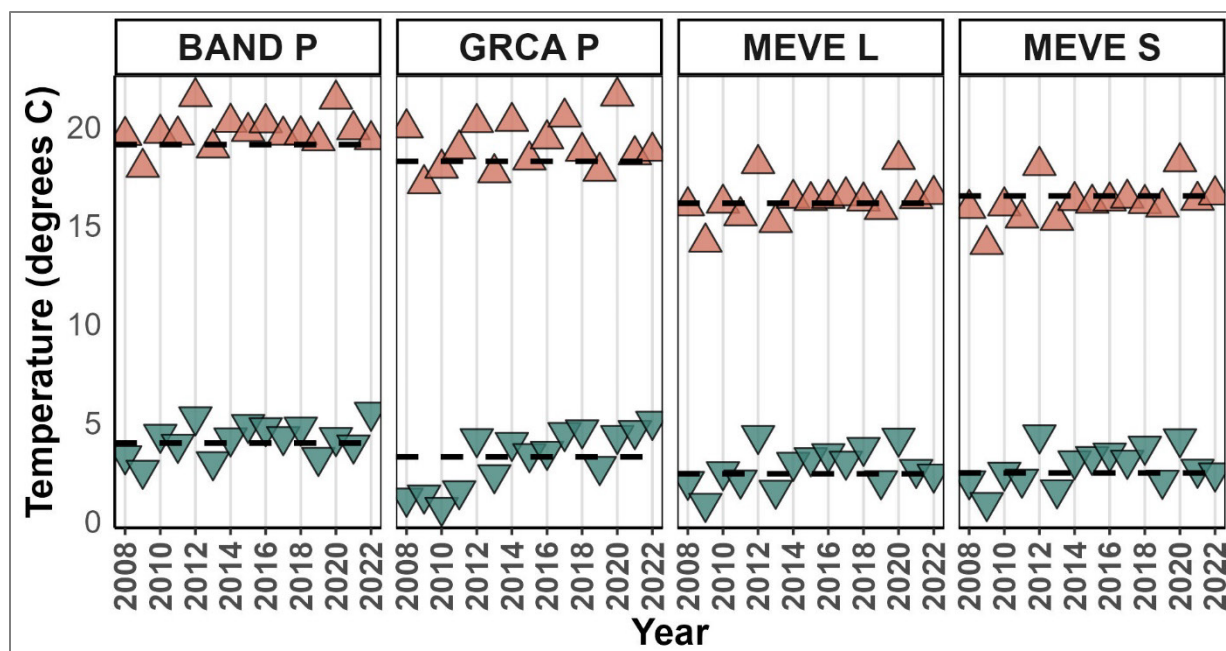


Figure 17. Annual median maximum temperature (Tmax, red triangles) and minimum temperature (Tmin, inverted green triangles) across plots at four ecosites in three National Parks (BAND, GRCA and MEVE) from 2008 to 2022. Dotted lines represent 30-year normal (1991–2020) (data from PRISM Climate Group, Oregon State University, <https://prism.oregonstate.edu>, accessed 16 August 2023).

NPS / MEGAN SWAN

Change over time in soil stability

We modeled change in mean soil stability rating over time at all four ecological sites. The model included the following covariates: Lag year deficit, winter deficit, spring deficit, and AI. Mean soil stability ranged from 2.4–5. (Figure 18a). Model predicted mean soil stability increased over time at the two MEVE sites (Figure 18b). Spring and lag year deficits and AI all had negative effects on soil stability rating, while the effect of winter deficit was not significant (Figure 18c).

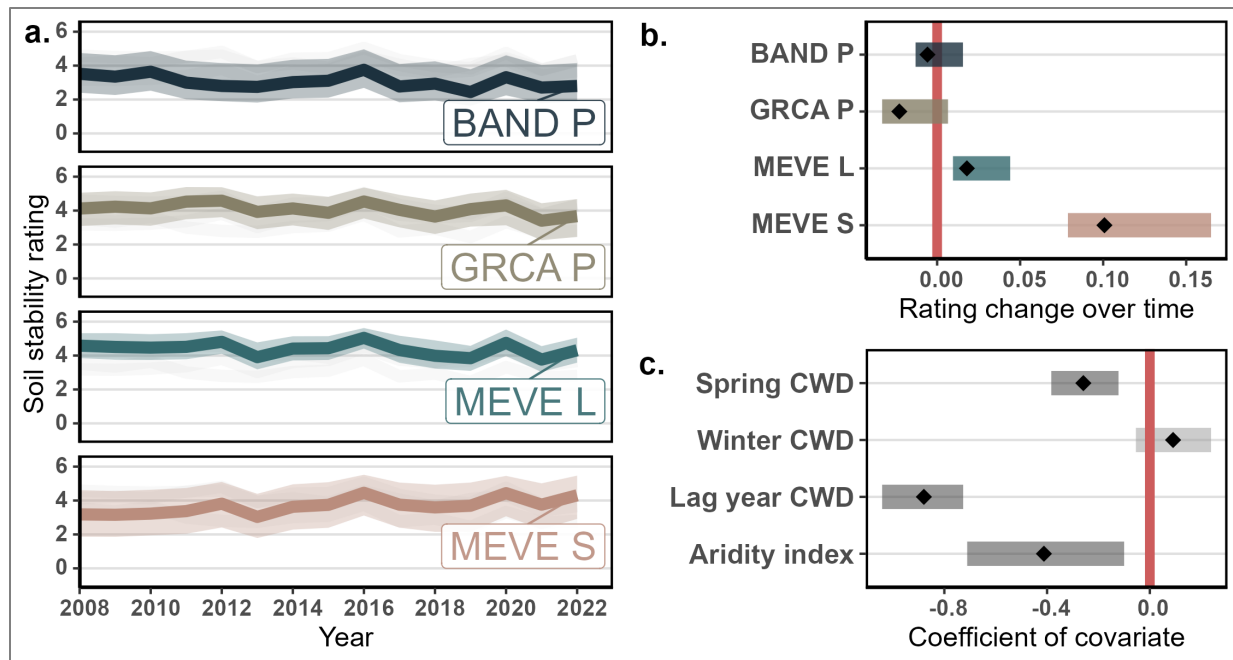


Figure 18. Model-based prediction of change over time in aggregate soil stability at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit.

NPS / MEGAN SWAN

Change over time in understory vegetation

We modeled lifeform groups (perennial grass, shrub, cactus/succulents and forbs) as well as all species that occurred in greater than 30% of sampled plots in at least one ecological site (we excluded species-specific models of annual forbs due to the extreme year to year variation). The general model included the following covariates: lag year deficit, winter deficit, spring deficit, AGDD, Aridity index (AI), total plot basal area of overstory trees and terrain. Two-year lagged deficit was added to shrub, seedling and sapling models. Basal area and terrain were dropped from most models to achieve convergence, as they were not influential on the responses modeled. Most covariates did not affect the presence/absence component of the beta-hurdle cover model so we focus our interpretation on the effect on cover, however significant covariate effects on presence/absence are provided in text.

Perennial grass cover—all ecological sites

Live perennial grass cover was modeled across all four ecological sites. The model included winter climatic water deficit (CWD), spring deficit, lag year deficit, and accumulated growing degree days (AGDD; Appendix D). AI was dropped from the model to achieve convergence. Inference on trend

for the presence/absence component of grass cover was also dropped from this model, since perennial grass cover was present in nearly every quadrat sampled (i.e., the model didn't have enough zeros to estimate trend in presence/absence).

Model predictions of mean perennial grass cover were similar across all ecosites (~5%), but higher than means calculated from cover class midpoints (Figure 19a; Table 9). Bayesian p-values for all perennial grass models were also high, indicating that the model was consistently over-estimating perennial grass cover (Appendix D). To reduce the complexity of the model, and because there were very few observations in the smallest cover classes for perennial grass, I post-hoc reduced the number of cover classes from twelve to ten by combining the first 3 cover classes, which resulted in a better model fit.

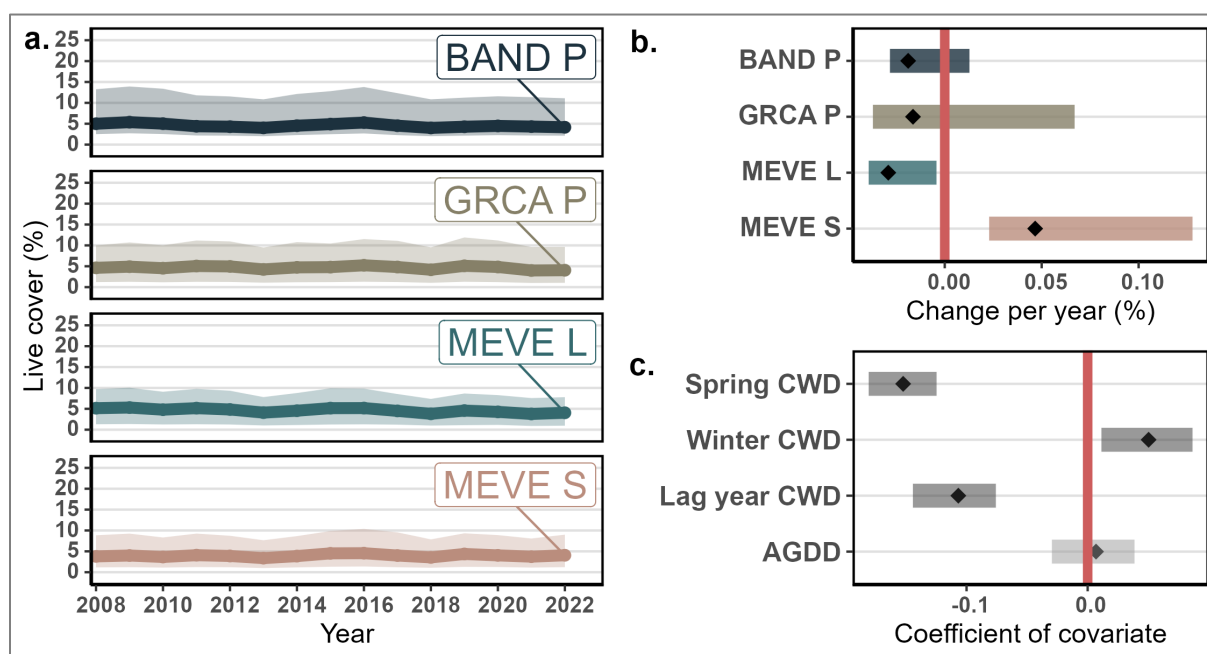


Figure 19. Model-based prediction of change over time in total live perennial grass cover at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit, and AGDD = aggregate growing degree days.

NPS / MEGAN SWAN

Based on the model, perennial grass cover decreased over the monitoring period at MEVE L and increased at MEVE S (Figure 19b). There were no significant trends over time in BAND or GRCA. The effect of spring deficit and lag year's deficit on grass cover was negative, but winter deficit had a

positive effect on perennial grass cover (Figure 19c). An increase in the number of growing degree days did not influence grass cover significantly.

Poa fendleriana cover—GRCA, MEVE

Although muttongrass (*Poa fendleriana*) occurred in all four ecological sites, its frequency varied. It was present in most quadrats ($\geq 90\%$) at GRCA and the two MEVE ecological sites, but less than 20% of quadrats at BAND (Appendix B). Models including all 4 sites failed to pass posterior predictive checks, but models including the three ecosites at GRCA and MEVE were fit successfully (Appendix D).

Mean model-predicted cover of muttongrass ranged from 2.3–5.7% and was greatest at MEVE S and lowest at GRCA P (Figure 20a). Cover of muttongrass increased during the monitoring period at all sites, although the effect at MEVE L was weaker (Figure 20b). Covariate effects were mixed; AI had a strongly positive effect on cover of muttongrass, indicating more cover at less arid sites. Winter deficit also had a positive effect on muttongrass cover, while spring and lag year's deficits and increased growing degree days had negative effects (Figure 20c).

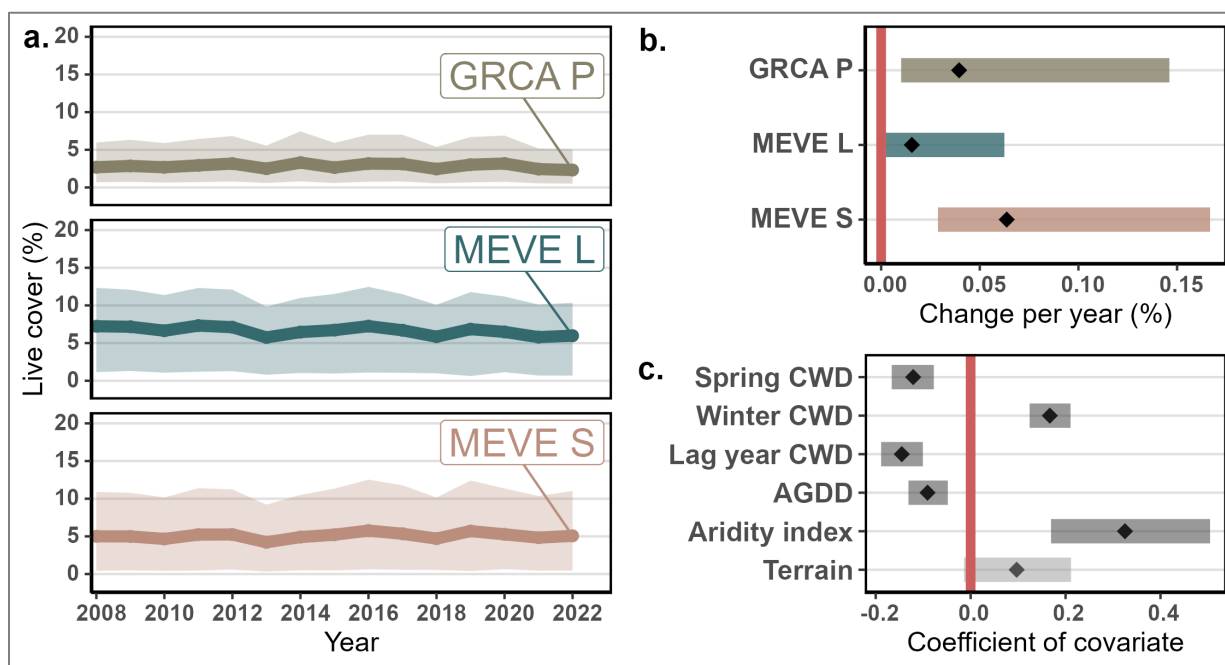


Figure 20. Model-based prediction of change over time in total live muttongrass cover at four ecosites in two National Parks (GRCA, MEVE) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit, and AGDD = aggregate growing degree days.

NPS / MEGAN SWAN

Bouteloua gracilis cover—BAND, GRCA

Blue grama (*Bouteloua gracilis*) occurred in > 60% of plots at BAND P and GRCA P, and in trace amounts at MEVE S (< 1%, Appendix B). A model including BAND and GRCA was fit with the standard covariates (spring, winter and lag year deficits, AI and AGDD).

Model-predicted blue grama cover ranged from 2.3% to 3.3% and was similar between the two ecological sites (Figure 21a). Blue grama cover increased during the monitoring period at GRCA P and did not change significantly at BAND (Figure 21b). Increasing lag year and spring deficits had a negative effect on blue grama cover (Figure 21c). AI had a positive effect, indicating more blue grama cover in less arid sites. The effect of winter deficit and AGDD were not significant.

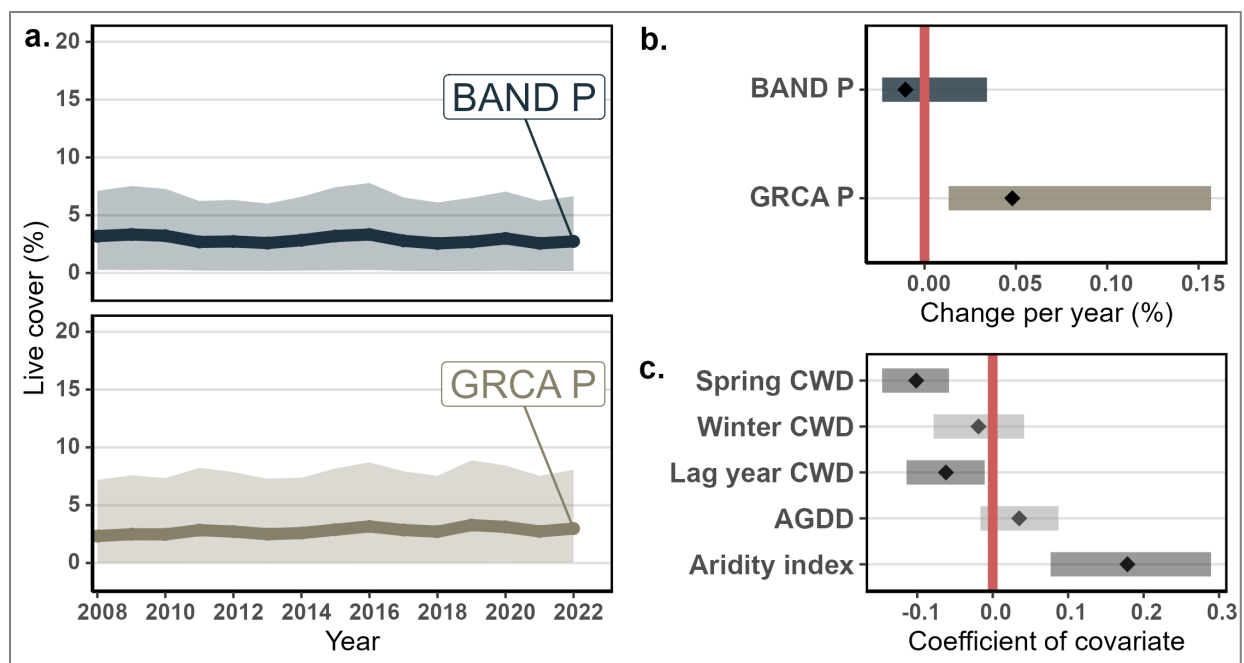


Figure 21. Model-based prediction of change over time in total live blue grama cover at four ecosites in two National Parks (BAND, GRCA) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit, and AGDD = aggregate growing degree days.

NPS / MEGAN SWAN

Squirreltail cover—all ecological sites

Squirreltail (*Elymus elymoides*) was found in all the ecosites sampled. It was most common at BAND P where it occurred in 67% of quadrats sampled, and least common at MEVE L where it occurred in just 11% of quadrats (Appendix B). Cover was low overall, ranging from > 0.1% to 2.2% and was lowest at MEVE L and highest at BAND P (Figure 22a). The model included all sites.

Cover of squirreltail increased significantly during the monitoring period at both sites in MEVE, but the increase was greater at MEVE S (Figure 22b). Winter, spring, and lag year deficits all had negative effects on squirreltail cover, while AGDD had a positive effect (Figure 22c). The effect of AI was not significant.

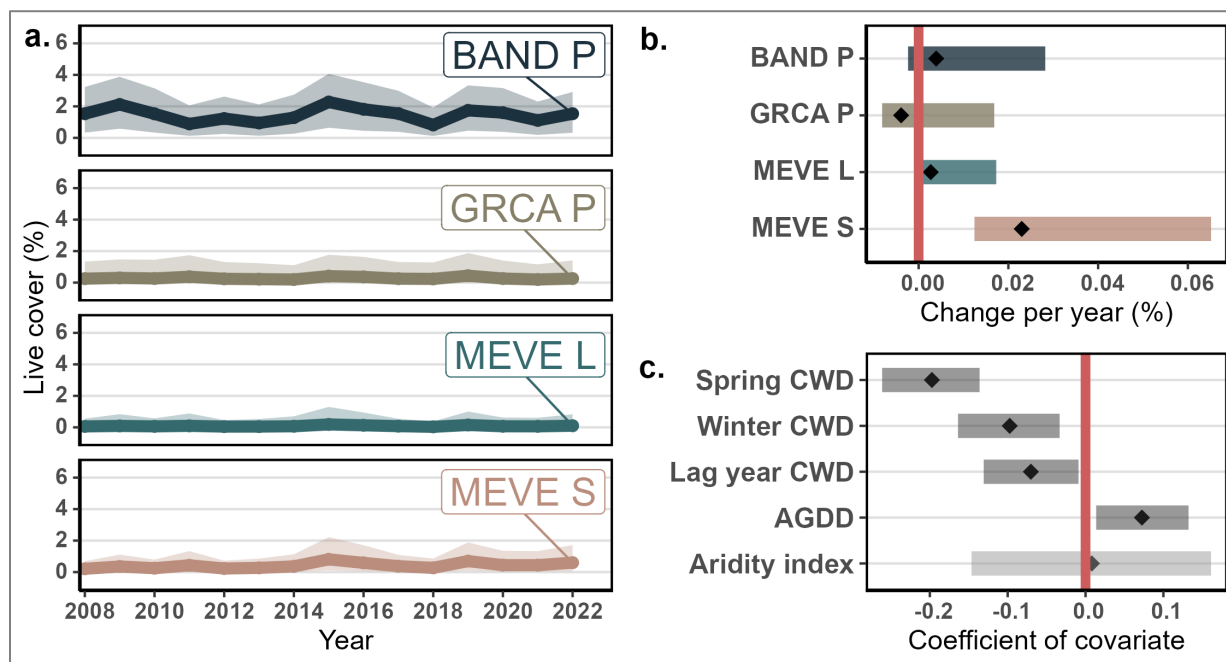


Figure 22. Model-based prediction of change over time in total live squirreltail cover at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit, and AGDD = aggregate growing degree days.

NPS / MEGAN SWAN

Shrub cover—all ecological sites

Shrub cover was modeled across all four ecological sites. The model included lag year deficit, 2-year lag deficit, winter deficit, spring deficit, AI and AGDD and terrain (Appendix D). Mean model-predicted shrub cover was highest overall at MEVE S (5.6%) and lowest at MEVE L (2.5%) (Figure 23a).

Three of the four ecological sites showed a positive trend in overall shrub cover. Trend was not significant at MEVE L (Figure 23b). Two-year lagged deficit and spring deficit both had a negative effect on shrub cover (Figure 23c). The effects of other included covariates were not significant.

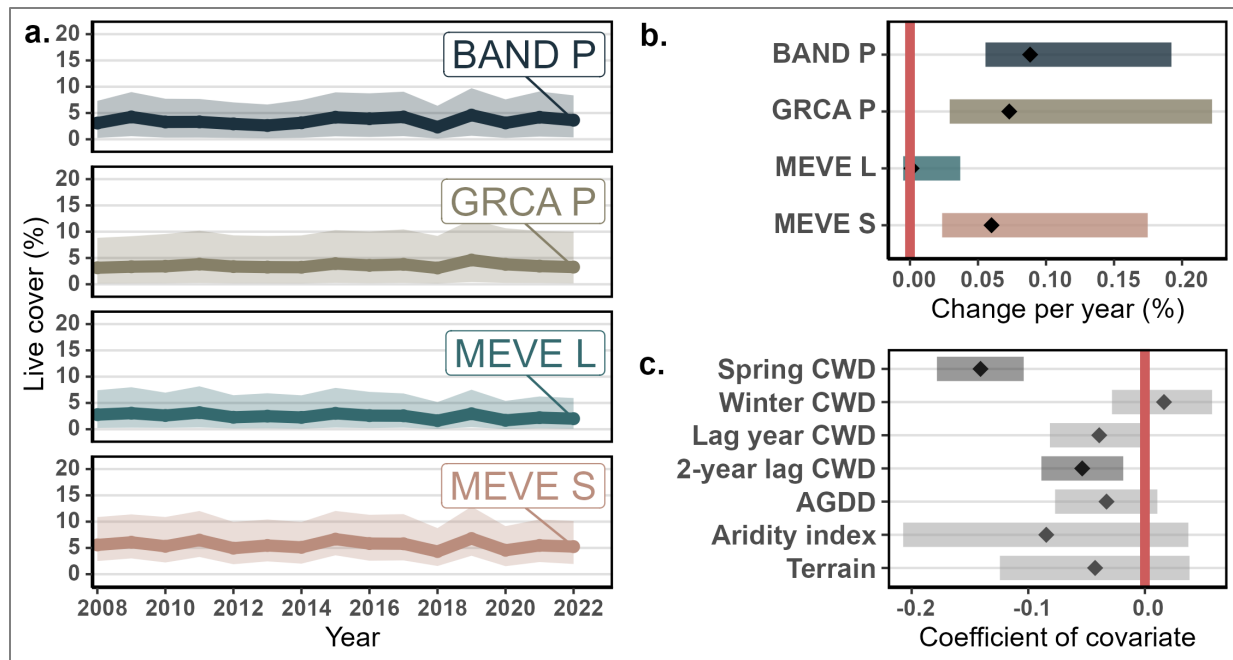


Figure 23. Model-based prediction of change over time in total live shrub cover at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit, and AGDD = aggregate growing degree days.

NPS / MEGAN SWAN

Cliffrose cover—GRCA P

Cliffrose (*Purshia mexicana* var. *stansburyana*) occurred only at GRCA in about 34% of plots sampled (Appendix B). We modeled cliffrose cover at GRCA from 2010–2021. Overall cover was less than 1%. There were no significant time trends or covariates on the cover of cliffrose (not shown).

Big sagebrush cover—GRCA P

Big sagebrush (*Artemisia tridentata*) occurred in > 30% of quadrats at GRCA P and MEVE L (39% and 33% respectively), it also occurred in a small number of plots at MEVE S (1.8%, Appendix B). Models including both GRCA P and MEVE L failed to converge, but a model was fit for GRCA P. Overall cover of big sagebrush at GRCA was 0.2%. There were no significant effects of time or covariates on the cover of big sagebrush (not shown).

Mountain mahogany cover—MEVE L and MEVE S

Mountain mahogany (*Cercocarpus montanus*) occurred in more than 35% of quadrats sampled at MEVE S, and < 10% of MEVE L plots (Appendix B), the model included both MEVE sites. Model-

predicted mean cover ranged from 0.5% to 2% and was greater at MEVE S. (Figure 24a). Cover increased slightly over time in the MEVE S site (Figure 24b), and none of the included covariates had a significant effect (Figure 24c).

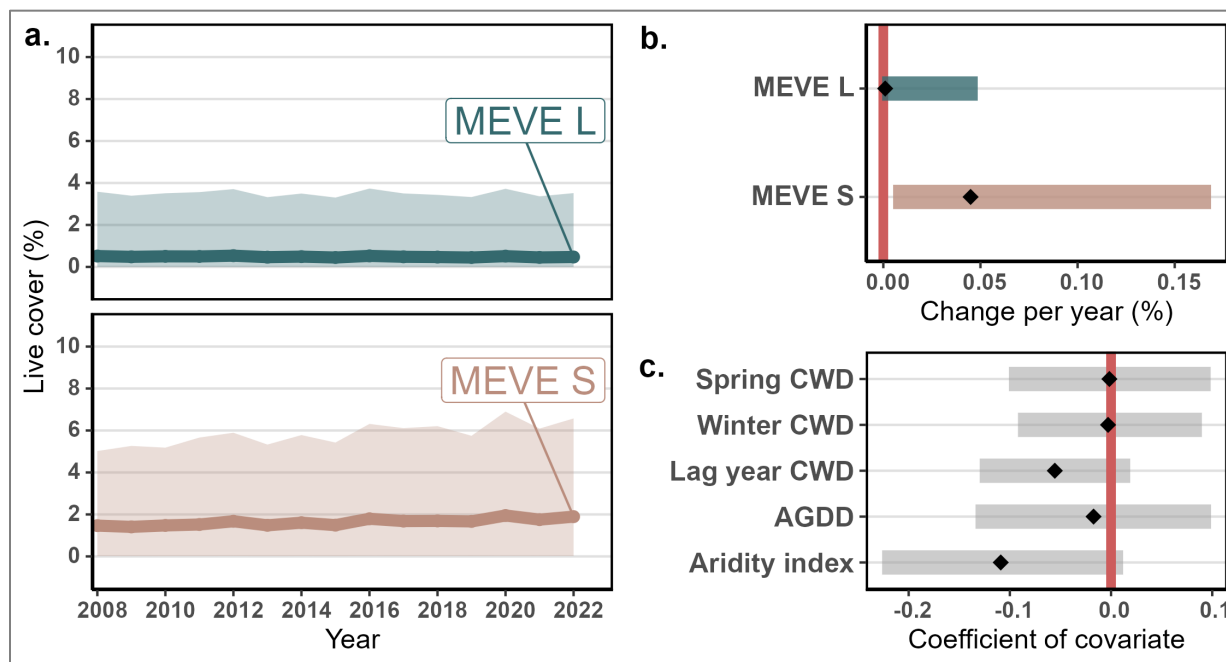


Figure 24. Model-based prediction of change over time in total live mountain mahogany cover at Mesa Verde National Park from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit, and AGDD = aggregate growing degree days.

NPS / MEGAN SWAN

Antelope bitterbrush cover—MEVE L and MEVE S

Antelope bitterbrush (*Purshia tridentata*) occurred in about 50% of plots in the two MEVE ecosites, and < 1% at GRCA (Appendix B). We modeled bitterbrush cover at MEVE. Model-predicted mean cover was similar between the two ecosites, ranging from 1.9–2.7% (Figure 25a). Cover of bitterbrush decreased slightly over time at MEVE L and did not change significantly at MEVE S (Figure 25b). Of the included covariates, AI was the only one to influence antelope bitterbrush cover, the positive effect (low values = hyper aridity) indicate more bitterbrush occurred at sites with lower overall aridity, sites with relatively humid conditions (Figure 25c).

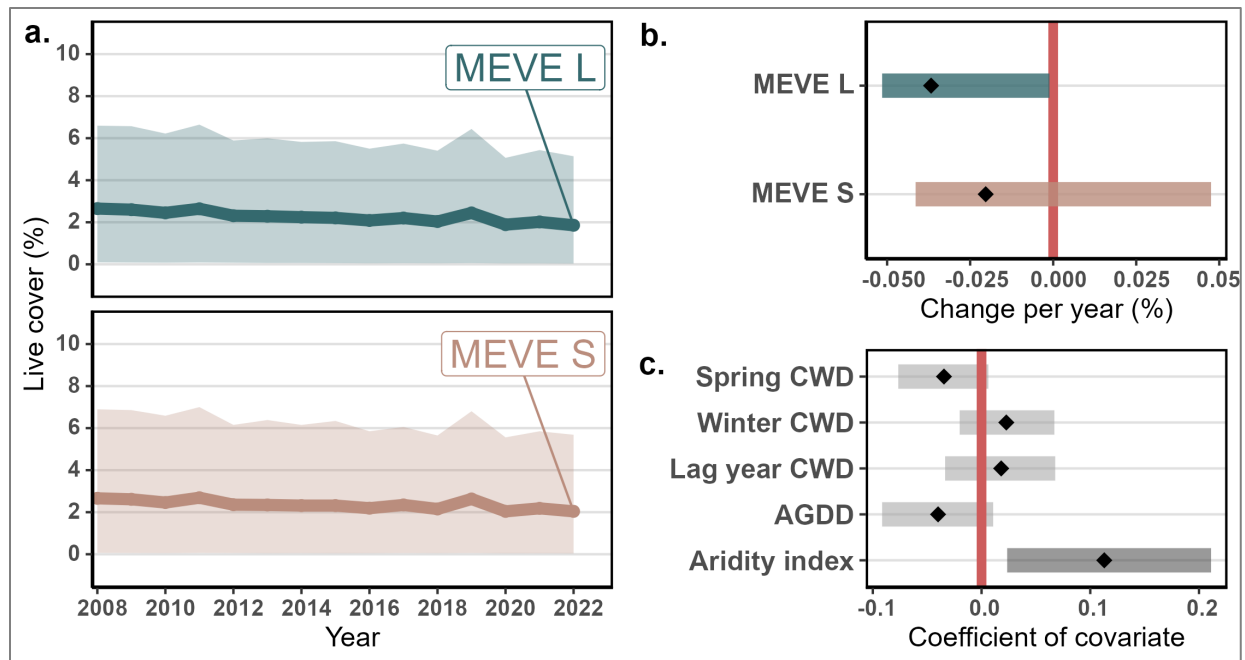


Figure 25. Model-based prediction of change over time in total live antelope bitterbrush cover at Mesa Verde National Park from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit, and AGDD = aggregate growing degree days.

NPS / MEGAN SWAN

Snakeweed cover—BAND P and GRCA P

Snakeweed (*Gutierrezia sarothrae*) occurred in close to half the plots at BAND and GRCA, but less than 1% of plots at the two MEVE ecosites. It was modeled for BAND and GRCA. Overall cover ranged from < 0.1% to 2.6% and was relatively higher at BAND P (Figure 26a). Snakeweed cover increased at BAND P during the monitoring period (Figure 26b). Winter deficit had a positive effect on snakeweed cover, indicating greater cover with increased winter deficit, while spring deficit had a negative effect (Figure 26c). The effect of AI was also negative, indicating more snakeweed cover at more arid sites.

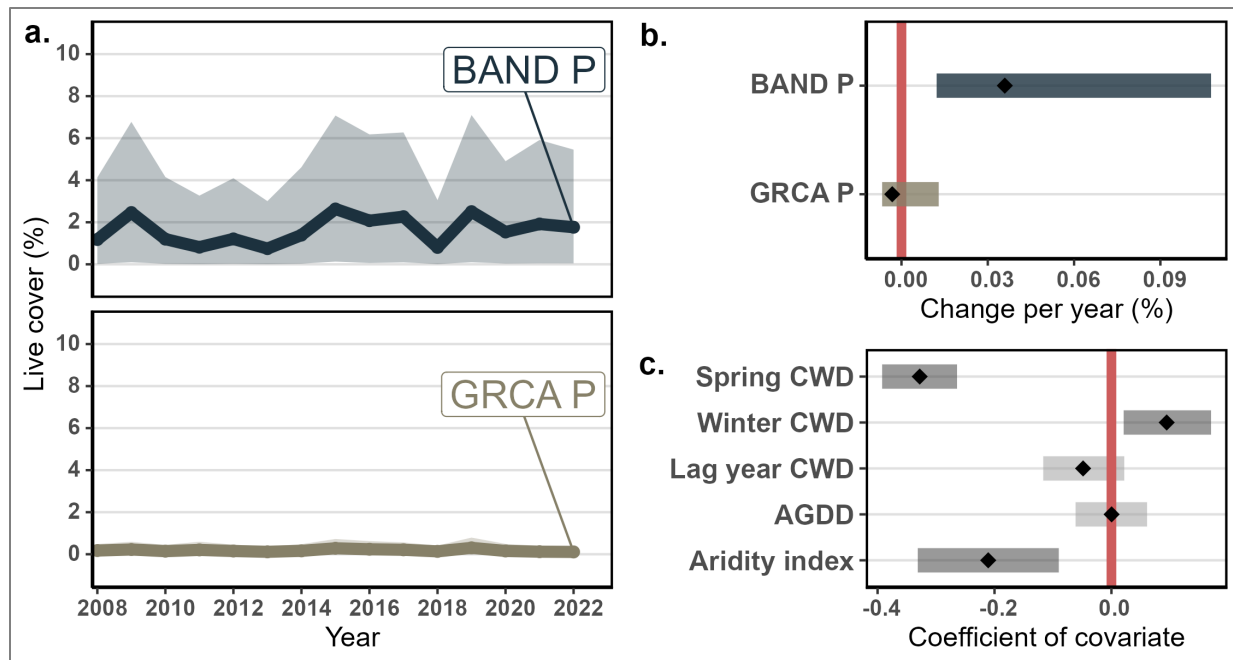


Figure 26. Model-based prediction of change over time in total live snakeweed cover at two national parks (BAND and GRCA) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit, and AGDD = aggregate growing degree days.

NPS / MEGAN SWAN

Cactus and yucca cover—all ecological sites

Cover of cactus and succulents was modeled across all four ecological sites. The model included lag year deficit, 2-year lag deficit, winter, and spring deficits, AGDD, AI and terrain (Appendix D). Mean model-predicted cover of cactus and succulents ranged from < 1%–1.5% and was highest at the two MEVE ecosites and lowest at GRCA P (Figure 27a). Cactus and succulent cover showed a significant time trend at MEVE, where it increased during the monitoring period at both ecosites (Figure 27b) and GRCA P, where it increased slightly, but significantly. None of the included covariates had a significant effect on cactus/succulent cover apart from AI. AI had a negative effect on cactus cover, indicating more cactus cover at sites with higher aridity (Figure 27c). Interestingly, AI also influenced the presence/absence component of cactus and yucca cover, indicating cactus was detected more frequently at less arid sites.

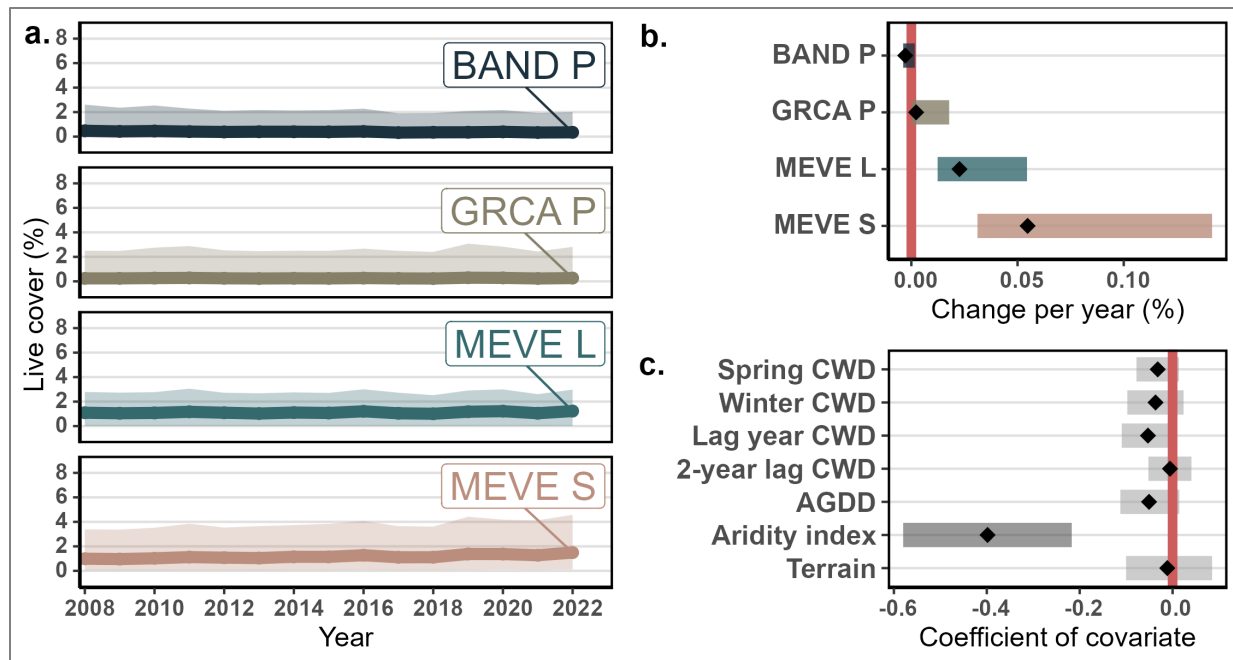


Figure 27. Model-based prediction of change over time in total live cactus and succulent cover at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit, and AGDD = aggregate growing degree days.

NPS / MEGAN SWAN

Opuntia cover—all ecological sites

Prickly pear (*Opuntia* spp.) occurred in > 30% of plots of all ecological sites and was most frequent in MEVE (Appendix B). Cover was low overall, ranging from 0.2%–0.7% across sites (Figure 28a). Credible intervals were wide, especially at GRCA P, indicating high spatial variability between plots. *Opuntia* cover increased during the monitoring period at the two MEVE ecological sites but did not change significantly at BAND or GRCA (Figure 28b). Winter deficit had a negative effect on cover of prickly pear, as did AI, indicating sites with higher AI (less arid sites) had lower cover of prickly pear (Figure 28c).

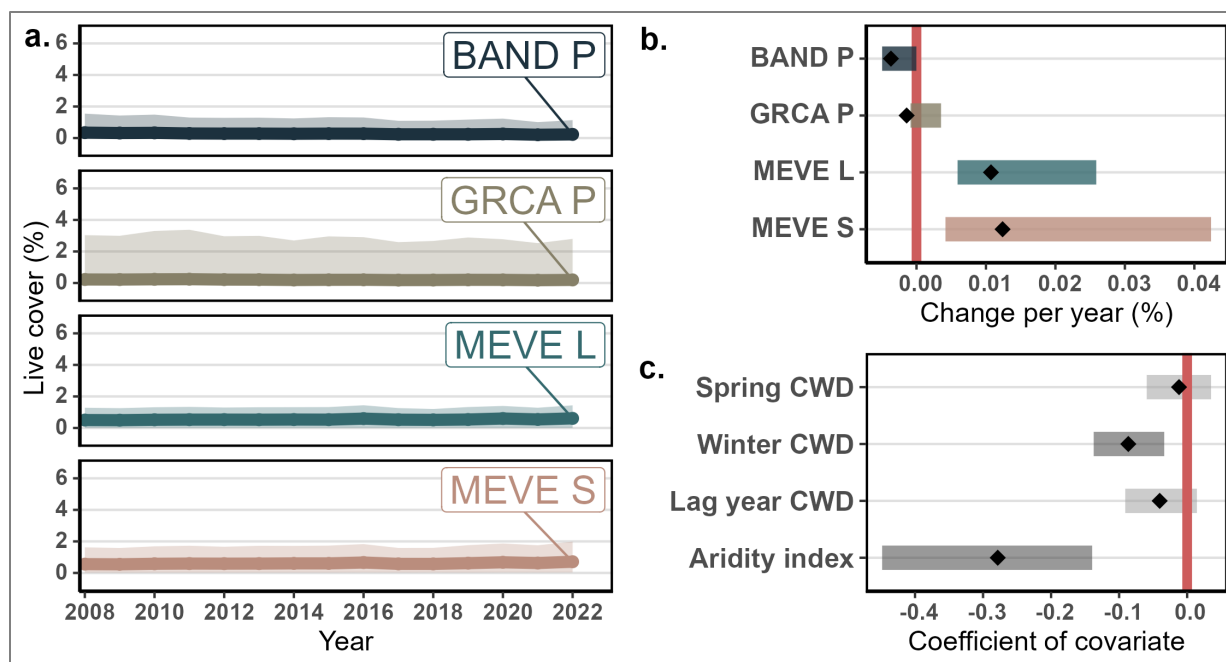


Figure 28. Model-based prediction of change over time in total live prickly pear cover at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit.

NPS / MEGAN SWAN

Forb cover—BAND P

Forbs were a minor component of overall vegetation cover at all the ecosites except BAND P (Appendix B). The model for BAND included lag year deficit, winter deficit, spring deficit, AI and AGDD (Appendix D). Mean model-predicted forb cover ranged from 3.5–5.3% there (Figure 29a). Forb cover increased significantly at BAND during the monitoring period (Figure 29b). Lag year deficit and AGDD had negative effects on forb cover, while AI had a positive effect, indicating more arid sites had less cover of forbs at BAND (Figure 29c).

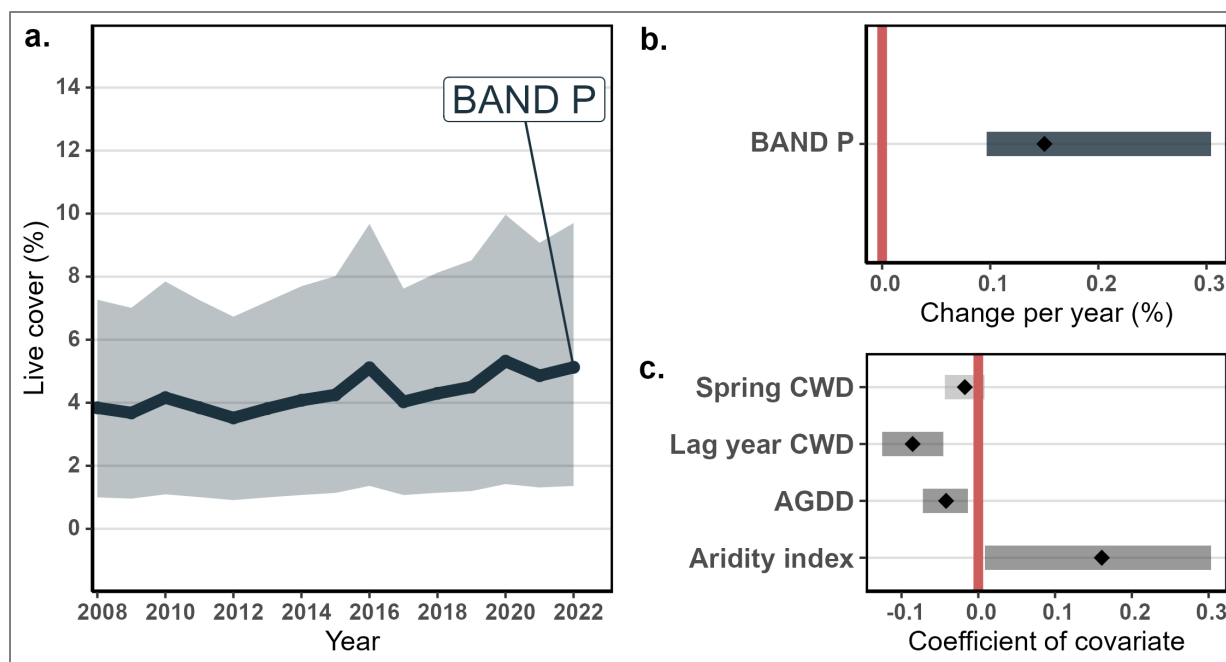


Figure 29. Model-based prediction of change over time in total live forb cover at one ecosite in Bandelier National Monument (BAND) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit, and AGDD = aggregate growing degree days.

NPS / MEGAN SWAN

Ragleaf bahia cover—BAND P

Ragleaf bahia (*Amauriopsis dissecta*) occurred primarily at BAND P where it was present in > 60% plots sampled (Appendix B). It was present at lesser amounts at GRCA P; however, models including both ecosites failed to pass posterior predictive checks. Covariates included in the final model for BAND P included lag year deficit, winter deficit, spring deficit, AGDD, AI, and basal area (BA). Predicted mean ragleaf bahia cover ranged from 0.1–0.8% at BAND over the monitoring period (Figure 30a). Ragleaf bahia cover increased significantly (Figure 30b). The effects of most of the covariates included in the model were not significant (Figure 30c). However, spring deficit had a negative effect on cover, while winter deficit had a positive effect for this species at BAND.

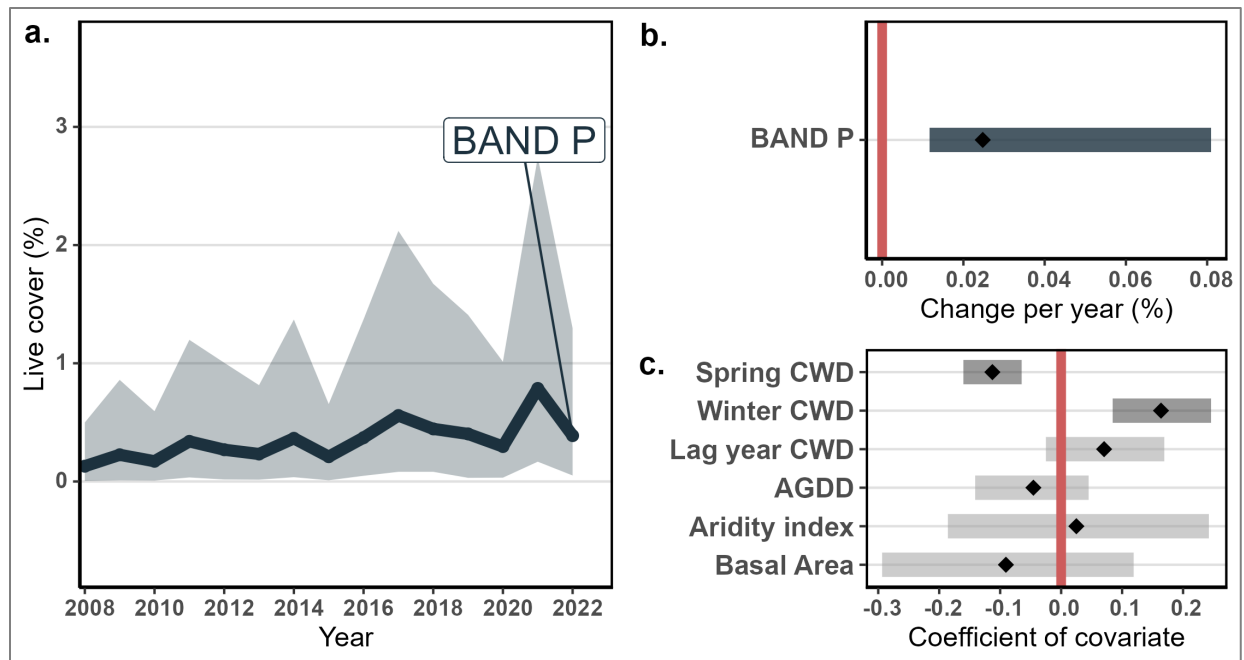


Figure 30. Model-based prediction of change over time in ragleaf bahia presence at one ecosite in Bandelier National Monument (BAND) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit, and AGDD = aggregate growing degree days.

NPS / MEGAN SWAN

Cheatgrass presence—GRCA P, BAND P

Cheatgrass (*Bromus tectorum*) occurred primarily at BAND P and GRCA P. Models including percent cover failed to converge, so we modeled presence of cheatgrass in 10 m² quadrats. Covariates included in the final model for BAND P included lag year deficit, winter deficit, spring deficit, AGDD, and AI. Cheatgrass occurred in relatively fewer quadrats at GRCA (ranging from 4–17% of quadrats), than at BAND P where model predicted presence ranged from 17–55% of quadrats (Figure 31a). Presence of cheatgrass increased in plots at BAND P during the monitoring period and decreased slightly at GRCA P (Figure 31b). Credible intervals were extremely wide at both ecosites, indicating low model certainty. However, the increase at BAND corresponds with anecdotal crew observations of increased cheatgrass prevalence in the field. Spring deficit had a negative effect on the presence of cheatgrass, indicating it was encountered less frequently in years with higher deficits. Winter and lag year deficits had the opposite effect (Figure 31c).

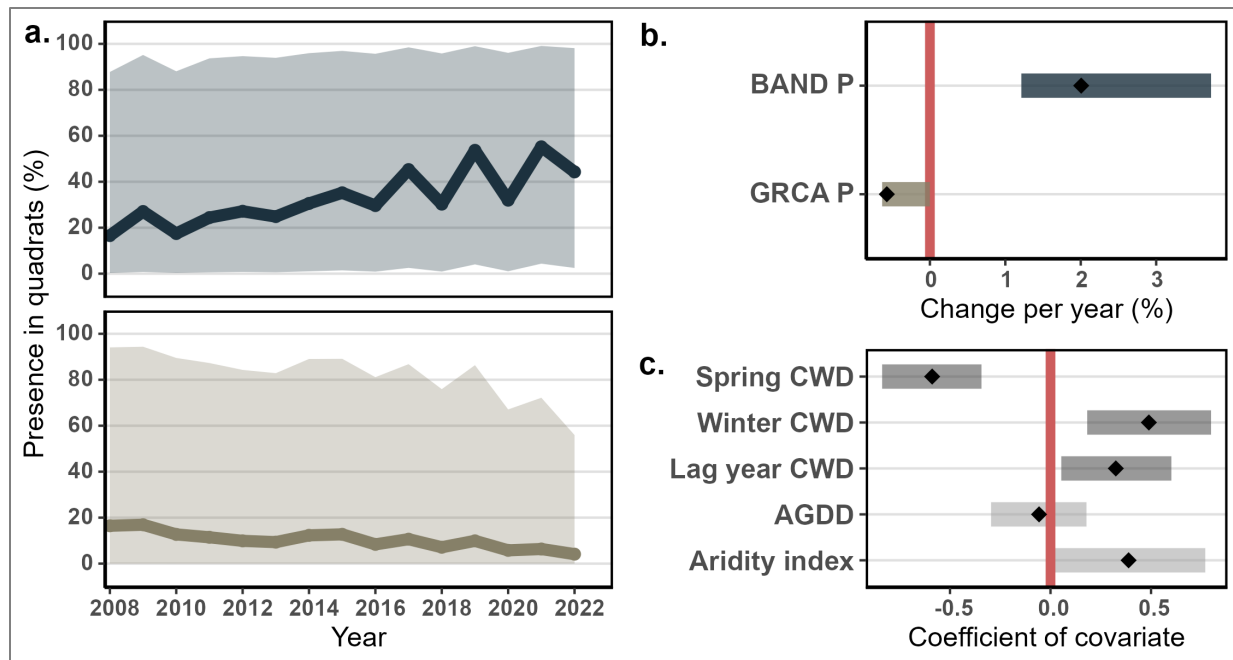


Figure 31. Model-based prediction of change over time in cheatgrass presence at two ecosites in two National Parks (BAND, GRCA) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit, and AGDD = aggregate growing degree days.

NPS / MEGAN SWAN

Toadflax penstemon presence—MEVE L, MEVE S

Toadflax penstemon (*Penstemon linarioides*) occurred primarily at MEVE where it was found in 78% of plots at MEVE L and 51% at MEVE S (Appendix B). Models including percent cover failed to converge, so we modeled presence of this species in 10 m² quadrats. Covariates included in the final model included lag year deficit, winter deficit, spring deficit, AGDD, AI, and basal area. Model-predicted mean frequency was similar to calculated overall frequency, ranging from 46–66% at MEVE S, and 72–87% of plots at MEVE L, but credible intervals were extremely wide, especially at MEVE S (Figure 32a). Presence of toadflax penstemon increased at MEVE S and did not change significantly at MEVE L (Figure 32b). Winter deficit had a positive effect on presence, indicating it was encountered more frequently in years with higher winter deficits. Lag year deficit and AGDD had negative effects (Figure 32c).

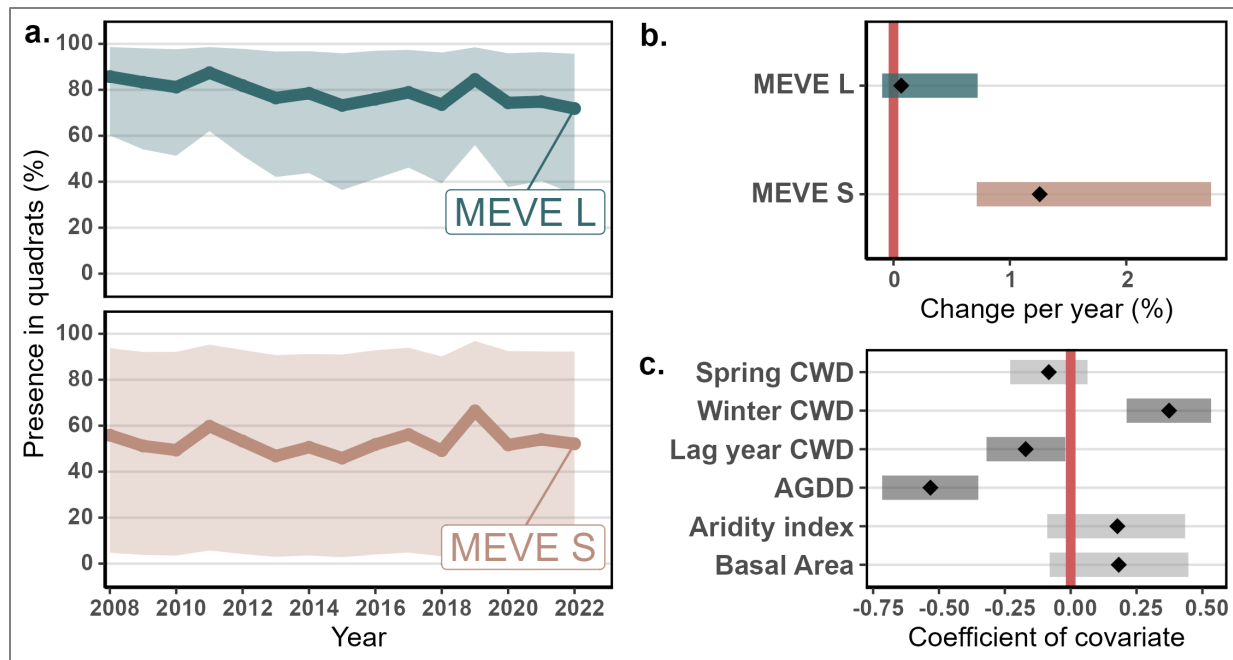


Figure 32. Model-based prediction of change over time in total live toadflax penstemon cover at two ecosites in Mesa Verde National Park (MEVE) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit, and AGDD = aggregate growing degree days.

NPS / MEGAN SWAN

Spiny phlox presence—MEVE L, MEVE S

Spiny phlox (*Phlox hoodii*) occurred primarily at MEVE where it was found in just over 30% of plots at MEVE L and 9% at MEVE S (Appendix B). Models including percent cover failed to converge, so the presence of this species in 10 m² quadrats was modeled at both ecological sites. Covariates included in the final model included lag year deficit, winter deficit, spring deficit, AGDD, and AI and basal area. Model-predicted mean frequency matched calculated overall frequency closely, ranging from 27–32% at MEVE L, and 8–9% of plots at MEVE L, but credible intervals were extremely wide, especially at MEVE S (not shown). Spiny phlox presence increased at MEVE L, but did not change significantly at MEVE S. None of the included covariates significantly influenced spiny phlox presence in plots (not shown).

Field wormwood—BAND P

Field wormwood (*Artemisia campestris*) occurred at BAND in about 34% of plots sampled (Appendix B). Models of percent cover for this species failed to converge, but a model of presence absence was fit successfully. There were no significant time trends (not shown), but Spring CWD

had a negative effect and lag year CWD, along with AGDD and AI had significant positive effects on wormwood cover.

Species Richness

Quadrat-scale species richness was modeled for each ecological site and included lag year, winter and spring deficit, AI and AGDD covariates (Appendix D). Species richness is commonly under dispersed, and this was the case at our ecological sites, so a generalized Poisson model was used instead of a standard Poisson (Lynch et al. 2014). Although standard Poisson models did adequately estimate mean species richness, models failed to pass posterior predictive checks for variance of the response (Harris et al. 2012).

Mean model-predicted richness ranged from 6.0 to 10.4 species per 10 m² quadrat and estimates were similar to quadrat richness values summarized for plot status (Table 10). Overall species richness was lowest at the two sites at MEVE and highest at BAND (Figure 33a). Species richness increased over the monitoring period at all ecological sites, but most strongly at BAND (Figure 33b). The effects of climate covariates on richness were mixed (Figure 33c). Lag year deficit had no significant effect on richness at any ecological site modeled. Winter deficit had a negative effect on BAND P and MEVE L, but a slight positive effect on MEVE S. Spring deficit had a negative effect on richness at GRCA P and MEVE L. An increase in the number of growing degree days (AGDD) had a positive effect on richness at both BAND P sites and MEVE L. Aridity index had negative effects on richness at BAND P, GRCA P and MEVE S, indicating higher richness at more arid sites, but a positive effect at MEVE L indicated greater richness at relatively more humid sites (Figure 33c).

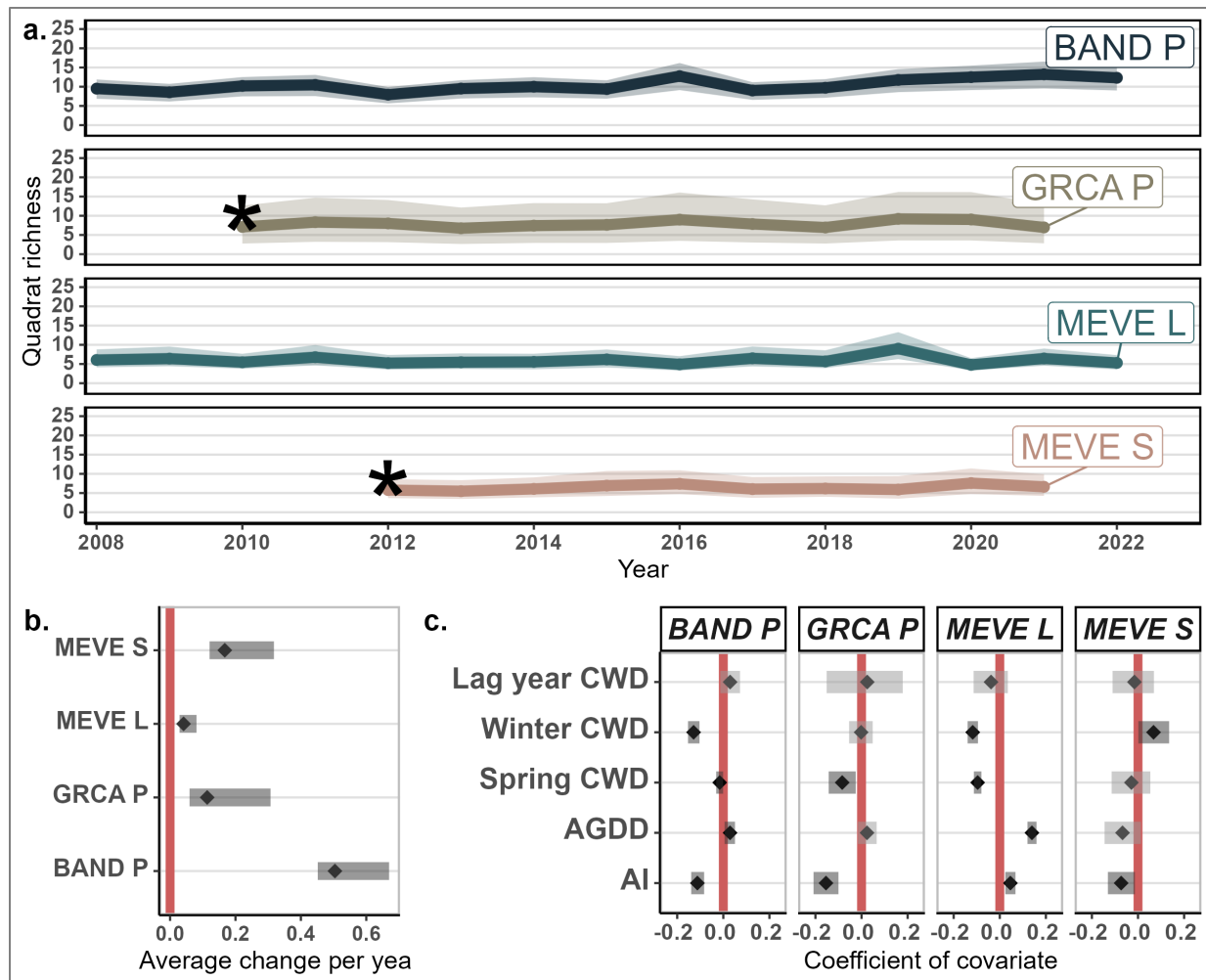


Figure 33. Model-based prediction of change over time in quadrat-scale species richness at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect, * indicates sites where sampling began later than 2008. CWD = climatic water deficit, AGDD = aggregate growing degree days, AI = aridity index.

NPS / MEGAN SWAN

Change over time in overstory trees

Change over time in seedling density

Density of seedlings was modeled across all four ecological sites for junipers and two-needle pinyon. The models included previous-year deficit, winter deficit, and spring deficit (Appendix D). Mean model-predicted juniper seedling density ranged from > 0.01 seedlings per m^2 at BAND to 0.8 seedlings per m^2 at MEVE L (Figure 34a). Juniper seedling density increased significantly over time

during the monitoring period at MEVE L (Figure 34b). None of our coefficients had a significant effect on the density of juniper seedlings (Figure 34c).

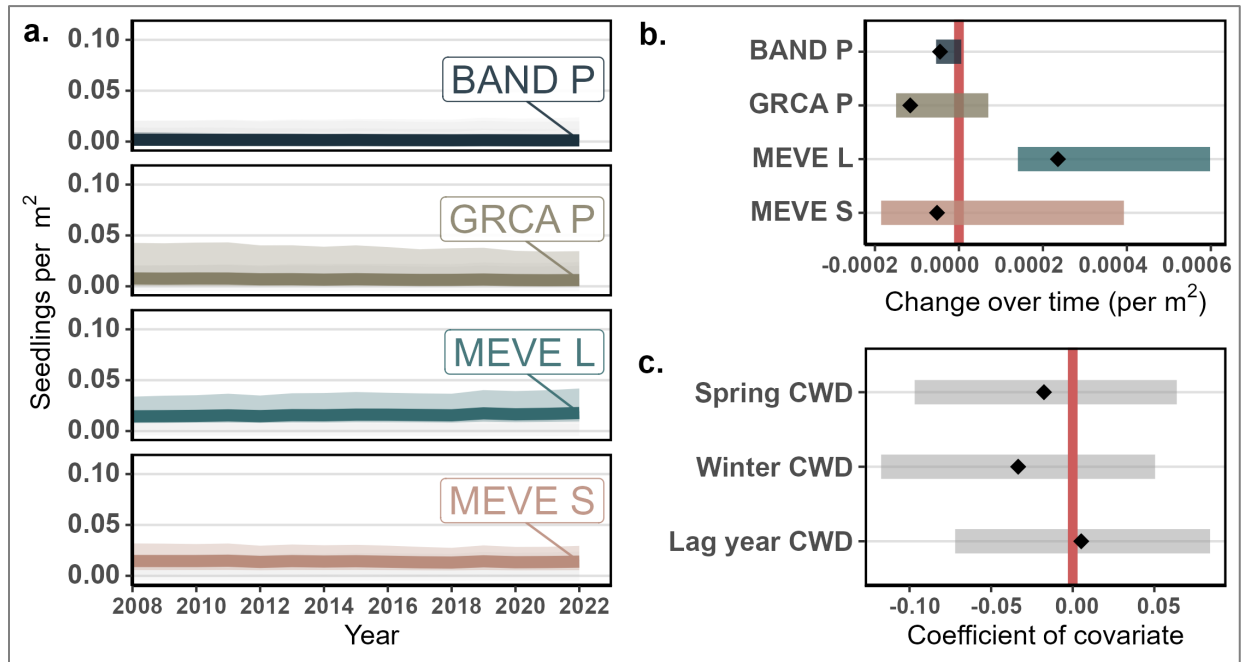


Figure 34. Model-based prediction of change over time in juniper seedling density at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit.

NPS / MEGAN SWAN

Pinyon seedling density ranged from .004 to 0.32 seedlings per m² and was lowest at BAND P and highest at GRCA P (Figure 35a). Pinyon seedling density increased over time at both GRCA P and MEVE L (Figure 35b). Covariates did not influence pinyon seedling densities (Figure 35c).

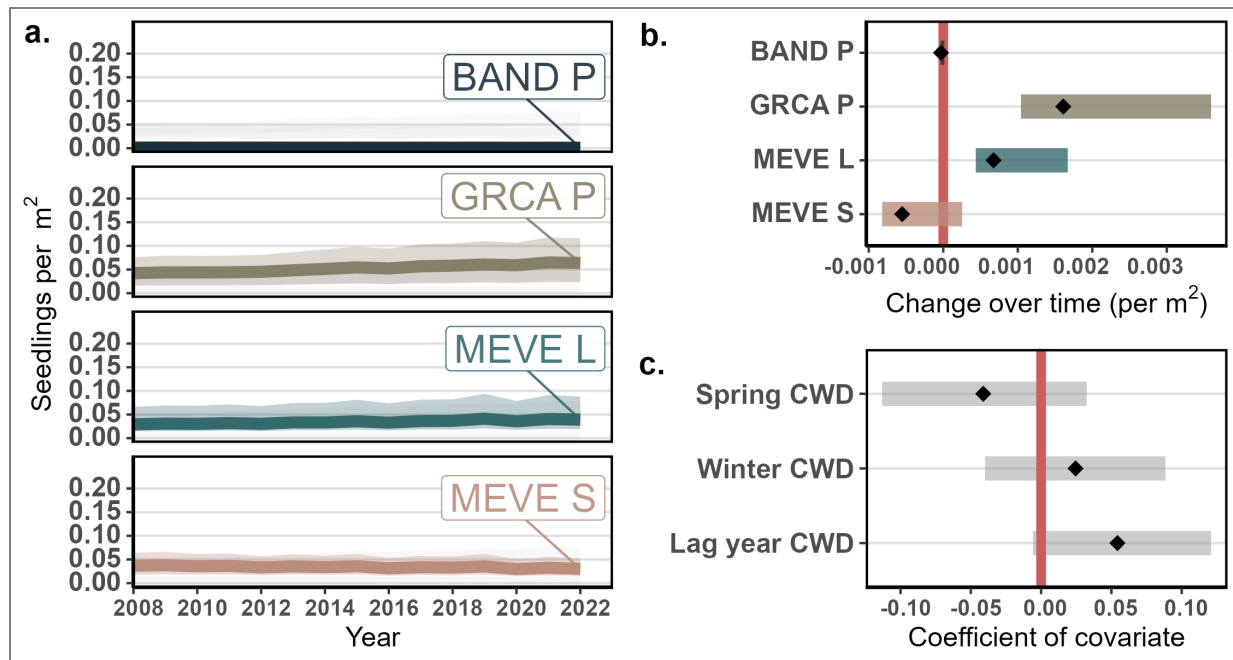


Figure 35. Model-based prediction of change over time in pinyon seedling density at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit.

NPS / MEGAN SWAN

Change over time in sapling density

Density of saplings was modeled across all four ecological sites for juniper and pinyons. The model included both current year winter and spring deficit, lag year and 2 years previous deficits and total basal area (Appendix D).

Juniper sapling density ranged from .002 to 0.09 saplings per m² and was lowest at BAND P and highest at MEVE S (Figure 36a). Sapling density of junipers tended to increase over time at all sites, but that effect was only weakly significant at most sites, and no change was detected at MEVE S (Figure 36b). None of the included covariates had a significant effect on juniper sapling density (Figure 36c).

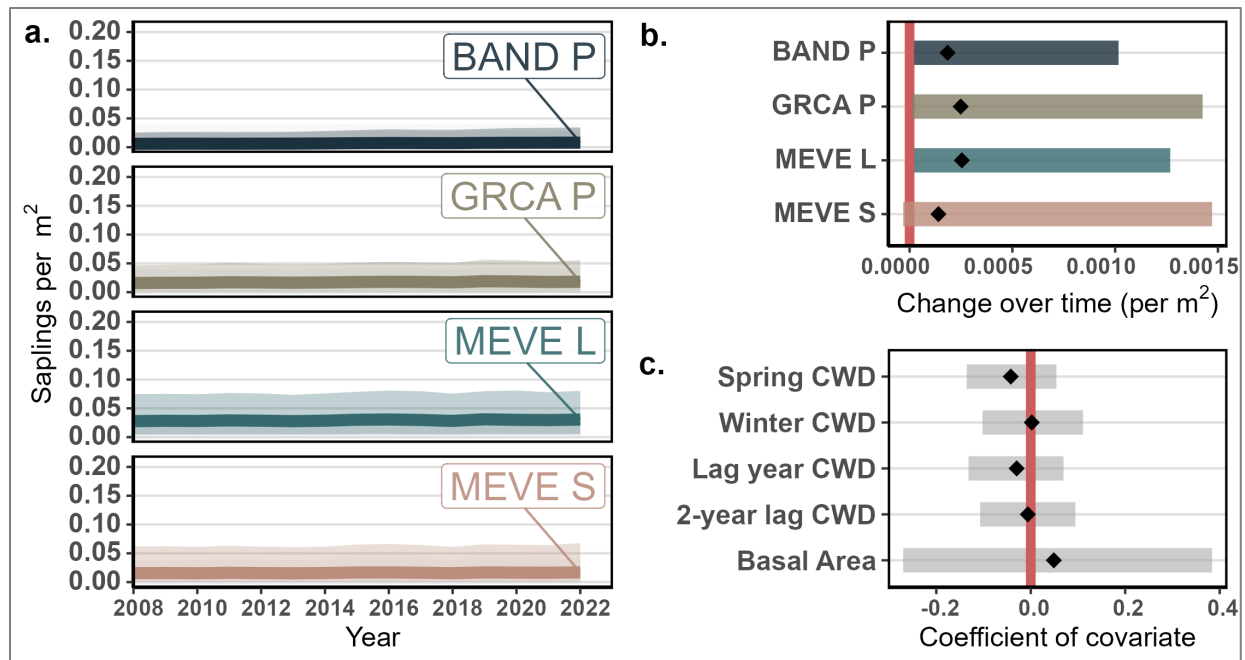


Figure 36. Model-based prediction of change over time in juniper sapling density at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distributions that don't overlap 0 indicate a significant time trend. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit.

NPS / MEGAN SWAN

Model predicted pinyon density ranged from < 0.002 to 0.09 saplings per m². Pinyon sapling density was lowest at BAND P and highest at MEVE L (Figure 37a). Time trends were mostly nonsignificant, but there was a decreasing trend at MEVE S (Figure 37b). The effect of included covariates on pinyon seedling density was also mostly neutral, except for spring deficit which negatively influenced pinyon sapling density (Figure 37c).

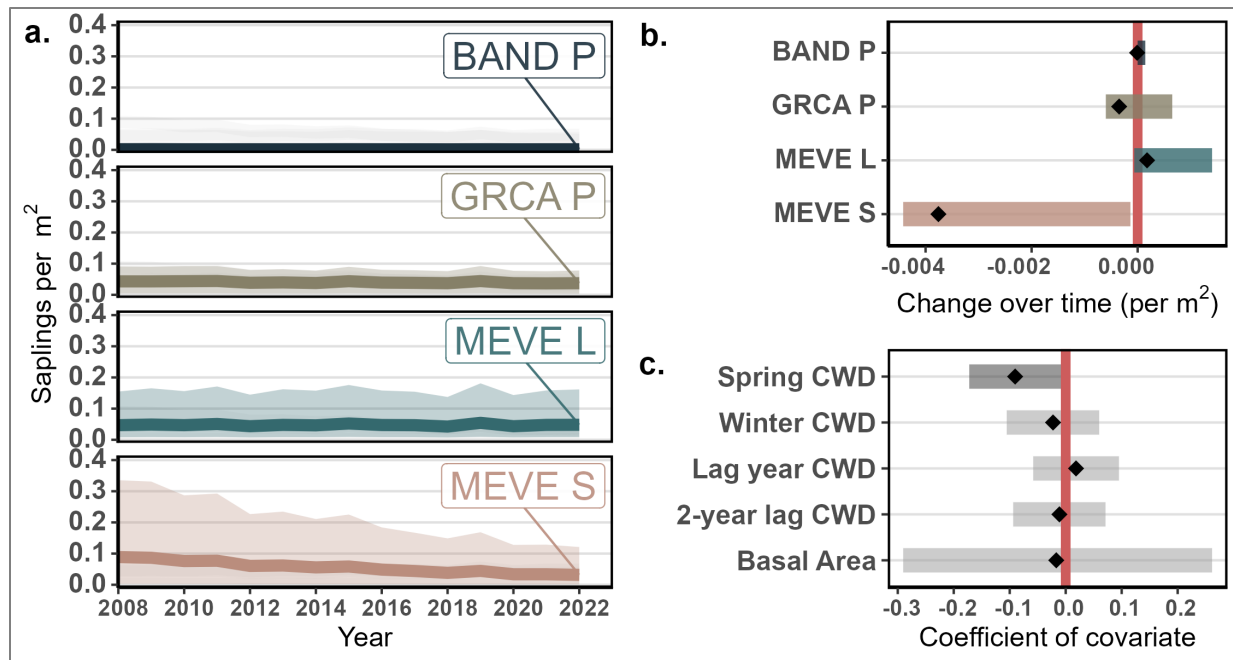


Figure 37. Model-based prediction of change over time in pinyon sapling density at four ecosites in three National Parks (BAND, GRCA, MEVE) from 2008 to 2022. a.) Colored lines indicate the predicted mean for sampled plots and colored shaded area indicates the 95% credible interval. b.) Posterior distribution of the model estimate of trend over time. The horizontal bar represents the 95% credible interval for each ecological site. Means of the distributions are indicated by black diamonds. c.) Posterior distribution of the estimate of covariate effects. The horizontal bar represents the 95% credible interval for each coefficient. Means of the distributions are indicated by black diamonds. Distance and direction from 0 indicate the relative size and direction of effect. CWD = climatic water deficit.

NPS / MEGAN SWAN

Change over time in overstory trees

Mortality of overstory trees was not widespread during the monitoring period. The vast majority (> 90%) of trees did not change status between their initial assessment during the first visit to a plot and the most recent visit. Out of 135 plots across four ecosites, more than half the plots ($n = 80$) had no overstory tree mortality during the monitoring period. Overall, 29 pinyon, 22 Utah juniper and 12 one-seed junipers died after being assessed for the first time (excluding trees that were cut at BAND). The maximum number of individual trees that died within a single plot was 21 at MEVE L29, which experienced wildfire in August 2018. When averaged across all the plots in an ecosite, the greatest mortality was experienced by pinyon at GRCA (Table 12).

Table 12. Average tree mortality by ecological site and species for three park units. Table excludes cut trees (n = 291 at BAND only) and trees of uncertain status (n = 69).

Ecological Site	Species	Mean plot mortality (range) (trees per hectare)
BAND P	<i>Juniperus monosperma</i>	2.9 (0, 50)
	<i>Pinus edulis</i>	0 (0, 0)
GRCA P	<i>Juniperus osteosperma</i>	0.55 (0, 20)
	<i>Pinus edulis</i>	3.4 (0, 80)
MEVE L	<i>Juniperus osteosperma</i>	2.7 (0, 210)
	<i>Pinus edulis</i>	1.4 (0, 30)
MEVE S	<i>Juniperus osteosperma</i>	1.0 (0, 20)
	<i>Pinus edulis</i>	1.6 (0, 60)

At BAND, 27 plots were impacted by park-sponsored juniper thinning that took place between 2007–2010. A total of 291 trees were recorded as cut, either prior to or following the initial monitoring visit. Thirteen of these were identified as pinyon pine, the rest were juniper; thinned pinyon were dead prior to thinning. Trees were thinned more heavily in denser areas, but the median number of cut trees in thinned plots was 10 and ranged from 2–21 individual trees cut. Due to the timing of thinning and onset of monitoring, only 108 trees are confirmed live prior to being cut, however, most cut junipers were likely live prior to being thinned. In addition to cut trees at BAND, a single tree in one plot at MEVE (L29) was cut as part of a fire suppression effort.

Summary: temporal trends

More than half the modeled responses showed significant temporal trends, i.e., directional changes over time that were *not* explained by included covariates (Figure 38). Most of those trends were small, but positive, representing slight increases over time in modeled responses during the monitoring period (2008–2022). One notable exception was the nonnative annual grass, cheatgrass, which showed a relatively large increase in prevalence at BAND.

	BAND P	GRCA P	MEVE L	MEVE S
Perennial grasses	o	o	-	+
Muttongrass		+	+	+
Blue grama	o	+		
Squirreltail	o	o	+	+
Shrubs	+	+	o	+
Big sagebrush		o		
Mountain mahogany			o	+
Snakeweed	+	o		
Antelope bitterbrush			-	o
Cliffrose		o		
Cactus	o	+	+	+
Opuntia spp.	-	o	+	+
Forbs	+			
Ragleaf bahia	+			
Field wormwood	o			
Toadflax penstemon			o	+
Spiny phlox			+	o
Cheatgrass	+	-		
Juniper seedlings	o	o	+	o
Pinyon seedlings	o	+	+	o
Juniper saplings	+	+	+	o
Pinyon saplings	o	o	o	-

Figure 38. Summary of direction of year effects (trend) for modeled responses. Green (+) indicates the covariate had a significant positive effect on the response, red (-) a significant negative effect and a gray box (o) indicates that the effect was non-significant. Non-colored, no symbol boxes indicate that a given response was not modeled for the ecological site. Fully accessible tabular data for this figure is presented in Appendix E, [Table 16](#).

NPS / MEGAN SWAN

Overall perennial grass cover did not change significantly at BAND or GRCA, and exhibited alternate trends at the two sites at MEVE, increasing at MEVE S and decreasing at MEVE L. However, the cover of individual species of grass increased, at least for some species, at all ecosites except BAND P, where they did not change. Modeled grass species included both warm-season C₄ (blue grama) and cool-season C₃ (muttongrass and squirreltail) species. Although recent analysis of vegetation trends in SCPN grasslands found consistent decreases over time in cover of most grass species (2007–2021, Swan 2024), the relatively dense (~40%) overstory canopy cover at PJ sites (with the exception of BAND), may ameliorate increasing soil temperature and decreasing water availability through shading, potentially buffering the effects of drought in these ecological sites compared to grasslands (Royer et al. 2012). Additionally, in contrast to the grassland sites, these PJ sites had a sequence of less stressful, low-deficit years spaced relatively evenly throughout the monitoring period in 2011, 2015, and 2019, the timing of which would tend to decrease trends caused by drought in intervening years and potentially allow vegetation to recover (Figure 39).

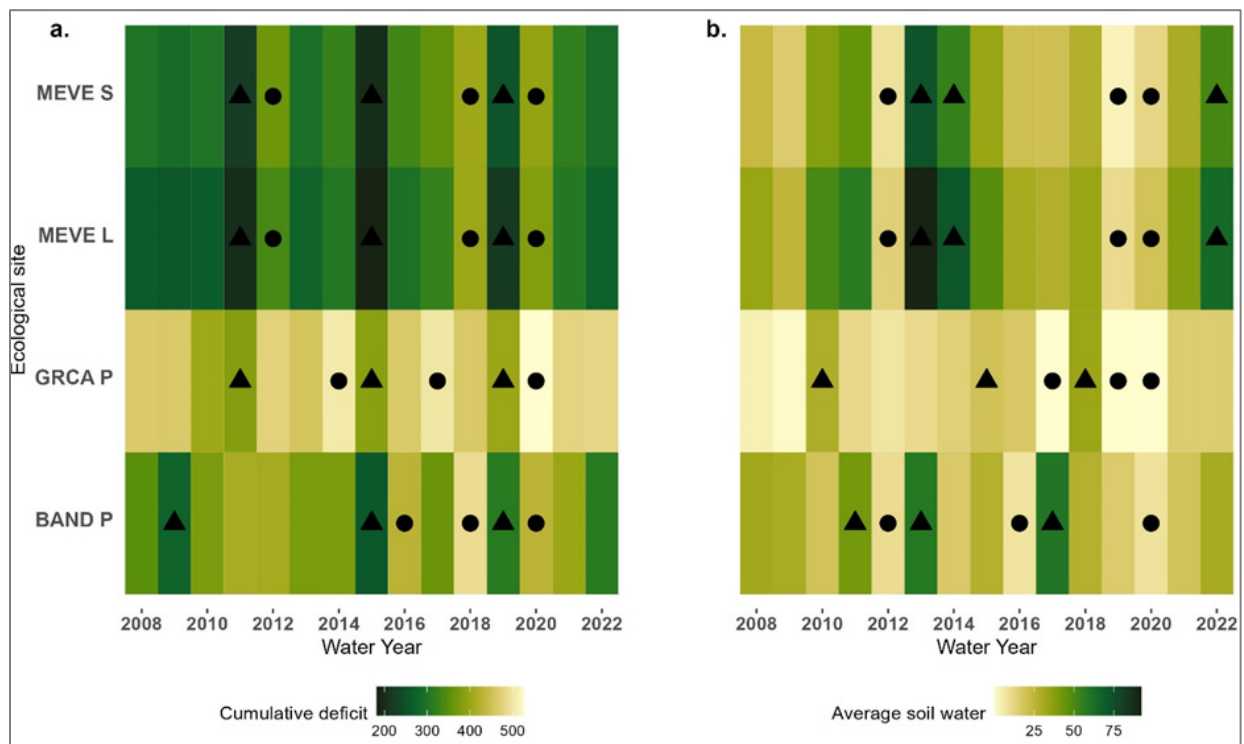


Figure 39. Cumulative annual (a) climatic water deficit (mm) and (b) soil water (mm) for each water year (Oct–Sept) at four ecosites in three National Parks (BAND, GRCA, MEVE). Circles indicate extreme dry years (i.e., the three highest deficit/lowest rainfall years) and triangles indicate extreme wet years (i.e., the three lowest deficit/highest rainfall years) for each ecological site (2008–2022) (data from Daymet: Daily Surface Weather Data on a 1-km Grid for North America, Version 4 R1 <https://doi.org/10.3334/ORNLDAAAC/2129>).

NPS / MEGAN SWAN

Lifeform cover of cactus and succulents also increased in two of the four ecological sites during the monitoring period. Prickly pear cover increased at both ecological sites at MEVE. Conversely, prickly pear cover decreased significantly at BAND, which was the only park to experience significant changes in both tree density (due to thinning) and the addition of slash mulch to the soil surface.

Shrub models displayed fewer significant trends than grasses or cactus, but where trends existed they were positive, with the single exception of antelope bitterbrush at MEVE L. Shrubs are longer-lived with persistent woody structure and deeper root systems which results in less and slower changes in cover in response to relatively short-term fluctuations in conditions compared to herbaceous species, and showed little reduction in cover during extreme drought (Noy-Meir 1973, Flake and Weisberg 2021). Deeper rooting systems allow shrubs to access deep water reserves in the soil profile, and other recent studies have reported shrubs are less vulnerable to drought induced mortality than perennial grasses (Hoover et al., 2015, Finger-Higgins et al. 2023). Soil texture may influence shrub response to drought; shrubs growing on deep, finer textured clayey soils, like those at MEVE L, may be more affected by drought than those growing on coarser textured or shallower soils, due to decreased infiltration (Ji et al. 2019, Whipple et al. 2019).

Forbs are not a dominant lifeform in any ecological site aside from BAND P, and only a few species occurred in > 30% of plots (Appendix B). The forb responses that were successfully modeled showed increases in cover or presence or did not change during the monitoring period. The only modeled exotic species, cheatgrass, was prevalent at BAND, where it increased significantly in presence. It was less common overall at GRCA P, where it decreased slightly, possibly due to the addition of plots (in 2012 and 2014) that did not contain cheatgrass (first figure in Appendix A).

Trends in overstory tree metrics also tended to be positive. Density of juniper seedlings and saplings increased over time at MEVE L. Pinyon seedlings also increased at MEVE L and at GRCA P, while pinyon saplings decreased over time at MEVE S. Density of juniper saplings increased during the monitoring period at all sites but MEVE S. Since survival of seedlings tends to decrease with age, increases in juniper sapling density may indicate recruitment into the system (Van Auken et al. 2003, Chambers 1999). However, seed production, germination and seedling growth are complicated multiyear processes that are difficult to model. Moreover, all size class categories were combined for analysis.

Positive seedling and sapling trends, coupled with limited mortality of overstory trees suggest that monitoring plots did not experience widespread population declines in overstory species during the current monitoring period (2008–2022). Although localized mortality events have already affected many nearby areas and future range shifts are almost certain for pinyon juniper ecosystems in the West (Noel et al. 2024), these monitoring sites have not yet been strongly affected. Although importantly, BAND and MEVE experienced widespread pinyon mortality (as much as > 90% at BAND) *prior* to the monitoring period. Recent research in the Great Basin reported overall population declines at about 20% of sites, with declines more likely at hotter and drier sites (Shriver

et al. 2022). Pinyon in the Great Basin were most vulnerable to declines, and results suggest Utah juniper may be more resilient than one-seed juniper (Hartsell 2020, Shriver et al. 2022).

Quadrat-scale species richness increased across all sites (Figure 33). The effect was strongest at BAND P, where a large-scale overstory thinning and slash mulch treatment intended to decrease soil erosion and increase understory vegetation was undertaken by the park in 2007–2010. A preliminary study showed a several-fold increase in understory cover, despite drought, 3–5 years post treatment (Meddens et al. 2016). Shrubs and snakeweed cover both increased at the park.

In general, credible intervals for model-predicted means of our response variables were wide. This reflects a high degree of spatial variation between plots and (relatively) small sample size. The effect of a small sample size is further compounded by plots not being sampled every year and highly variable weather conditions at these sites, both seasonally and inter-annually. Although 15 years of data collection is an accomplishment, additional data collection will increase the precision of our estimates and our confidence in the robustness of our time trends.

Summary: covariate effects

A summary table of the direction of covariate effects on modeled responses is provided in Figure 40. Most significant covariate effects were negative. Herbaceous vegetation (perennial grasses and forbs) was relatively more responsive to modeled covariates compared to woody shrubs or cactus. Terrain (a combined metric of slope and aspect) and average basal area for the plot were not significant in any models in which they were included, so they were often dropped to reduce model complexity and aid convergence.

	Spring deficit	Winter deficit	Lag year deficit	2 year lag deficit	AGDD	Aridity index
Perennial grasses	-	+	-		o	
Muttongrass	-	+	-		-	+
Blue grama	-	o	-		o	+
Squirreltail	-	-	-		+	o
Shrubs	-	o	o	-	o	o
Big sagebrush	o	o	o		o	o
Mountain mahogany	o	o	o		o	o
Snakeweed	-	+	o		o	-
Antelope bitterbrush	o	o	o		o	+
Cliffrose	o	o	o		o	o
Cactus	o	o	o	o	o	-
Opuntia spp.	o	-	o			-
Forbs	o		-		-	+
Ragleaf bahia	-	+	o		o	o
Field wormwood	-	o	+		+	-
Toadflax penstemon	o	+	-		-	o
Spiny phlox	o	o	o		o	o
Cheatgrass	-	+	+		o	o
Juniper seedlings	o	o	o			
Pinyon seedlings	o	o	o			
Juniper saplings	o	o	o	o		
Pinyon saplings	-	o	o	o		

Figure 40. Summary of direction of covariate effects on modeled responses. Green (+) indicates the covariate had a significant positive effect on the response, red (-) a significant negative effect and a gray box (o) indicates that the effect was non-significant. Non-colored, no symbol boxes indicate that a given model did not include that covariate. Fully accessible tabular data for this figure is presented in Appendix E, [Table 17](#).

NPS / MEGAN SWAN

Overall, accumulated growing degree days (AGDD) had nonsignificant effects on perennial grasses and forbs, but did show significant effects at the species level. The effect of increasing AGDD on grass species was mixed, the effect of warmer spring temperatures on muttongrass cover was negative while the effect on squirreltail cover was positive. Both muttongrass and squirreltail are C_3 species that typically begin growth in the winter or early spring. While longer periods of springtime temperature favorable to plant growth generally has a positive effect on plant cover (given sufficient available water), other studies suggest at least some exotic or annual species in semi-arid grasslands might benefit from cool, wet springs (Munson 2011, Prevey and Seastedt 2014). Squirreltail typically grows under shrubs, so it may have more favorable water conditions during warm spring seasons. It also has a wider ecological amplitude than muttongrass and is commonly found in hotter sites, so it may be adapted for warmer temperatures (Clary 1975). Toadflax penstemon at MEVE and overall forbs at BAND had a negative response to AGDD, but field wormwood at BAND had a positive response to increasing AGDD.

The plot-based aridity index (AI) also had mixed effects. With this index, more arid sites have lower AI values. AI had a positive association with muttongrass, blue grama and antelope bitterbrush, i.e., cover of these species was higher on plots that were *less* arid (higher AI). The effect of AI was negative on cactus and opuntia cover indicating cactus and prickly-pear cover was higher at *more* arid sites (lower AI). Forb effects were mixed.

Of the included seasonal deficits, spring climatic water deficit (CWD) had the strongest negative effect on vegetation cover (Figure 40). Overall grass and shrub cover, as well as cover of many of the species modeled, showed reduced cover in response to higher spring water deficit. This is particularly concerning since spring deficits are expected to increase in the coming decades due to anthropogenic climate change (Bradford et al. 2020). Earlier spring onset and earlier spring snowmelt are robust predictions that will increase stress in these grasslands (Bradford et al. 2021). Previous-year deficit also had entirely neutral or negative effects on grass cover in these models.

With one exception, none of the included variables influenced seedling or sapling dynamics in our plots. Climatic controls on seed production, germination and survival and growth of seedlings are understudied (particularly in junipers) but together form a multiyear response that likely depends on combinations of different variables for each stage. Mast seed production has been linked to lag-year water availability and temperature controls (Parmenter 2018), but the climate variables included in our models failed to detect lag year effects on seedlings. The negative effect of spring deficit on pinyon saplings was slight.

The effect of covariates on species richness was mixed across ecosites (Figure 33c). AI had a negative effect on richness at all sites except MEVE L (Figure 33b), indicating higher species richness at more arid sites. Higher winter (BAND P and MEVE L) and spring (GRCA P and MEVE L) deficits also had negative impacts on species richness at three of four ecosites, indicating cooler and wetter winter and spring conditions were favorable to richness in these ecosites. Species richness is positively correlated with increased precipitation in dryland ecosystems (Harrison et al. 2015), and annual and ephemeral forbs exhibit positive responses to cooler wetter springs (Munson et al. 2011).

Thus, it's not surprising that species richness was higher on relatively more humid plots as richness at these sites was largely derived from forbs.

Mixed results of covariate effects may indicate differences between ecosystems in critical timing of deficits, soil textures and depths or other variables. Although more complicated interaction models generally failed to pass model checks and are therefore not presented here, preliminary results did indicate that covariate effects varied in size and direction between ecological sites for some species. Earlier studies showed differences between ecosystems in critical timing of soil moisture (Andrews et al. 2019 a–d). Additional data will allow us to examine interaction effects in the future.

Conclusions

Ecological sites varied in soil characteristics and overstory and understory species composition. Soil surfaces were dominated by duff and litter, except at BAND, where the soil surface was dominated by volcanic gravel in some areas. Overall soil stability was moderately high and did not change or increased slightly during the monitoring period. Of the 337 plant species encountered, only 30 species were common to all four ecosites. Two-hundred species were specific to a single ecological site. Grasses and shrubs composed most of the understory cover overall at all sites. Forb cover was higher at BAND P than the other sites. Exotic species were infrequent, except for cheatgrass, which occurred in over 33% of plots sampled at BAND P and 10% of sampled plots at GRCA P.

The three ecological sites monitored in MEVE and GRCA can be classified as persistent, old growth pinyon-juniper woodlands. These stands have limited understory vegetation, contain very old trees (> 400 years old) and historically had long fire-return intervals. When fire does occur, it tends to be severe and stand replacing (Romme et al. 2009). In contrast, BAND has much lower canopy cover and tree density, younger trees, and a richer and more abundant understory vegetation layer.

Models revealed significant and mostly positive time trends in just over half the life forms and species modeled (i.e., changes over time that were not explained by covariates). Just five responses showed trends that were negative, and these were not common to a single park or response type. Most of the effects were very small. Although these ecosites have experienced extreme drought conditions, in terms of climatic water deficit, dry years have been interspersed with wetter-than-average years at regular intervals during the monitoring period, which may ameliorate the near-term effects of increased drought, along with increased water availability under canopy at the denser overstory sites. It is likely that future conditions will increase changes to the understory and overstory (Flake and Weisberg 2021, Shriver et al. 2022, Noel et al. 2024).

The responses we modeled (i.e., plant cover, richness, seedling density) were influenced somewhat by included covariates, and the direction of those effects were mostly negative. The most consistent effect was that increased spring (April–June) water stress tended to decrease perennial grass cover. Increasing water stress in the spring tended to have negative effects on most responses, which is concerning since predicted earlier snowmelt and higher spring temperatures will almost certainly result in drier springs in the coming decades. Semi-arid woodlands are expected to be highly affected by severe drought driven by robust predictions of increasing temperature ($> 2^{\circ}\text{C}$ in the near-term future) and decreasing soil water availability, especially in the spring season (Andrews et al. 2019 a–c).

Tree mortality results from a complex of factors, including climate, soils, characteristics of individual trees, interactions between trees, and the dynamics of pests and pathogens. Although mortality was limited and seedling and sapling densities showed slight increases in many sites during the monitoring period, predicted increasingly dry conditions may lead to range shifts in the coming decades (Noel et al. 2024).

Management Implications

Overall frequency and cover of nonnative species in monitored plots was low. This is important because introduction of nonnatives, especially annual grasses, can alter fire regimes and increase the risk of stand replacing fires (Balch et al. 2013). Research indicates that old-growth persistent pinyon-juniper woodlands are not well adapted to fire and may not recover pre-fire structure and composition following high-intensity fire (Romme et al. 2009, Phillips et al. 2024). Disturbance is a common vector of introduction of nonnative plants and should be limited as much as possible in these woodland sites. Evidence of trespass livestock use has been observed by field crews at GRCA and MEVE. Trespass livestock generate ground disturbance, introduce nonnative seeds, and selectively graze certain species, which can lead to establishment and spread of nonnative species (Fleischner 1994, Floyd et al. 2003). Road maintenance, fire operations and trail building are other sources of disturbance that can lead to increased presence of nonnative species. At BAND, field crews have seen an increase in cheatgrass (*Bromus tectorum*) throughout the mesa top area in recent years, and, as it spreads, it is increasingly likely to be transported into additional areas of the park by hikers and vehicles. In addition to altering fire regimes, high cover of nonnative plants can increase erosion, decrease species richness, and otherwise degrade the sites.

Although we did not find evidence of significant tree dieback in our plots, overstory trees did experience limited mortality, especially pinyon pine at GRCA P. Climate-related tree mortality is almost certain to increase in the future, particularly for pinyon, and many areas currently suitable for pinyon-juniper woodlands may become unsuitable (Noel et al. 2024). High tree densities in persistent woodlands do not necessarily make stands more susceptible to drought-related die-off, especially for junipers (Floyd et al. 2009, Ganey et al. 2011, Clifford et al. 2011, Flake and Weisberg 2019), and intensive thinning might negatively impact community dynamics and reduce recruitment (Phillips et al. 2024). Therefore, thinning to protect sites from drought-induced mortality is not strongly supported. In addition, tree removal leads to decreased habitat use by mammals (Gallo et al. 2016) and thinning impacts and subsequent uneven stand structure, may reduce habitat quality for birds (Jones et al. in revision). Additionally, the disturbance caused by thinning may introduce invasive species (Shinneman et al. 2023).

Literature Cited

- Adams, D. K., and A. C. Comrie. 1997. The North American Monsoon. *Bulletin of the American Meteorological Society*. 78(10):2197–2214.
- Adler, P. B., and J. M. Levine. 2007. Contrasting relationships between precipitation and species richness in time and space. *Oikos*. 116(2):221–232.
- Andrews, C., J. Bradford, J. Norris, J. Gremer, M. Duniway, S. Munson, L. Thomas, and M. Swan. 2019a. Describing past and future soil moisture in the mesa-top pinyon-juniper woodland ecosystem in Bandelier National Monument. NPS/CHCU/NRR—2019/1998. National Park Service. Fort Collins, Colorado
- Andrews, C., J. Bradford, J. Norris, J. Gremer, M. Duniway, S. Munson, L. Thomas, and M. Swan. 2019b. Describing past and future soil moisture in the pinyon-juniper woodland ecosystem in Grand Canyon National Park. NPS/CHCU/NRR—2019/1998. National Park Service. Fort Collins, Colorado
- Andrews, C., J. Bradford, J. Norris, J. Gremer, M. Duniway, S. Munson, L. Thomas, and M. Swan. 2019c. Describing past and future soil moisture in the loamy mesa-top pinyon-juniper woodland ecosystem in Mesa Verde National Park. NPS/CHCU/NRR—2019/1998. National Park Service. Fort Collins, Colorado
- Andrews, C., J. Bradford, J. Norris, J. Gremer, M. Duniway, S. Munson, L. Thomas, and M. Swan. 2019d. Describing past and future soil moisture in the shallow loamy mesa-top pinyon-juniper woodland ecosystem in Mesa Verde National Park. NPS/CHCU/NRR—2019/1998. National Park Service. Fort Collins, Colorado
- Balch, J. K., B. A. Bradley, C. M. D’Antonio, and J. Gómez-Dans. 2013. Introduced annual grass increases regional fire activity across the arid western USA (1980–2009). *Global Change Biology*, 19: 173–183. <https://doi.org/10.1111/gcb.12046>
- Bradford, J., D. Schlaepfer, W. Lauenroth, and K. Palmquist. 2020. Robust ecological drought projections for drylands in the 21st century. *Global Change Biology* 26:3906–3919. doi: 10.1111/gcb.15075
- Bradford, J. B., D. R. Schlaepfer, W. K. Lauenroth, K. A. Palmquist, J. C. Chambers, J. D. Maestas and S. B. Campbell. 2021. Climate-driven shifts in soil temperature and moisture regimes suggest opportunities to enhance assessments of dryland resilience and resistance. *Global Change Biology*. 28(17):5086–5103. doi: 10.1111/gcb.16270
- Belnap, J. S., L. Phillips, D. L. Witwicki, and M. E. Miller. 2008. Visually assessing the level of development and soil surface stability of cyanobacterially dominated biological soil crusts. *Journal of Arid Environments* 72:1257–1264.

- BirdLife International. 2020. *Gymnorhinus cyanocephalus*. *The IUCN Red List of Threatened Species* 2020: e.T22705608A179592026. <https://dx.doi.org/10.2305/IUCN.UK.2020-3.RLTS.T22705608A179592026.en>. Accessed on 24 February 2025.
- Breshears, D. D., O. B. Myers, C. W. Meyer, F. J. Barnes, C. B. Zou, C. D. Allen, N. G. McDowell, and W. T. Pockman. 2009. Tree die-off in response to global change-type drought: mortality insights from a decade of plant water potential measurements. *Frontiers in Ecology and the Environment*, 7: 185–189. <https://doi.org/10.1890/080016>
- Byrne, R., and J. McAndrews. 1975. Pre-Columbian purslane (*Portulaca oleracea* L) in the New World. *Nature* 253:726–727. <https://doi.org/10.1038/253726a0>
- Clary, W. P. 1975. Ecotypic adaptation in *Sitanion hystrix*. *Ecology*. 56(6): 1407–1415.
- Clifford, M. J., N. S. Cobb, and M. Buenemann. 2011. Long-term tree cover dynamics in a pinyon-juniper woodland: climate-change-type drought resets successional clock. *Ecosystems* 14:949–962. <https://doi.org/10.1007/s10021-011-9458-2>
- Bhattacharya, T. 2022. An energetic perspective on the Holocene North American Monsoon. *Geophysical Research Letters*. 49:19. e2022GL100782
- Caudle, D., J. DiBenedetto, M. S. Karl, H. Sanchez, and C. Talbot. 2013. Interagency Ecological Site Handbook for Rangelands. U.S. Department of the Interior, Bureau of Land Management: U.S. Department of Agriculture, Forest Service: U.S. Department of Agriculture, Natural Resources Conservation Service.
- Chambers, J.C., Schupp, E.W., Wall, S.B.V., 1999. Seed dispersal and seedling establishment of pinon and juniper species within the pinon-juniper woodland. In S. B. Monsen et al. (eds.), *Proceedings: ecology and management of pinyon-juniper communities within the interior west*. General Technical Report RM-000. U.S.D.A. Forest Service, Rocky Mountain Research Station, Ogden, Utah.
- Comstock, J. P., and J. R. Ehleringer. 1992. Plant adaptation in the Great Basin and Colorado Plateau. *Great Basin Naturalist* 52(3):195–215.
- DeCoster, J. K., C. L. Lauver, M. E. Miller, J. R. Norris, A. E. C. Snyder, M. C. Swan, L. P. Thomas, and D. L. Witwicki. 2012. Integrated upland monitoring protocol for the Southern Colorado Plateau Network. Natural Resource Report. NPS/SCPN/NRR–2012/577. National Park Service. Fort Collins, Colorado.
- de Dios Miranda, J., F. M. Padilla, R. Lázaro, and F. I. Pugnaire. 2009. Do changes in rainfall patterns affect semiarid annual plant communities? *Journal of Vegetation Science*, 20(2):269–276.

- Endress, B. A., J.P. Averett, S. Steinmetz, and E. J. Quaempts. 2022. Forgotten forbs: Standard vegetation surveys underrepresent ecologically and culturally important forbs in a threatened grassland ecosystem. *Conservation Science and Practice*, 4(10), e12813. <https://doi.org/10.1111/csp2.12813>
- Finger-Higgins, R., T. B. Bishop, J. Belnap, E. L. Geiger, E. E. Grote, D. L. Hoover, S. C. Reed, M. C. Duniway. 2023. Droughting a megadrought: Ecological consequences of a decade of experimental drought atop aridification on the Colorado Plateau *Global Change Biology*. 29(12): 3235–3515.
- Flake, S. W. and P. J. Weisberg. 2019. Fine-scale stand structure mediates drought-induced tree mortality in pinyon–juniper woodlands. *Ecological Applications* 29(2):e01831. [10.1002/eap.1831](https://doi.org/10.1002/eap.1831)
- Flake, S. W. and P. J. Weisberg. 2021. Drought alters the understory of pinyon-juniper woodlands indirectly through tree dieback. *Rangeland Ecology & Management*, 76:118–128. <https://doi.org/10.1016/j.rama.2021.02.007>
- Fleischner, T. L. 1994. Ecological costs of livestock grazing in Western North America. *Conservation Biology*. 8: 629–644.
- Floyd, M. L. (Ed.), 2003. *Ancient Pinon–Juniper Woodlands: A Natural History of Mesa Verde Country*. University Press of Colorado, Boulder, Colorado.
- Floyd, M. L., D. Hanna, and W. H Romme. 2004. Historical and recent fire regimes in piñon–juniper woodlands on Mesa Verde, Colorado, USA. *Forest Ecology and Management* 198(1–3): 269–89. <https://doi.org/10.1016/j.foreco.2004.04.006>
- Floyd, M. L., M. Clifford, N. S. Cobb, D. Hanna, R. Delph, P. Ford, and D. Turner. 2009. Relationship of stand characteristics to drought-induced mortality in three Southwestern piñon–juniper woodlands. *Ecological Applications*, 19: 1223–1230. <https://doi.org/10.1890/08-1265.1>
- Floyd, M. L., and W. H. Romme. 2012. Ecological restoration priorities and opportunities in piñon–juniper woodlands. *Ecological Restoration* 30(1):37–49. <https://doi.org/10.3368/er.30.1.37>
- Ganey, J. L., J. M. Iniguez,, S. C. Vojta, and A. R. Iniguez. 2021. Twenty years of drought-mediated change in snag populations in mixed-conifer and ponderosa pine forests in Northern Arizona. *Forest Ecosystems* 8(20). <https://doi.org/10.1186/s40663-021-00298-9>
- Gallo, T., L. T. Stinson, L. Pejchar. Pinyon-juniper removal has long-term effects on mammals. 2016. *Forest Ecology and Management*. 377: 93–100. <https://doi.org/10.1016/j.foreco.2016.06.029>
- Gelman, A., and D. B. Rubin. 1992. Inference from iterative simulation using multiple sequences. *Statistical Science* 7:457–511.

- Gremer, J. R., C. Andrews, J. R. Norris, L. P. Thomas, S. M. Munson, M.C. Duniway, and J.B. Bradford. 2018. Increasing temperature seasonality may overwhelm shifts in soil moisture to favor shrub over grass dominance in Colorado Plateau drylands. *Oecologia* 188:1195–1207.
- Harrison, S. P., E. S. Gornish, and S. Copeland. 2015. Climate-driven diversity loss in a grassland community. *The Proceedings of the National Academy of Sciences*. 11(28)8672–8677.
- Hartsell, J. A., S. M. Copeland, S. M. Munson, B. J. Butterfield, J. B. Bradford. 2020. Gaps and hotspots in the state of knowledge of pinyon-juniper communities. *Forest Ecology and Management*. 455. <https://doi.org/10.1016/j.foreco.2019.117628>
- Herpigny, B., and F. Gosselin. 2015. Analyzing plant cover class data quantitatively: Customized zero-inflated cumulative beta distributions show promising results. *Ecological Informatics* 26:18–26.
- Herrick, J. E., J. W. Van Zee, K. M. Havstad, L. M. Burkett, and W.G. Whitford. 2009. *Monitoring Manual for Grassland, Shrubland and Savanna Ecosystems*. USDA-ARS Jornada Experimental Range.
- Hobbs, N. T., and M. B. Hooten. 2015. *Bayesian models: A statistical primer for ecologists*. Princeton University Press, Princeton New Jersey, USA.
- Hoover, D. L., M. C. Duniway, and J. Belnap. 2015. Pulse-drought atop press-drought: Unexpected plant responses and implications for dryland ecosystems. *Oecologia*, 179(4):1211–1221.
- Harris, T., Z. Yang, and J. W. Hardin. 2012. Modeling Underdispersed count data with generalized Poisson regression. *The Stata Journal*, 12(4):736–747.
- IPCC, 2022: *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp.
- Irvine, K. M., T. J. Rodhouse, and I. N. Keren. 2016. Extending ordinal regression with a latent zero-augmented beta distribution. *Journal of Agricultural, Biological and Environmental Statistics* 21 (4): 619–40. <https://doi.org/10.1007/s13253-016-0265-2>
- Ji, W., N. P. Hanan, D. M. Browning, H. C. Monger, D. P. C. Peters, B. T. Bestelmeyer, S. R. Archer, C. W. Ross, B. M. Lind, J. Anchang, S. S. Kumar and L. Prihodko. 2019. Constraints on shrub cover and shrub–shrubs competition in a U.S. Southwest desert.” *Ecosphere* 10 (2): e02590. <https://doi.org/10.1002/ecs2.2590>

- Jones, H, B Merriell, M Swan, M Johnson, R Siegel. In revision. Using structural and floristic microhabitat associations in Southwestern pinyon-juniper woodlands to understand effects of thinning and tree mortality on bird habitat suitability. *Avian Conservation and Ecology*.
- Lynch, H., J. Thorson, and A. Shelton. 2014. Dealing with Under- and over-Dispersed Count Data in Life History, Spatial, and Community Ecology. *Ecology* 95:3173–80. <https://doi.org/10.1890/13-1912.1>
- McCune, B. and D. Keon. 2002. Equations for potential annual direct incident radiation and heat load. *Journal of Vegetation Science*. 13: 603–606. <https://doi.org/10.1111/j.1654-1103.2002.tb02087.x>
- McMaster, G. S., and W. W. Wilhelm. 1997. Growing degree-days: One equation, two interpretations. *Agricultural and Forest Meteorology* 87 (4): 291–300. [https://doi.org/10.1016/S0168-1923\(97\)00027-0](https://doi.org/10.1016/S0168-1923(97)00027-0)
- Meddens, A. J. H., J. A. Hicke, B. F. Jacobs. 2016. Characterizing the Response of piñon-juniper woodlands to mechanical restoration using high-resolution satellite imagery. *Rangeland Ecology & Management*. 69(3): 215–223. <https://doi.org/10.1016/j.rama.2015.12.006>
- Munson, S.M., R.H. Webb, and J.A. Hubbard. 2011. A comparison of methods to assess long-term changes in Sonoran Desert vegetation. *Journal of Arid Environments* 75 (11): 1228–31. <https://doi.org/10.1016/j.jaridenv.2011.04.032>
- Noel, A. R., D. R. Schlaepfer, B. J. Butterfield, M. C. Swan, J. Norris, K. Hartwig, M. C. Duniway, J. B. Bradford. 2024. Most pinyon-juniper woodland species distributions are projected to shrink rather than shift under climate change. *Rangeland Ecology and Management*. 10.1016/j.rama.2024.09.002.
- Noy-Meir, I. 1979. Structure and function of desert ecosystems. *Israel Journal of Botany*, 28(1): 1–19. <https://www.tandfonline.com/doi/abs/10.1080/0021213X.1979.10676851>
- Parmenter, R.R., Zlotin, R.I., Moore, D.I., Myers, O.B., 2018. Environmental and endogenous drivers of tree mast production and synchrony in piñon–juniper–oak woodlands of New Mexico. *Ecosphere* 9, e02360. <https://doi.org/10.1002/ecs2.2360>
- Phillips, M. L., C. Lauria, T. Spector, J. B. Bradford, C. Gehring, B. B. Osborne, A. Howell, E. E. Grote, R. J. Rondeau, G. M. Trimber, B. Robinson, and S. C. Reed. 2024. Trajectories and tipping points of piñon–juniper woodlands after fire and thinning. *Global Change Biology*, 30, e17149. <https://doi.org/10.1111/gcb.17149>
- Plummer M. 2022. *_rjags: Bayesian Graphical Models using MCMC_*. R package version 4-13, <https://CRAN.R-project.org/package=rjags>

PRISM Climate Group, Oregon State University, <https://prism.oregonstate.edu>, data created 4 Feb 2014, accessed 14 September 2023.

R Core Team. 2023. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>

Romme, W. H., C. D. Allen, J. D. Bailey, W. L. Baker, B. T. Bestelmeyer, P. M. Brown, K. S. Eisenhart, M. L. Floyd, D. W. Huffman, B. F. Jacobs, R. F. Miller, E. H. Muldavin, T. W. Swetnam, R. J. Tausch, and P. J. Weisberg. 2009. Historical and Modern Disturbance Regimes, Stand Structures, and Landscape Dynamics in Piñon–Juniper Vegetation of the Western United States. *Rangeland Ecology & Management* 62(3): 203–222. <https://doi.org/10.2111/08-188R1.1>

Royer, P. D., D. D. Breshears, C. B. Zou, J. C. Villegas, N. S. Cobb, S. A. Kurc. 2012. Density-Dependent Ecohydrological Effects of Piñon–Juniper Woody Canopy Cover on Soil Microclimate and Potential Soil Evaporation. *Rangeland Ecology & Management* 65: 11–20. <https://doi.org/10.2111/REM-D-11-00007.1>

Schoeneberger, P. J., D. A. Wysocki, E. C. Benham, and Soil Survey Staff. 2012. Field book for describing and sampling soils, Version 3.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Schwinning, S. and J. R. Ehleringer. 2001. Water use trade-offs and optimal adaptations to pulse-driven arid ecosystems. *Journal of Ecology* 89: 464–480. <https://doi.org/10.1046/j.1365-2745.2001.00576.x>

Shinneman, D. J., McIlroy, S. K., Poessel, S. A., Johnson, T. N., Downing, R. L., Young, A. C., and Katzner, T. E., 2023, Ecological effects of pinyon-juniper removal in the western United States—a synthesis of scientific research, January 2014–March 2021: U.S. Geological Survey Open-File Report 2023-1041. 56 p. <https://doi.org/10.3133/ofr20231041>

Shriver, R. K., C. B. Yackulic, D. M. Bell, and J. B. Bradford. 2022. Dry forest decline is driven by both declining recruitment and increasing mortality in response to warm, dry conditions. *Global Ecology and Biogeography*, 31, 2259–2269. <https://doi.org/10.1111/geb.13582>

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at <https://websoilsurvey.nrcs.usda.gov/>. Accessed 2007–2012.

Stage, A.R. 1976. An expression for the effect of aspect, slope, and habitat type on tree growth. *Forest Science* 22(4):457–460.

Stephenson, N. L. 1998. Actual evapotranspiration and deficit: biologically meaningful correlates of vegetation distribution across spatial scales. *Journal of Biogeography* 25: 855–870.

Stevens, D. L., and A. R. Olsen. 2004. Spatially balanced sampling of natural resources. *Journal of the American Statistical Association*, 99(465) :262–278.

- Swan MC. 2024. Site characterization and change over time in semi-arid grassland and shrublands at three parks—Chaco Culture National Historic Park, Petrified Forest National Park, and Wupatki National Monument: Upland vegetation and soils monitoring 2007–2021. Natural Resource Report. NPS/SCPN/NRR—2024/2616. National Park Service. Fort Collins, Colorado.
<https://doi.org/10.36967/2301582>
- Tercek, M. T., D. Thoma, J. E. Gross, K. Sherrill, S. Kagone, and G. Senay. 2021. Historical changes in plant water use and need in the Continental United States. PLOS ONE 16 (9): e0256586.
<https://doi.org/10.1371/journal.pone.0256586>
- Thoma D. P., M. T. Tercek, E. W. Schweiger, S. M. Munson, J. E. Gross, and S. T. Olliff. 2020. Water Balance as an indicator of natural resource condition: Case studies from Great Sand Dunes National Park and Preserve. Global Ecology and Conservation 24 e01300.
- Thomas L.P., M. N. Hendrie, C. L. Lauver, S. A. Monroe, N. J. Tancreto, S. L. Garman, M. E. Miller. 2006. Vital signs monitoring plan for the Southern Colorado Plateau Network. Natural Resource Report. NPS/SCPN/NRR—2006/002. National Park Service. Fort Collins, Colorado
- Thornton, P. E., M. M. Thornton, B. W. Mayer, Y. Wei, R. Devarakonda, R. S. Vose, and R. B. Cook. 2016. Daymet: Daily Surface Weather Data on a 1-km Grid for North America, Version 3. ORNL DAAC, Oak Ridge, Tennessee, USA.
- Trabucco, A., and R. Zomer. 2019. Global Aridity Index and Potential Evapotranspiration (ET0) Climate Database v2. figshare. Dataset. <https://doi.org/10.6084/m9.figshare.7504448.v3>
- USDA, NRCS. 2023. The PLANTS Database (<http://plants.usda.gov>, accessed 2/02/2023). National Plant Data Team, Greensboro, NC USA.
- Van Auken, O.W., Jackson, J.T., Jurena, P.N., 2004. Survival and growth of Juniperus seedlings in Juniperus woodlands. Plant Ecology 175:245–257.
- Wang, J.Y. (1960), A critique of the heat unit approach to plant response studies. Ecology, 41: 785–790. <https://doi.org/10.2307/1931815>
- Wickham, H. 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.
- Williams, A. P., B. I. Cook, and J. E. Smerdon. 2022. Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. Nature. Climate Change 12: 232–234.
<https://doi.org/10.1038/s41558-022-01290-z>
- Whipple, A.V., Cobb, N.S., Gehring, C.A., Mopper, S., Flores-Rentería, L., Whitham, T.G., 2019. Long-term studies reveal differential responses to climate change for trees under soil- or herbivore-related Stress. Frontiers in Plant Science. 10:132.
<https://doi.org/10.3389/fpls.2019.00132>

Zachmann, L. J., E. M. Borgman, D. L. Witwicki, M. S. Swan, and C. McIntyre. 2021. Bayesian models for analysis of inventory and monitoring data with non-ignorable missingness. *Journal of Agricultural, Biological, and Environmental Statistics* 27, 125–148 (2022).
<https://doi.org/10.1007/s13253-021-00473-z>

Appendix A: Plot Sampling History

Figures 41 and 42 show the years each plot was sampled from 2007 to 2022.

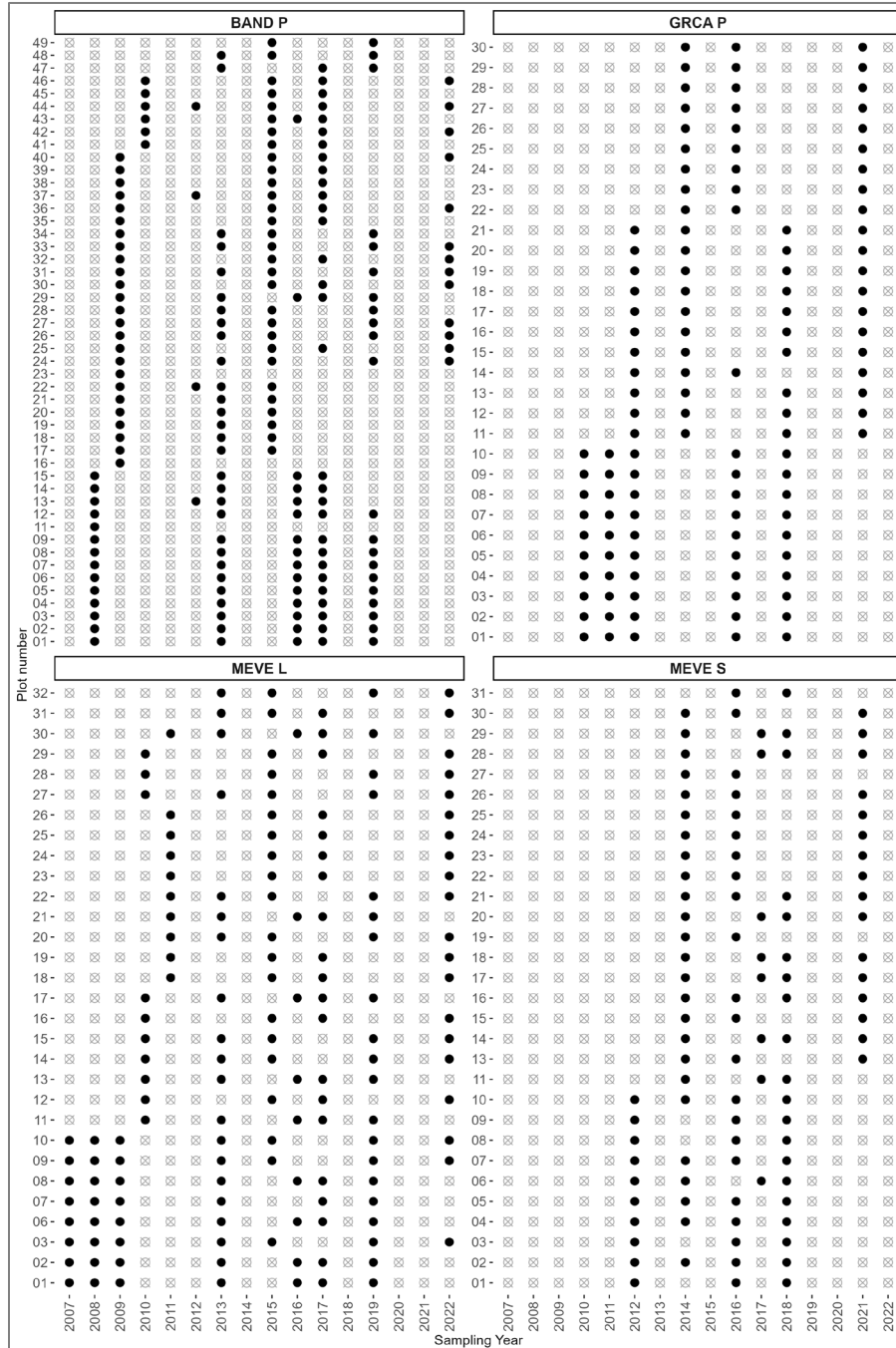


Figure 41. Plot sampling history at four ecosites in three National Parks (BAND, GRCA, MEVE). Plot numbers are provided on y-axes, sampling year on x-axes, and black dots indicate plot was sampled during a year. Data from 2007 was dropped from analysis since only one site was sampled that year. These data are provided in tabular form in Appendix E, [Table 18](#).

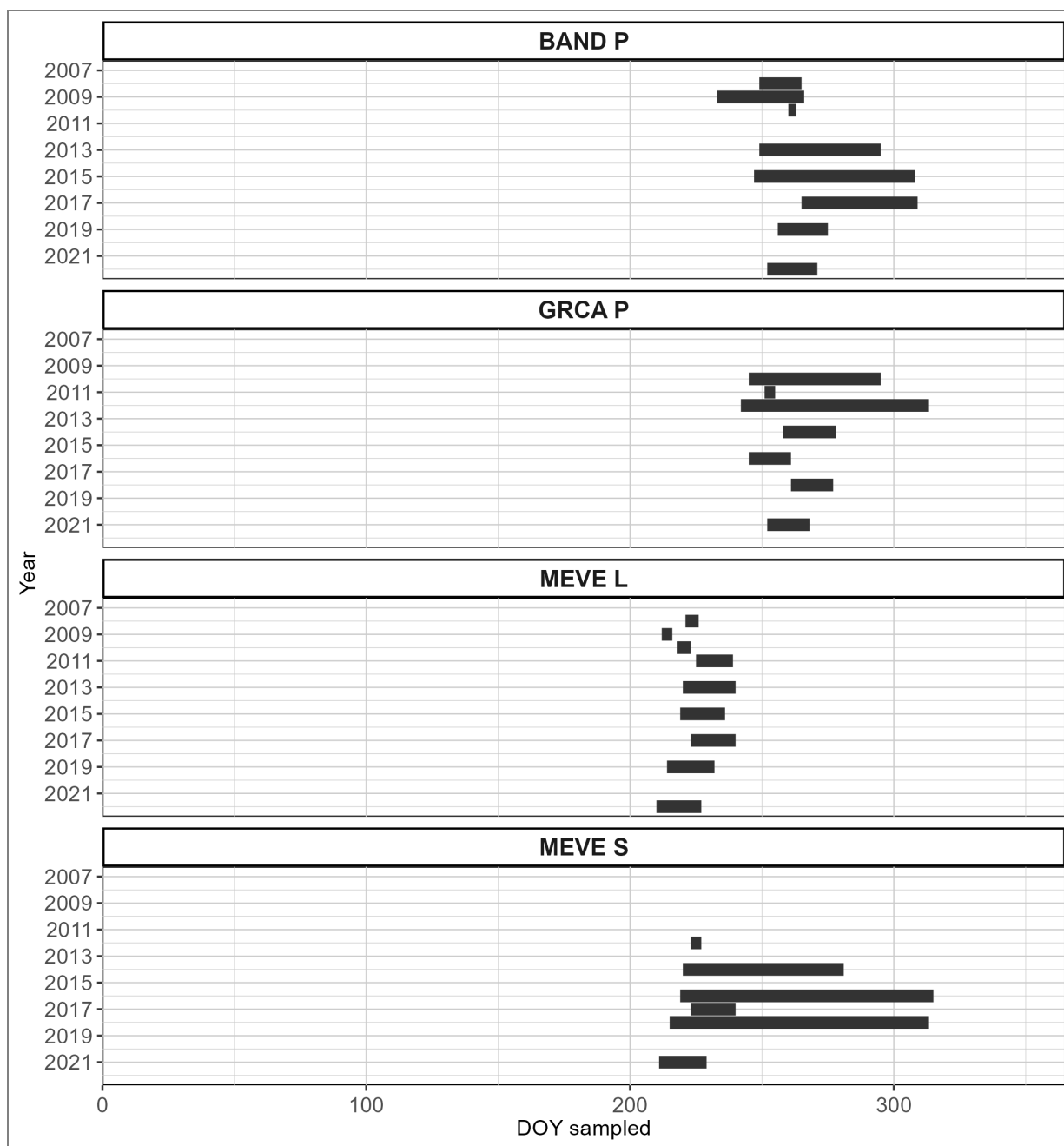


Figure 42. Plot sampling intervals at four ecosites in three National Parks (BAND, GRCA, MEVE). Segment indicates sampling interval (start day of year (DOY) to end DOY). Extended sampling periods indicate revisits to complete plots that weren't completed during the initial visit.

NPS / MEGAN SWAN

Appendix B: Vascular Plant Species Detected at Pinyon Juniper Ecological Sites (2008–2022)

Table 13 presents lists of species that were detected during sampling, and each species' percent quadrat frequency in each ecological site reported.

Table 13. List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022. Lifeform abbreviations include (F = forb, G = graminoid, S = shrub, C = cactus or succulent, V = vine). Nativity (N = native, NN = nonnative), N/A = not applicable for group species, and NP (Not Present) indicates species did not occur in ecological site. Lifeform and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>, accessed Jan 15, 2024).

Family	Species	Lifeform	Nativity	Duration	BAND P	GRCA P	MEVE L	MEVE S
Amaranthaceae	<i>Amaranthus</i> spp.	F	N/A	N/A	16.61	1.53	NP	NP
Amaranthaceae	<i>Atriplex canescens</i>	S	P	N	0.23	NP	NP	NP
Amaranthaceae	<i>Chenopodium album</i>	F	A	NN	NP	NP	1.06	0.15
Amaranthaceae	<i>Chenopodium fremontii</i>	F	A	N	NP	0.24	NP	2
Amaranthaceae	<i>Chenopodium leptophyllum</i>	F	A	N	NP	0.06	NP	NP
Amaranthaceae	<i>Chenopodium</i> spp.	F	N/A	N/A	39.55	0.06	8.55	0.3
Amaranthaceae	<i>Dysphania graveolens</i>	F	A	N	16.58	10.63	NP	NP
Amaranthaceae	<i>Kochia scoparia</i>	F	A	NN	0.35	NP	NP	NP
Amaranthaceae	<i>Krascheninnikovia lanata</i>	S	P	N	NP	NP	0.22	0.22
Amaranthaceae	<i>Salsola collina</i>	F	A	NN	1.09	NP	NP	NP
Amaranthaceae	<i>Salsola tragus</i>	F	A	NN	0.65	0.04	0.56	0.07
Amaryllidaceae	<i>Allium cernuum</i>	F	P	N	NP	0.09	NP	NP
Anacardiaceae	<i>Rhus aromatica</i>	S	P	N	7.26	NP	NP	NP
Apiaceae	<i>Cymopterus</i> spp.	F	N/A	N/A	NP	NP	NP	0.07
Apiaceae	<i>Lomatium</i> spp.	F	N/A	N/A	NP	NP	NP	0.56
Apiaceae	<i>Pseudocymopterus montanus</i>	F	P	N	NP	NP	0.11	NP
Apocynaceae	<i>Asclepias</i> spp.	F	N/A	N/A	0.22	NP	NP	NP

Table 13 (continued). List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022. Lifeform abbreviations include (F = forb, G = graminoid, S = shrub, C = cactus or succulent, V = vine). Nativity (N = native, NN = nonnative), N/A = not applicable for group species, and NP (Not Present) indicates species did not occur in ecological site. Lifeform and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>, accessed Jan 15, 2024).

Family	Species	Lifeform	Nativity	Duration	BAND P	GRCA P	MEVE L	MEVE S
Apocynaceae	<i>Asclepias subverticillata</i>	F	P	N	NP	0.37	NP	NP
Asparagaceae	<i>Yucca angustissima</i>	C	P	N	0.96	NP	0.09	NP
Asparagaceae	<i>Yucca baccata</i>	C	P	N	3.7	7.23	20.6	23.22
Asteraceae	<i>Agoseris glauca</i>	F	P	N	0.15	NP	NP	NP
Asteraceae	<i>Amauriopsis dissecta</i>	F	P	N	64.02	1.11	NP	NP
Asteraceae	<i>Antennaria marginata</i>	F	P	N	NP	NP	0.04	NP
Asteraceae	<i>Antennaria parvifolia</i>	F	P	N	0.04	NP	0.36	0.22
Asteraceae	<i>Artemisia bigelovii</i>	S	P	N	NP	NP	4.19	1.48
Asteraceae	<i>Artemisia campestris</i>	F	P	N	34.67	NP	NP	NP
Asteraceae	<i>Artemisia carruthii</i>	F	P	N	16.53	NP	NP	NP
Asteraceae	<i>Artemisia dracunculus</i>	F	P	N	14.37	NP	NP	NP
Asteraceae	<i>Artemisia frigida</i>	F	P	N	0.61	NP	NP	NP
Asteraceae	<i>Artemisia ludoviciana</i>	F	P	N	7.09	1.33	NP	0.3
Asteraceae	<i>Artemisia tridentata</i>	S	P	N	NP	37.84	3.72	2.04
Asteraceae	<i>Balsamorhiza sagittata</i>	F	P	N	NP	NP	NP	2.81
Asteraceae	<i>Brickellia brachyphylla</i>	F	P	N	0.07	NP	NP	NP
Asteraceae	<i>Brickellia californica</i>	S	P	N	0.19	0.44	NP	NP
Asteraceae	<i>Brickellia eupatorioides</i>	S	P	N	5.33	NP	NP	NP
Asteraceae	<i>Brickellia</i> spp.	N/A	P	N/A	0.74	NP	NP	NP
Asteraceae	<i>Brickelliastrum fendleri</i>	F	P	N	0.26	NP	NP	NP
Asteraceae	<i>Carduus nutans</i>	F	P	NN	NP	NP	0.91	0.3
Asteraceae	<i>Centaurea diffusa</i>	F	A	NN	0.04	NP	NP	NP
Asteraceae	<i>Chaenactis douglasii</i>	F	P	N	NP	NP	1.07	1.15

Table 13 (continued). List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022. Lifeform abbreviations include (F = forb, G = graminoid, S = shrub, C = cactus or succulent, V = vine). Nativity (N = native, NN = nonnative), N/A = not applicable for group species, and NP (Not Present) indicates species did not occur in ecological site. Lifeform and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>, accessed Jan 15, 2024).

Family	Species	Lifeform	Nativity	Duration	BAND P	GRCA P	MEVE L	MEVE S
Asteraceae	<i>Chaetopappa ericoides</i>	F	P	N	0.4	3.2	0.17	0.37
Asteraceae	<i>Chrysothamnus depressus</i>	S	P	N	NP	2.62	10.39	2.59
Asteraceae	<i>Cirsium neomexicanum</i>	F	P	N	1.61	NP	NP	NP
Asteraceae	<i>Cirsium</i> spp.	F	N/A	N/A	0.22	NP	NP	0.37
Asteraceae	<i>Cirsium wheeleri</i>	F	P	N	NP	0.74	NP	NP
Asteraceae	<i>Conyza canadensis</i>	F	A	N	0.78	NP	0.11	NP
Asteraceae	<i>Dieteria</i> spp.	F	N/A	N/A	5.22	NP	12.42	7.33
Asteraceae	<i>Ericameria nauseosa</i>	S	P	N	0.38	1.1	0.17	NP
Asteraceae	<i>Erigeron concinnus</i>	F	P	N	NP	7.96	NP	NP
Asteraceae	<i>Erigeron divergens</i>	F	P	N	15.15	12.77	2.83	1.15
Asteraceae	<i>Erigeron flagellaris</i>	F	P	N	1.48	4.25	0.25	1.89
Asteraceae	<i>Erigeron formosissimus</i>	F	P	N	NP	0.09	NP	NP
Asteraceae	<i>Erigeron speciosus</i>	F	P	N	NP	NP	NP	0.89
Asteraceae	<i>Erigeron</i> spp.	F	N/A	N/A	0.07	0.22	NP	0.26
Asteraceae	<i>Gutierrezia sarothrae</i>	S	P	N	50.67	42.01	0.77	0.52
Asteraceae	<i>Helianthus annuus</i>	F	A	N	12.84	NP	NP	NP
Asteraceae	<i>Heliomeris multiflora</i>	F	P	N	1.36	NP	0.22	NP
Asteraceae	<i>Heterotheca villosa</i>	F	P	N	7.78	0.97	0.41	4.67
Asteraceae	<i>Hymenopappus filifolius</i>	F	P	N	6.04	11.09	0.28	0.41
Asteraceae	<i>Hymenoxys bigelovii</i>	F	P	N	NP	NP	NP	0.15
Asteraceae	<i>Hymenoxys richardsonii</i>	F	P	N	1.89	0.47	0.11	0.74
Asteraceae	<i>Hymenoxys</i> spp.	F	N/A	N/A	NP	NP	0.06	NP
Asteraceae	<i>Lactuca serriola</i>	F	A	NN	2.33	NP	3.97	0.07

Table 13 (continued). List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022. Lifeform abbreviations include (F = forb, G = graminoid, S = shrub, C = cactus or succulent, V = vine). Nativity (N = native, NN = nonnative), N/A = not applicable for group species, and NP (Not Present) indicates species did not occur in ecological site. Lifeform and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>, accessed Jan 15, 2024).

Family	Species	Lifeform	Nativity	Duration	BAND P	GRCA P	MEVE L	MEVE S
Asteraceae	<i>Liatris punctata</i>	F	P	N	0.36	NP	NP	NP
Asteraceae	<i>Machaeranthera tanacetifolia</i>	F	A	N	NP	0.34	NP	NP
Asteraceae	<i>Packera fendleri</i>	F	P	N	NP	NP	NP	0.15
Asteraceae	<i>Packera multilobata</i>	F	A	N	NP	6.93	0.42	1.85
Asteraceae	<i>Packera neomexicana</i>	F	P	N	NP	4.31	0.31	0.41
Asteraceae	<i>Packera</i> spp.	F	N/A	N/A	NP	0.99	0.04	NP
Asteraceae	<i>Pectis angustifolia</i>	F	A	N	0.29	NP	NP	NP
Asteraceae	<i>Petradoria pumila</i>	F	P	N	NP	NP	24.56	20.37
Asteraceae	<i>Pseudognaphalium macounii</i>	F	A	N	NP	0.11	NP	NP
Asteraceae	<i>Psilostrophe sparsiflora</i>	F	P	N	NP	0.22	NP	NP
Asteraceae	<i>Sanvitalia abertii</i>	F	A	N	NP	6.84	NP	NP
Asteraceae	<i>Schkuhria multiflora</i>	F	A	N	NP	1.89	NP	NP
Asteraceae	<i>Senecio eremophilus</i>	F	P	N	0.05	NP	NP	NP
Asteraceae	<i>Senecio flaccidus</i>	F	P	N	1.75	NP	NP	NP
Asteraceae	<i>Senecio spartioides</i>	F	P	N	9.57	NP	NP	NP
Asteraceae	<i>Solidago</i> spp.	F	N/A	N/A	0.04	NP	NP	NP
Asteraceae	<i>Stenotus armerioides</i>	F	P	N	NP	NP	NP	9.52
Asteraceae	<i>Stephanomeria pauciflora</i>	F	P	N	1.99	NP	NP	NP
Asteraceae	<i>Stephanomeria</i> spp.	F	P	N/A	NP	0.22	NP	NP
Asteraceae	<i>Taraxacum officinale</i>	F	P	NN	0.14	NP	0.07	NP
Asteraceae	<i>Tetraneuris acaulis</i>	F	P	N	NP	1.64	NP	NP
Asteraceae	<i>Tetraneuris ivesiana</i>	F	P	N	1.83	NP	0.33	3.81
Asteraceae	<i>Thelesperma filifolium</i>	F	A	N	9.84	NP	NP	NP

Table 13 (continued). List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022. Lifeform abbreviations include (F = forb, G = graminoid, S = shrub, C = cactus or succulent, V = vine). Nativity (N = native, NN = nonnative), N/A = not applicable for group species, and NP (Not Present) indicates species did not occur in ecological site. Lifeform and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>, accessed Jan 15, 2024).

Family	Species	Lifeform	Nativity	Duration	BAND P	GRCA P	MEVE L	MEVE S
Asteraceae	<i>Thelesperma megapotamicum</i>	F	P	N	0.09	NP	NP	NP
Asteraceae	<i>Townsendia eximia</i>	F	P	N	0.6	NP	NP	NP
Asteraceae	<i>Townsendia exscapa</i>	F	P	N	NP	NP	NP	1.96
Asteraceae	<i>Townsendia incana</i>	F	A	N	NP	2.61	0.16	0.44
Asteraceae	<i>Tragopogon dubius</i>	F	P	NN	3.41	NP	0.25	NP
Asteraceae	<i>Xanthisma gracile</i>	F	A	N	0.79	1.49	NP	0.11
Berberidaceae	<i>Berberis fremontii</i>	S	P	N	NP	2.42	NP	NP
Berberidaceae	<i>Berberis repens</i>	S	P	N	0.07	NP	0.17	NP
Boraginaceae	<i>Cryptantha bakeri</i>	F	P	N	NP	NP	0.72	6.15
Boraginaceae	<i>Cryptantha cinerea</i>	F	P	N	17.6	NP	NP	NP
Boraginaceae	<i>Cryptantha crassisejala</i>	F	A	N	0.45	NP	NP	NP
Boraginaceae	<i>Cryptantha</i> spp.	F	N/A	N/A	0.98	1.11	0.44	1.56
Boraginaceae	<i>Lappula occidentalis</i>	F	A	N	14.79	1.71	0.81	1.7
Boraginaceae	<i>Lithospermum incisum</i>	F	P	N	1.04	NP	0.17	0.22
Boraginaceae	<i>Lithospermum multiflorum</i>	F	P	N	0.07	NP	0.22	0.37
Boraginaceae	<i>Nama dichotoma</i>	F	A	N	14.95	26.93	NP	NP
Boraginaceae	<i>Phacelia</i> spp.	F	N/A	N/A	0.73	NP	NP	NP
Brassicaceae	<i>Alyssum desertorum</i>	F	A	NN	NP	NP	NP	0.15
Brassicaceae	<i>Alyssum simplex</i>	F	A	NN	NP	NP	NP	0.22
Brassicaceae	<i>Arabis</i> spp.	F	N/A	N/A	0.4	0.81	NP	NP
Brassicaceae	<i>Boechera</i> spp.	F	N/A	N/A	1.02	17.58	13.78	27.56
Brassicaceae	<i>Descurainia pinnata</i>	F	A	N	6.04	6.2	1.36	1.63
Brassicaceae	<i>Descurainia sophia</i>	F	A	NN	NP	NP	0.7	NP

Table 13 (continued). List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022. Lifeform abbreviations include (F = forb, G = graminoid, S = shrub, C = cactus or succulent, V = vine). Nativity (N = native, NN = nonnative), N/A = not applicable for group species, and NP (Not Present) indicates species did not occur in ecological site. Lifeform and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>, accessed Jan 15, 2024).

Family	Species	Lifeform	Nativity	Duration	BAND P	GRCA P	MEVE L	MEVE S
Brassicaceae	<i>Draba cuneifolia</i>	F	A	N	NP	21.72	NP	NP
Brassicaceae	<i>Draba</i> spp.	F	N/A	N/A	NP	NP	3.92	13.89
Brassicaceae	<i>Erysimum capitatum</i>	F	P	N	5.86	NP	0.89	3.44
Brassicaceae	<i>Hesperidanthus linearifolius</i>	F	P	N	2.13	NP	1.46	7.07
Brassicaceae	<i>Lepidium latifolium</i>	F	P	NN	NP	NP	0.24	NP
Brassicaceae	<i>Lepidium</i> spp.	F	N/A	N/A	0.3	NP	NP	0.07
Brassicaceae	<i>Noccaea fendleri</i>	F	P	N	0.05	4.17	0.04	NP
Brassicaceae	<i>Physaria acutifolia</i>	F	P	N	NP	NP	0.28	3.89
Brassicaceae	<i>Physaria intermedia</i>	F	P	N	NP	16.85	NP	NP
Brassicaceae	<i>Physaria newberryi</i>	F	P	N	NP	NP	NP	4.11
Brassicaceae	<i>Physaria rectipes</i>	F	P	N	NP	NP	5.95	29.33
Brassicaceae	<i>Sisymbrium altissimum</i>	F	A	NN	3.84	NP	0.86	0.22
Brassicaceae	<i>Streptanthus cordatus</i>	F	P	N	1.34	NP	0.61	10.37
Brassicaceae	<i>Streptanthus</i> spp.	F	P	N/A	NP	NP	NP	0.07
Brassicaceae	<i>Thelypodium wrightii</i>	F	P	N	0.07	NP	NP	NP
Cactaceae	<i>Cylindropuntia imbricata</i>	C	P	N	2.9	NP	NP	NP
Cactaceae	<i>Cylindropuntia whipplei</i>	C	P	N	NP	0.22	NP	NP
Cactaceae	<i>Echinocereus</i> spp.	C	P	N/A	0.83	1.56	0.04	1.44
Cactaceae	<i>Echinocereus triglochidiatus</i>	C	P	N	NP	NP	NP	0.07
Cactaceae	<i>Escobaria</i> spp.	C	P	N/A	1.47	3.81	NP	0.3
Cactaceae	<i>Escobaria vivipara</i>	C	P	N	NP	NP	0.37	NP
Cactaceae	<i>Opuntia</i> spp.	C	P	N/A	31.99	31.6	44.2	50.74
Capparaceae	<i>Peritoma serrulata</i>	F	P	N	0.03	NP	NP	NP

Table 13 (continued). List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022. Lifeform abbreviations include (F = forb, G = graminoid, S = shrub, C = cactus or succulent, V = vine). Nativity (N = native, NN = nonnative), N/A = not applicable for group species, and NP (Not Present) indicates species did not occur in ecological site. Lifeform and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>, accessed Jan 15, 2024).

Family	Species	Lifeform	Nativity	Duration	BAND P	GRCA P	MEVE L	MEVE S
Caprifoliaceae	<i>Symphoricarpos rotundifolius</i>	S	P	N	NP	NP	NP	1.37
Caryophyllaceae	<i>Drymaria molluginea</i>	F	A	N	1.75	NP	NP	NP
Caryophyllaceae	<i>Silene antirrhina</i>	F	P	N	0.26	NP	NP	NP
Caryophyllaceae	<i>Silene</i> spp.	F	N/A	N/A	NP	1.24	NP	0.81
Cleomaceae	<i>Polanisia dodecandra</i>	F	A	N	1.64	NP	NP	NP
Commelinaceae	<i>Tradescantia</i> spp.	F	N/A	N/A	NP	NP	NP	0.11
Convolvulaceae	<i>Ipomoea cristulata</i>	F	A	N	0.27	NP	NP	NP
Cyperaceae	<i>Carex</i> spp.	G	N/A	N/A	0.12	1.28	1.26	14.67
Cyperaceae	<i>Cyperus fendlerianus</i>	G	P	N	0.2	NP	NP	NP
Ephedraceae	<i>Ephedra viridis</i>	S	P	N	NP	6.9	NP	10.93
Euphorbiaceae	<i>Croton texensis</i>	F	A	N	13.18	NP	NP	NP
Euphorbiaceae	<i>Euphorbia exstipulata</i>	F	A	N	0.05	NP	NP	NP
Euphorbiaceae	<i>Euphorbia fendleri</i>	F	P	N	4.51	0.13	NP	2.74
Euphorbiaceae	<i>Euphorbia</i> spp.	F	N/A	N/A	37.78	21.48	NP	0.3
Fabaceae	<i>Astragalus calycosus</i>	F	P	N	NP	5	NP	NP
Fabaceae	<i>Astragalus deterior</i>	F	P	N	NP	NP	NP	0.22
Fabaceae	<i>Astragalus humistratus</i>	F	P	N	NP	2.07	NP	NP
Fabaceae	<i>Astragalus newberryi</i>	F	P	N	NP	9.6	NP	NP
Fabaceae	<i>Astragalus oophorus</i>	F	P	N	NP	3.28	NP	NP
Fabaceae	<i>Astragalus schmolliae</i>	F	P	N	NP	NP	NP	1.96
Fabaceae	<i>Astragalus</i> spp.	F	N/A	N/A	0.54	2.81	18.49	3.41
Fabaceae	<i>Astragalus wingatanus</i>	F	P	N	NP	NP	0.88	0.15
Fabaceae	<i>Dalea candida</i>	F	P	N	1.82	NP	NP	NP

Table 13 (continued). List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022. Lifeform abbreviations include (F = forb, G = graminoid, S = shrub, C = cactus or succulent, V = vine). Nativity (N = native, NN = nonnative), N/A = not applicable for group species, and NP (Not Present) indicates species did not occur in ecological site. Lifeform and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>, accessed Jan 15, 2024).

Family	Species	Lifeform	Nativity	Duration	BAND P	GRCA P	MEVE L	MEVE S
Fabaceae	<i>Dalea polygonoides</i>	F	A	N	1.58	NP	NP	NP
Fabaceae	<i>Dalea</i> spp.	F	N/A	N/A	NP	NP	0.07	NP
Fabaceae	<i>Hedysarum boreale</i>	F	P	N	NP	NP	NP	0.67
Fabaceae	<i>Lotus utahensis</i>	F	P	N	NP	0.28	NP	NP
Fabaceae	<i>Lotus wrightii</i>	F	P	N	29.43	0.21	NP	NP
Fabaceae	<i>Lupinus kingii</i>	F	A	N	5.72	2.07	NP	NP
Fabaceae	<i>Lupinus</i> spp.	F	N/A	N/A	NP	NP	21.49	1.11
Fabaceae	<i>Melilotus officinalis</i>	F	A	NN	0.13	NP	NP	0.07
Fabaceae	<i>Psoralegium</i> spp.	F	N/A	N/A	NP	0.12	NP	NP
Fabaceae	<i>Psoralegium tenuiflorum</i>	F	P	N	NP	1.99	NP	NP
Fabaceae	<i>Trifolium gymnocarpon</i>	F	P	N	NP	0.07	NP	NP
Fabaceae	<i>Trifolium</i> spp.	F	N/A	N/A	NP	0.75	NP	NP
Fabaceae	<i>Vicia</i> spp.	vine	N/A	N/A	0.75	NP	NP	NP
Fagaceae	<i>Quercus gambelii</i>	S	P	N	NP	1.63	NP	4.37
Fagaceae	<i>Quercus</i> spp.	S	P	N/A	6.14	NP	2	NP
Gentianaceae	<i>Frasera albomarginata</i>	F	P	N	NP	0.06	NP	0.15
Gentianaceae	<i>Frasera paniculata</i>	F	P	N	NP	0.2	NP	NP
Geraniaceae	<i>Erodium cicutarium</i>	F	A	NN	0.36	3.14	0.03	NP
Geraniaceae	<i>Geranium caespitosum</i>	F	P	N	1.45	NP	NP	NP
Grossulariaceae	<i>Ribes cereum</i>	S	P	N	0.07	NP	NP	NP
Grossulariaceae	<i>Ribes</i> spp.	S	P	N/A	NP	NP	0.04	NP
Hydrangeaceae	<i>Fendlera rupicola</i>	S	P	N	NP	NP	NP	4.52
Lamiaceae	<i>Dracocephalum parviflorum</i>	F	A	N	0.04	NP	NP	NP

Table 13 (continued). List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022. Lifeform abbreviations include (F = forb, G = graminoid, S = shrub, C = cactus or succulent, V = vine). Nativity (N = native, NN = nonnative), N/A = not applicable for group species, and NP (Not Present) indicates species did not occur in ecological site. Lifeform and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>, accessed Jan 15, 2024).

Family	Species	Lifeform	Nativity	Duration	BAND P	GRCA P	MEVE L	MEVE S
Lamiaceae	<i>Hedeoma drummondii</i>	F	A	N	0.53	1.63	NP	NP
Lamiaceae	<i>Hedeoma</i> spp.	F	N/A	N/A	0.05	NP	NP	NP
Liliaceae	<i>Calochortus nuttallii</i>	F	P	N	NP	0.27	NP	NP
Liliaceae	<i>Calochortus</i> spp.	F	N/A	N/A	NP	NP	0.96	0.15
Linaceae	<i>Linum lewisii</i>	F	P	N	0.48	0.7	NP	0.3
Linaceae	<i>Linum neomexicanum</i>	F	A	N	1	NP	NP	NP
Linaceae	<i>Linum</i> spp.	F	N/A	N/A	0.12	0.22	NP	NP
Loasaceae	<i>Mentzelia albicaulis</i>	F	A	N	2.01	0.39	NP	NP
Loasaceae	<i>Mentzelia</i> spp.	F	N/A	N/A	22.39	NP	0.09	NP
Malvaceae	<i>Sphaeralcea coccinea</i>	F	P	N	NP	NP	NP	0.15
Malvaceae	<i>Sphaeralcea</i> spp.	F	N/A	N/A	0.5	9.46	0.06	NP
Montiaceae	<i>Phemeranthus parviflorus</i>	F	P	N	NP	NP	NP	0.15
Montiaceae	<i>Phemeranthus</i> spp.	F	N/A	N/A	NP	0.22	NP	NP
Nyctaginaceae	<i>Mirabilis linearis</i>	F	P	N	1.31	2.76	NP	0.26
Nyctaginaceae	<i>Mirabilis multiflora</i>	F	P	N	4.57	1.78	NP	NP
Nyctaginaceae	<i>Mirabilis oxybaphoides</i>	F	P	N	1.06	NP	NP	NP
Oleaceae	<i>Forestiera pubescens</i>	S	P	N	0.31	NP	NP	NP
Oleaceae	<i>Menodora scabra</i>	F	P	N	0.2	NP	NP	NP
Onagraceae	<i>Epilobium brachycarpum</i>	F	A	N	NP	0.04	NP	NP
Onagraceae	<i>Oenothera caespitosa</i>	F	P	N	0.96	NP	NP	NP
Onagraceae	<i>Oenothera</i> spp.	F	N/A	N/A	0.09	0.3	NP	NP
Onagraceae	<i>Oenothera suffrutescens</i>	F	P	N	0.06	NP	NP	NP
Orobanchaceae	<i>Castilleja integra</i>	F	P	N	0.36	NP	NP	NP

Table 13 (continued). List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022. Lifeform abbreviations include (F = forb, G = graminoid, S = shrub, C = cactus or succulent, V = vine). Nativity (N = native, NN = nonnative), N/A = not applicable for group species, and NP (Not Present) indicates species did not occur in ecological site. Lifeform and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>, accessed Jan 15, 2024).

Family	Species	Lifeform	Nativity	Duration	BAND P	GRCA P	MEVE L	MEVE S
Orobanchaceae	<i>Castilleja linariifolia</i>	F	P	N	0.04	NP	NP	NP
Orobanchaceae	<i>Castilleja</i> spp.	F	N/A	N/A	NP	1.03	NP	NP
Orobanchaceae	<i>Cordylanthus parviflorus</i>	F	A	N	NP	3.04	NP	NP
Orobanchaceae	<i>Cordylanthus wrightii</i>	F	A	N	4.53	1.62	23.95	2.52
Orobanchaceae	<i>Orobanche fasciculata</i>	F	A	N	0.07	NP	NP	NP
Orobanchaceae	<i>Orobanche ludoviciana</i>	F	A	N	0.26	0.04	NP	NP
Orobanchaceae	<i>Orobanche</i> spp.	F	N/A	N/A	0.07	NP	NP	NP
Orobanchaceae	<i>Orthocarpus purpureoalbus</i>	F	A	N	1.07	NP	0.11	NP
Orobanchaceae	<i>Pedicularis centranthera</i>	F	P	N	NP	NP	10.75	1.74
Oxalidaceae	<i>Oxalis violacea</i>	F	P	N	0.04	NP	NP	NP
Papaveraceae	<i>Corydalis aurea</i>	F	A	N	1.47	NP	NP	NP
Plantaginaceae	<i>Collinsia parviflora</i>	F	A	N	NP	0.06	0.22	0.15
Plantaginaceae	<i>Penstemon barbatus</i>	F	P	N	NP	10.58	4.6	3.15
Plantaginaceae	<i>Penstemon caespitosus</i>	F	N/A	N	NP	1.4	NP	NP
Plantaginaceae	<i>Penstemon eatonii</i>	F	P	N	NP	NP	NP	0.22
Plantaginaceae	<i>Penstemon linarioides</i>	F	P	N	NP	NP	78.33	50.67
Plantaginaceae	<i>Penstemon</i> spp.	F	N/A	N/A	2.75	14.97	4.11	0.67
Plantaginaceae	<i>Plantago patagonica</i>	F	A	N	1.25	0.72	NP	NP
Poaceae	<i>Achnatherum hymenoides</i>	G	P	N	0.81	0.28	2.24	5.67
Poaceae	<i>Andropogon gerardii</i>	G	P	N	0.04	NP	NP	NP
Poaceae	<i>Aristida adscensionis</i>	G	A	N	0.27	0.3	NP	NP
Poaceae	<i>Aristida divaricata</i>	G	P	N	0.1	NP	NP	NP
Poaceae	<i>Aristida havardii</i>	G	P	N	0.1	NP	NP	NP

Table 13 (continued). List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022. Lifeform abbreviations include (F = forb, G = graminoid, S = shrub, C = cactus or succulent, V = vine). Nativity (N = native, NN = nonnative), N/A = not applicable for group species, and NP (Not Present) indicates species did not occur in ecological site. Lifeform and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>, accessed Jan 15, 2024).

Family	Species	Lifeform	Nativity	Duration	BAND P	GRCA P	MEVE L	MEVE S
Poaceae	<i>Aristida purpurea</i>	G	P	N	6.05	NP	NP	NP
Poaceae	<i>Bouteloua barbata</i>	G	A	N	0.39	0.06	NP	NP
Poaceae	<i>Bouteloua curtipendula</i>	G	P	N	0.37	0.58	NP	NP
Poaceae	<i>Bouteloua eriopoda</i>	G	P	N	3.93	NP	NP	NP
Poaceae	<i>Bouteloua gracilis</i>	G	P	N	67.87	61.92	NP	0.85
Poaceae	<i>Bromus japonicus</i>	G	A	NN	0.61	NP	NP	NP
Poaceae	<i>Bromus</i> spp.	G	N/A	N/A	NP	0.15	NP	0.07
Poaceae	<i>Bromus tectorum</i>	G	A	NN	35.52	11.26	2.12	5.3
Poaceae	<i>Dasyochloa pulchella</i>	G	P	N	NP	0.11	NP	NP
Poaceae	<i>Elymus elymoides</i>	G	P	N	67.4	22.46	11.51	38.33
Poaceae	<i>Enneapogon desvauxii</i>	G	P	N	NP	0.16	NP	NP
Poaceae	<i>Eragrostis mexicana</i>	G	A	N	NP	0.49	NP	NP
Poaceae	<i>Eragrostis pectinacea</i>	G	A	N	NP	0.43	NP	NP
Poaceae	<i>Hesperostipa comata</i>	G	P	N	1.25	1.7	0.06	0.3
Poaceae	<i>Hilaria jamesii</i>	G	P	N	4.05	NP	NP	NP
Poaceae	<i>Koeleria macrantha</i>	G	P	N	3.96	2.84	8.35	3.04
Poaceae	<i>Muhlenbergia alopecuroides</i>	G	P	N	2.94	NP	NP	NP
Poaceae	<i>Muhlenbergia brevis</i>	G	A	N	NP	1.1	NP	NP
Poaceae	<i>Muhlenbergia minutissima</i>	G	A	N	0.62	0.07	NP	NP
Poaceae	<i>Muhlenbergia montana</i>	G	P	N	3.57	NP	NP	NP
Poaceae	<i>Muhlenbergia tricholepis</i>	G	P	N	0.09	NP	NP	NP
Poaceae	<i>Muhlenbergia wrightii</i>	G	P	N	0.24	NP	NP	NP
Poaceae	<i>Munroa squarrosa</i>	G	A	N	0.47	1.03	NP	NP

Table 13 (continued). List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022. Lifeform abbreviations include (F = forb, G = graminoid, S = shrub, C = cactus or succulent, V = vine). Nativity (N = native, NN = nonnative), N/A = not applicable for group species, and NP (Not Present) indicates species did not occur in ecological site. Lifeform and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>, accessed Jan 15, 2024).

Family	Species	Lifeform	Nativity	Duration	BAND P	GRCA P	MEVE L	MEVE S
Poaceae	<i>Pappostipa speciosa</i>	G	P	N	NP	NP	NP	0.15
Poaceae	<i>Piptatherum micranthum</i>	G	P	N	7.16	NP	NP	NP
Poaceae	<i>Poa fendleriana</i>	G	P	N	16.86	94.14	97.2	89.44
Poaceae	<i>Schizachyrium scoparium</i>	G	P	N	3.6	NP	NP	NP
Poaceae	<i>Sporobolus</i> spp.	G	N/A	N/A	17.56	0.96	NP	0.07
Poaceae	<i>Triticum aestivum</i>	G	P	NN	0.03	NP	NP	NP
Poaceae	<i>Vulpia octoflora</i>	G	A	N	3.24	5.01	NP	NP
Polemoniaceae	<i>Gilia</i> spp.	F	N/A	N/A	0.14	5.37	NP	0.96
Polemoniaceae	<i>Ipomopsis aggregata</i>	F	P	N	3.86	NP	0.14	1.37
Polemoniaceae	<i>Ipomopsis congesta</i>	F	P	N	0.23	NP	NP	NP
Polemoniaceae	<i>Ipomopsis longiflora</i>	F	A	N	11.59	NP	NP	NP
Polemoniaceae	<i>Ipomopsis multiflora</i>	F	P	N	NP	5.67	NP	NP
Polemoniaceae	<i>Ipomopsis</i> spp.	F	N/A	N/A	0.95	NP	NP	NP
Polemoniaceae	<i>Microsteris gracilis</i>	F	A	N	NP	NP	0.24	NP
Polemoniaceae	<i>Phlox austromontana</i>	F	P	N	NP	10	NP	NP
Polemoniaceae	<i>Phlox hoodii</i>	F	P	N	NP	NP	30.3	8.97
Polemoniaceae	<i>Phlox longifolia</i>	F	P	N	NP	4.91	2.2	NP
Polygonaceae	<i>Eriogonum alatum</i>	F	P	N	NP	0.72	0.89	3.37
Polygonaceae	<i>Eriogonum cernuum</i>	F	A	N	0.17	NP	0.03	NP
Polygonaceae	<i>Eriogonum jamesii</i>	F	P	N	3.58	0.33	0.44	3.3
Polygonaceae	<i>Eriogonum microthecum</i>	S	P	N	NP	4.19	NP	NP
Polygonaceae	<i>Eriogonum polycladon</i>	F	A	N	0.42	NP	NP	NP
Polygonaceae	<i>Eriogonum racemosum</i>	F	P	N	0.89	11.11	14.98	5.41

Table 13 (continued). List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022. Lifeform abbreviations include (F = forb, G = graminoid, S = shrub, C = cactus or succulent, V = vine). Nativity (N = native, NN = nonnative), N/A = not applicable for group species, and NP (Not Present) indicates species did not occur in ecological site. Lifeform and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>, accessed Jan 15, 2024).

Family	Species	Lifeform	Nativity	Duration	BAND P	GRCA P	MEVE L	MEVE S
Polygonaceae	<i>Eriogonum umbellatum</i>	F	P	N	NP	5.01	7.57	10.56
Polygonaceae	<i>Eriogonum wrightii</i>	S	P	N	NP	0.77	NP	NP
Polygonaceae	<i>Polygonum douglasii</i>	F	A	N	NP	0.86	3.91	4.3
Polygonaceae	<i>Polygonum sawatchense</i>	F	A	N	0.76	3.52	29.69	NP
Polygonaceae	<i>Polygonum</i> spp.	F	N/A	N/A	0.05	NP	NP	0.37
Portulacaceae	<i>Portulaca oleracea</i>	F	A	NN	12.4	7.58	0.1	0.07
Portulacaceae	<i>Portulaca pilosa</i>	F	A	N	1.28	1.04	NP	NP
Primulaceae	<i>Androsace septentrionalis</i>	F	A	N	NP	7.8	0.56	0.15
Ranunculaceae	<i>Delphinium scaposum</i>	F	P	N	NP	0.18	0.15	NP
Ranunculaceae	<i>Myosurus minimus</i>	F	A	N	NP	0.27	NP	NP
Ranunculaceae	<i>Ranunculus testiculatus</i>	F	A	NN	NP	0.78	1.27	NP
Rosaceae	<i>Amelanchier utahensis</i>	S	P	N	NP	NP	2.49	14.33
Rosaceae	<i>Cercocarpus montanus</i>	S	P	N	9.09	NP	7.93	35.99
Rosaceae	<i>Chamaebatiaria millefolium</i>	S	P	N	NP	0.89	NP	NP
Rosaceae	<i>Fallugia paradoxa</i>	S	P	N	8.36	1.67	NP	NP
Rosaceae	<i>Peraphyllum ramosissimum</i>	S	P	N	NP	NP	NP	0.3
Rosaceae	<i>Purshia mexicana</i> var. <i>stansburyana</i>	S	P	N	NP	34.23	NP	NP
Rosaceae	<i>Purshia tridentata</i>	S	P	N	NP	0.11	50.32	46.6
Santalaceae	<i>Arceuthobium divaricatum</i>	S	P	N	NP	4.78	NP	2.44
Santalaceae	<i>Comandra umbellata</i>	F	P	N	NP	6.69	3.59	6.56
Santalaceae	<i>Phoradendron juniperinum</i>	S	P	N	0.17	1.01	5.5	1.04
Scrophulariaceae	<i>Verbascum thapsus</i>	F	P	NN	19.59	NP	NP	NP
Solanaceae	<i>Physalis hederifolia</i>	F	P	N	9.14	NP	NP	NP

Table 13 (continued). List of species detected and their percent quadrat frequency during grassland monitoring at four ecosites in three National Parks (BAND, GRCA, MEVE) during 2008 to 2022. Lifeform abbreviations include (F = forb, G = graminoid, S = shrub, C = cactus or succulent, V = vine). Nativity (N = native, NN = nonnative), N/A = not applicable for group species, and NP (Not Present) indicates species did not occur in ecological site. Lifeform and duration were derived from USDA Plants database (<https://plants.sc.egov.usda.gov/java>, accessed Jan 15, 2024).

Family	Species	Lifeform	Nativity	Duration	BAND P	GRCA P	MEVE L	MEVE S
Solanaceae	<i>Physalis</i> spp.	F	N/A	N/A	NP	0.22	NP	NP
Solanaceae	<i>Solanum jamesii</i>	F	P	N	0.89	NP	NP	NP
Solanaceae	<i>Solanum</i> spp.	F	N/A	N/A	0.14	NP	NP	NP
Solanaceae	<i>Solanum triflorum</i>	F	A	N	0.07	NP	NP	NP

Appendix C: Cover class midpoint medians of dominant species

Table 14 presents a list of dominant species and each species median percent cover in each ecological site reported.

Table 14. Median percent cover of dominant plants at four ecosites in three National Parks (BAND, GRCA, MEVE). Median percent covers were calculated using cover class midpoints (see Table 2).

Scientific name	Common name	Lifeform	BAND P	GRCA P	MEVE L	MEVE S
<i>Amauriopsis dissecta</i>	ragleaf bahia	forb	0.358	N/A	N/A	N/A
<i>Amelanchier utahensis</i>	Utah serviceberry	shrub	N/A	N/A	0.103	0.742
<i>Artemisia bigelovii</i>	Bigelow sage	shrub	N/A	N/A	0.068	N/A
<i>Artemisia campestris</i>	field sagewort	forb	0.631	N/A	N/A	N/A
<i>Artemisia carruthii</i>	Carruth's sagewort	forb	0.205	N/A	N/A	N/A
<i>Artemisia dracunculus</i>	tarragon	forb	0.264	N/A	N/A	N/A
<i>Artemisia ludoviciana</i>	white sagebrush	forb	0.055	N/A	N/A	N/A
<i>Artemisia tridentata</i>	big sagebrush	shrub	N/A	0.893	0.088	N/A
<i>Berberis fremontii</i>	Fremont's mahonia	shrub	N/A	0.177	N/A	N/A
<i>Bouteloua eriopoda</i>	black grama	graminoid	0.065	N/A	N/A	N/A
<i>Bouteloua gracilis</i>	blue grama	graminoid	2.288	1.902	N/A	N/A
<i>Bromus tectorum</i>	cheatgrass	graminoid	1.825	0.122	N/A	N/A
<i>Cercocarpus montanus</i>	alderleaf mountain mahogany	shrub	0.442	N/A	0.344	1.761
<i>Cordylanthus wrightii</i>	Wright's bird's beak	forb	N/A	N/A	0.112	N/A
<i>Croton texensis</i>	Texas croton	forb	0.171	N/A	N/A	N/A
<i>Cylindropuntia imbricata</i>	tree cholla	cactus succulent	0.066	N/A	N/A	N/A
<i>Dysphania graveolens</i>	fetid goosefoot	forb	0.105	N/A	N/A	N/A
<i>Elymus elymoides</i>	squirreltail	graminoid	0.815	0.057	N/A	0.109
<i>Ephedra viridis</i>	mormon tea	shrub	N/A	N/A	N/A	0.164
<i>Fallugia paradoxa</i>	Apache plume	shrub	0.505	0.082	N/A	N/A

Table 14 (continued). Median percent cover of dominant plants at four ecosites in three National Parks (BAND, GRCA, MEVE). Median percent covers were calculated using cover class midpoints (see Table 2).

Scientific name	Common name	Lifeform	BAND P	GRCA P	MEVE L	MEVE S
<i>Fendlera rupicola</i>	cliff fendlerbush	shrub	N/A	N/A	N/A	0.229
<i>Gutierrezia sarothrae</i>	broom snakeweed	shrub	2.08	0.188	N/A	N/A
<i>Helianthus annuus</i>	common sunflower	forb	0.127	N/A	N/A	N/A
<i>Heterotheca villosa</i>	hairy false goldenaster	forb	0.053	N/A	N/A	N/A
<i>Hilaria jamesii</i>	galleta	graminoid	0.072	N/A	N/A	N/A
<i>Lotus wrightii</i>	Wright's deervetch	forb	0.068	N/A	N/A	N/A
<i>Mirabilis multiflora</i>	Colorado four o'clock	forb	0.054	N/A	N/A	N/A
<i>Opuntia</i> spp.	prickly pear	cactus succulent	0.112	0.081	0.306	0.223
<i>Sporobolus</i> spp.	dropseed	graminoid	0.079	N/A	N/A	N/A
<i>Quercus</i> spp.	oak	shrub	0.439	N/A	N/A	N/A
<i>Nama dichotoma</i>	wishbone fiddleleaf	forb	0.074	N/A	N/A	N/A
<i>Penstemon linarioides</i>	toadflax penstemon	forb	N/A	N/A	0.243	0.109
<i>Petradoria pumila</i>	rock goldenrod	forb	N/A	N/A	0.166	0.109
<i>Phlox hoodii</i>	spiny phlox	forb	N/A	N/A	0.081	N/A
<i>Poa fendleriana</i>	muttongrass	graminoid	0.156	1.224	3.626	2.578
<i>Portulaca oleracea</i>	little hogweed	forb	0.19	N/A	N/A	N/A
<i>Purshia mexicana</i> var. <i>stansburyana</i>	Stansbury cliffrose	shrub	N/A	1.961	N/A	N/A
<i>Purshia tridentata</i>	antelope bitterbrush	shrub	N/A	N/A	2.1	1.958
<i>Quercus gambelii</i>	Gambel oak	shrub	N/A	0.104	N/A	0.604
<i>Rhus aromatica</i>	fragrant sumac	shrub	0.507	N/A	N/A	N/A
<i>Senecio spartioides</i>	broom-like ragwort	forb	0.069	N/A	N/A	N/A
<i>Stenotus armerioides</i>	thrift mock goldenweed	forb	N/A	N/A	N/A	0.1
<i>Thelesperma filifolium</i>	stiff greenthread	forb	0.083	N/A	N/A	N/A

Table 14 (continued). Median percent cover of dominant plants at four ecosites in three National Parks (BAND, GRCA, MEVE). Median percent covers were calculated using cover class midpoints (see Table 2).

Scientific name	Common name	Lifeform	BAND P	GRCA P	MEVE L	MEVE S
<i>Verbascum thapsus</i>	common mullein	forb	0.172	N/A	N/A	N/A
<i>Yucca baccata</i>	banana yucca	cactus succulent	0.134	N/A	0.564	0.641

Appendix D: Bayesian Models

Table 15 contains technical model specifications and details for the trend models used in the report

Table 15. Model specifications for all responses presented in this report. Models were run using three chains and 8,000–12,000 iterations. Model indicates the 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, in addition to visually assessing convergence, P_{mean} and P_{sd} are Bayesian p-values for the mean and variance and are used to indicate lack of fit. 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-Rubin (Gel) diagnostic is an indicator of convergence and should be close to one.

Response	EcoSite ^A	Model	Model type	Variance level and type	Likelihood	Covariates ^B	Percent Cover		Presence/Absence		PPL	Gel
							P_{mean}	P_{sd}	P_{mean}	P_{sd}		
Perennial grass cover	All	Inverse logit	b0	stratum, hierarchical	hurdle-ordinal-latent-beta	Spring D, Winter D, Lag year D, AGDD	0.94	0.51	0.61	0.59	14622	1.05
Muttongrass cover	MEVE L MEVE S GRCA P	Inverse logit	b0 g0	Site, hierarchical	Hurdle-ordinal-latent-beta	Spring D, Winter D, Lag year D, AGDD, AI, Terrain	0.96	0.41	0.6	0.6	10939	1.02
Blue grama cover	BAND P GRCA P	Inverse logit	b0 g0	Site, hierarchical	Hurdle-ordinal-latent-beta	Spring D, Winter D, Lag year D, AGDD, AI	0.86	0.36	0.51	0.51	7270	1.01
Squirreltail cover	ALL	Inverse logit	b0 g0	Site, hierarchical	Hurdle-ordinal-latent-beta	Spring D, Winter D, Lag year D, AGDD, AI	0.9	0.88	0.49	0.51	3715	1.1
Shrub cover	ALL	Inverse logit	b0	Site, hierarchical	Hurdle-ordinal-latent-beta	Spring D, Winter D, Lag year D, 2 year D, AGDD, AI, Terrain	0.69	0.28	0.53	0.53	42625	1.04
Antelope bitterbrush cover	MEVE L MEVE S	Inverse logit	b0 g0	Site, hierarchical	Hurdle-ordinal-latent-beta	Spring D, Winter D, Lag year D, AGDD, AI	0.45	0.480	0.5	0.5	4436	1.01

^A Ecological sites include BAND Mesa top pinyon-juniper, GRCA Pinyon-juniper woodland, MEVE Loamy mesa top pinyon-juniper woodland, MEVE Shallow loamy mesa top pinyon-juniper woodland.

^B Covariates include: AGDD = accumulated growing degree days, Terrain, winter D = cumulative climatic water deficit for November–March, spring D = cumulative climatic water deficit for April–June, Lag year D = cumulative climatic water deficit for previous water year, AI = aridity index.

Table 15 (continued). Model specifications for all responses presented in this report. Models were run using three chains and 8,000–12,000 iterations. Model indicates the 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, in addition to visually assessing convergence, P_{mean} and P_{sd} are Bayesian p-value for the mean and variance and are used to indicate lack of fit. 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-Rubin diagnostic is an indicator of convergence and should be close to one.

Response	EcoSite ^A	Model	Model type	Variance level and type	Likelihood	Covariates ^B	Percent Cover		Presence/Absence		PPL	Gel
							P_{mean}	P_{sd}	P_{mean}	P_{sd}		
Cliffrose cover	GRCA P	Inverse logit	b0 g0	site, hierarchical	hurdle-ordinal-latent-beta	Spring D, Winter D, Lag year D, AGDD, AI	0.64	0.77	0.51	0.51	2923	1.05
Mountain mahogany cover	MEVE L MEVE S	Inverse logit	b0 g0	site, hierarchical	hurdle-ordinal-latent-beta	Spring D, Winter D, Lag year D, AGDD, AI	0.41	0.35	0.47	0.54	2011	1.04
Big sagebrush	GRCA P	Inverse logit	b0 g0	site, hierarchical	hurdle-ordinal-latent-beta	Spring D, Winter D, Lag year D, AGDD, AI	0.58	0.77	0.51	0.5	2036	1.03
Broom snakeweed	ALL	Inverse logit	b0 g0	Site, hierarchical	Hurdle-ordinal-latent-beta	Spring D, Winter D, Lag year D, AGDD, AI	0.85	0.5	0.5	0.47	9151	1.04
Cactus	ALL	Inverse-logit	b0 g0	Site, hierarchical	Hurdle-ordinal-latent-beta	Spring D, Winter D, Lag year D, 2 year D, AGDD, AI, Terrain	0.89	0.50	0.51	0.50	5259	1.02
Opuntia spp.	ALL	Inverse logit	b0 g0	Site, hierarchical	Hurdle-ordinal-latent-beta	Spring D, Winter D, Lag year D, AI	0.83	0.57	0.52	0.49	9429	1.07
Ragleaf bahia cover	BAND P	Inverse logit	b0 g0	Site, hierarchical	Hurdle-ordinal-latent-beta	Spring D, Winter D, Lag year D, AGDD, AI, Basal area	0.83	0.64	0.51	0.51	3430	1.03
Spiny phlox presence	MEVE L MEVE S	Inverse logit	b0	Site, hierarchical	Zero inflated binomial	Spring D, Winter D, Lag year D, AGDD, AI, Basal area	0.58	0.46	–	–	337	1.02

^A Ecological sites include BAND Mesa top pinyon-juniper, GRCA Pinyon-juniper woodland, MEVE Loamy mesa top pinyon-juniper woodland, MEVE Shallow loamy mesa top pinyon-juniper woodland.

^B Covariates include: AGDD = accumulated growing degree days, Terrain, winter D = cumulative climatic water deficit for November–March, spring D = cumulative climatic water deficit for April–June, Lag year D = cumulative climatic water deficit for previous water year, AI = aridity index.

Table 15 (continued). Model specifications for all responses presented in this report. Models were run using three chains and 8,000–12,000 iterations. Model indicates the 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, in addition to visually assessing convergence, P_{mean} and P_{sd} are Bayesian p-value for the mean and variance and are used to indicate lack of fit. 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-Rubin diagnostic is an indicator of convergence and should be close to one.

Response	EcoSite ^A	Model	Model type	Variance level and type	Likelihood	Covariates ^B	Percent Cover		Presence/Absence		PPL	Gel
							P_{mean}	P_{sd}	P_{mean}	P_{sd}		
Toadflax penstemon presence	MEVE L MEVE S	Inverse logit	b0	Stratum, fixed	Beta binomial	Spring D, Winter D, Lag year D, AGDD, AI, basal area	0.5	0.52	–	–	1068	1.2
Cheatgrass presence	BAND P GRCA P	Inverse logit	B0	Stratum, fixed	Beta binomial	Spring D, Winter D, Lag year D, AGDD, AI	0.54	0.27	–	–	779	1.08
Field wormwood Presence	BAND P	Inverse logit	b0	Stratum, fixed	Zero-inflated beta-binomial	Spring D, Winter D, Lag year D, AGDD, AI	0.52	0.13	–	–	507	1.02
Juniper seedlings	ALL	Exponential	B0	Stratum, fixed	Negative binomial	Spring D, Winter D, Lag year D	0.83	0.57	–	–	9429	1.07
Pinyon seedlings	ALL	Exponential	B0	Stratum, fixed	Negative binomial	Spring D, Winter D, Lag year D	0.92	0.17	–	–	118795	1.01
Juniper saplings	ALL	Exponential	B0	Site, hierarchical	Poisson	Spring D, Winter D, Lag year D, 2 year D, AGDD, AI, Basal area total	0.54	0.45	–	–	4393	1.01
Pinyon saplings	ALL	Exponential	B0	Site, hierarchical	Poisson	Spring D, Winter D, Lag year D, 2 year D, AGDD, AI, Basal area total	0.79	0.27	–	–	10649	1.15
Quadrat Richness	BAND	Exponential	b0	Site, hierarchical	Generalized Poisson	Spring D, Winter D, Lag year D, AGDD, AI	0.49	0.71	–	–	5057306	1.03
Quadrat Richness	GRCA P	Exponential	b0	Site, hierarchical	Generalized Poisson	Spring D, Winter D, Lag year D, AGDD, AI	0.55	0.51	–	–	2958190	1.09

^A Ecological sites include BAND Mesa top pinyon-juniper, GRCA Pinyon-juniper woodland, MEVE Loamy mesa top pinyon-juniper woodland, MEVE Shallow loamy mesa top pinyon-juniper woodland.

^B Covariates include: AGDD = accumulated growing degree days, Terrain, winter D = cumulative climatic water deficit for November–March, spring D = cumulative climatic water deficit for April–June, Lag year D = cumulative climatic water deficit for previous water year, AI = aridity index.

Table 15 (continued). Model specifications for all responses presented in this report. Models were run using three chains and 8,000–12,000 iterations. Model indicates the 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, in addition to visually assessing convergence, P_{mean} , and P_{sd} are Bayesian p-value for the mean and variance and are used to indicate lack of fit. 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-Rubin diagnostic is an indicator of convergence and should be close to one.

Response	EcoSite ^A	Model	Model type	Variance level and type	Likelihood	Covariates ^B	Percent Cover		Presence/Absence		PPL	Gel
							P_{mean}	P_{sd}	P_{mean}	P_{sd}		
Quadrat Richness	MEVE L	Exponential	b0	Site, hierarchical	Generalized Poisson	Spring D, Winter D, Lag year D, AGDD, AI	0.52	0.67	–	–	1722237	1.06
Quadrat Richness	MEVE S	Exponential	b0	Site, hierarchical	Generalized Poisson	Spring D, Winter D, Lag year D, AGDD, AI	0.49	.053	–	–	1501484	1.06

^A Ecological sites include BAND Mesa top pinyon-juniper, GRCA Pinyon-juniper woodland, MEVE Loamy mesa top pinyon-juniper woodland, MEVE Shallow loamy mesa top pinyon-juniper woodland.

^B Covariates include: AGDD = accumulated growing degree days, Terrain, winter D = cumulative climatic water deficit for November–March, spring D = cumulative climatic water deficit for April–June, Lag year D = cumulative climatic water deficit for previous water year, AI = aridity index.

Appendix E. Fully Accessible Versions of Figure 38, Figure 40, and Figure 41

This appendix contains accessible tables (Table 16, Table 17, and Table 18) with data from figures (Figure 38, Figure 40, and Figure 41) found in the body of the report. Table captions include hyperlinks to the corresponding figures.

Table 16. Summary of direction of year effects (trend) for modeled responses. Data from [Figure 38](#). The significance of how a species changes over time at an ecological site is represented by lettering: PC = a significant positive change over time; NC = a significant negative change over time; NO = a non-significant change over time; a dash (–) indicates that the covariate was not modeled for that ecological site.

Species or Functional Group	BAND-P	GRCA-P	MEVE-L	MEVE-S
Perennial grasses	NO	NO	NC	PC
Mutton grass	–	PC	PC	PC
Blue gramma	NO	PC	–	–
Squirreltail	NO	NO	PC	PC
Shrubs	PC	PC	NO	PC
Big sagebrush	–	NO	–	–
Mountain mahogany	–	–	NO	PC
Snakeweed	PC	NO	–	–
Antelope bitterbrush	–	–	NC	NO
Cliffrose	–	NO	–	–
Cactus	NO	PC	PC	PC
<i>Opuntia</i> spp.	NC	NO	PC	PC
Forbs	PC	–	–	–
Ragleaf bahia	PC	–	–	–
Field wormwood	NO	–	–	–
Toadflax penstemon	–	–	NO	PC
Spiny phlox	–	–	PC	NO
Cheatgrass	PC	NC	–	–
Juniper seedlings	NO	NO	PC	NO

Table 16 (continued). Summary of direction of year effects (trend) for modeled responses. Data from [Figure 38](#). The significance of how a species changes over time at an ecological site is represented by lettering: PC = a significant positive change over time; NC = a significant negative change over time; NO = a non-significant change over time; a dash (–) indicates that the covariate was not modeled for that ecological site.

Species or Functional Group	BAND-P	GRCA-P	MEVE-L	MEVE-S
Pinyon seedlings	NO	PC	PC	NO
Juniper saplings	PC	PC	PC	NO
Pinyon saplings	NO	NO	NO	NC

Table 17. Summary of direction of covariate effects on modeled responses. Data from [Figure 40](#). The significance of how a covariate relates to each species or functional group is represented by lettering: PE = a significant positive effect; NE = a significant negative effect; NO = a non-significant effect; a dash (–) indicates that the covariate was not modeled for that species. The column labeled AGDD stands for accumulative growing degree-days.

Species or Functional Group	Spring deficit	Winter deficit	Lag year deficit	Two-year deficit	AGDD	Aridity index
Perennial grasses	NE	PE	NE	–	NO	–
Mutton grass	NE	PE	NE	–	NE	PE
Blue gramma	NE	NO	NE	–	SE	PE
Squirreltail	NE	NE	NE	–	SE	NO
Shrubs	NE	NO	NO	NE	NO	NO
Big sagebrush	NO	NO	NO	–	NO	NO
Mountain mahogany	NO	NO	NO	–	NO	NO
Snakeweed	NE	PE	NO	–	NO	NE
Antelope bitterbrush	NO	NO	NO	–	NO	PE
Cliffrose	NO	NO	NO	–	NO	NO
Cactus	NO	NO	NO	NO	NO	NE
<i>Opuntia</i> spp.	NO	NE	NO	–	–	PE
Forbs	NO	–	NE	–	NE	PE
Ragleaf bahia	NE	PE	NO	–	NO	NO

Table 17 (continued). Summary of direction of covariate effects on modeled responses. Data from [Figure 40](#). The significance of how a covariate relates to each species or functional group is represented by lettering: PE = a significant positive effect; NE = a significant negative effect; NO = a non-significant effect; a dash (–) indicates that the covariate was not modeled for that species. The column labeled AGDD stands for accumulative growing degree-days.

Species or Functional Group	Spring deficit	Winter deficit	Lag year deficit	Two-year deficit	AGDD	Aridity index
Field wormwood	NE	NO	PE	–	PE	NE
Toadflax penstemon	NO	PE	NE	–	NE	NO
Spiny phlox	NO	NO	NO	–	NO	NO
Cheatgrass	NE	PE	PE	–	NO	NO
Juniper seedlings	NO	NO	NO	–	–	–
Pinyon seedlings	NO	NO	NO	–	–	–
Juniper saplings	NO	NO	NO	NO	–	–
Pinyon saplings	NE	NO	NO	NO	–	–

Table 18. Plot sampling history at four ecosites in three National Parks (BAND, GRCA, MEVE). Data from [Figure 41](#). Data is represented by lettering: Y = the plot was sampled that year, and N = the plot was not sampled that year. Data from 2007 was dropped from analysis since only one site was sampled that year.

Plot Number	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
BAND P 1	N	Y	N	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N
BAND P 2	N	Y	N	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N
BAND P 3	N	Y	N	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N
BAND P 4	N	Y	N	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N
BAND P 5	N	Y	N	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N
BAND P 6	N	Y	N	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N
BAND P 7	N	Y	N	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N
BAND P 8	N	Y	N	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N
BAND P 9	N	Y	N	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N
BAND P 11	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N

Table 18 (continued). Plot sampling history at four ecosites in three National Parks (BAND, GRCA, MEVE). Data from [Figure 41](#). Data is represented by lettering: Y = the plot was sampled that year, and N = the plot was not sampled that year. Data from 2007 was dropped from analysis since only one site was sampled that year.

Plot Number	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
BAND P 12	N	Y	N	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N
BAND P 13	N	Y	N	N	N	Y	Y	N	N	Y	Y	N	N	N	N	N
BAND P 14	N	Y	N	N	N	N	Y	N	N	Y	Y	N	N	N	N	N
BAND P 15	N	Y	Y	N	N	N	Y	N	N	Y	Y	N	N	N	N	N
BAND P 16	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N
BAND P 17	N	N	Y	N	N	N	Y	N	Y	N	N	N	N	N	N	N
BAND P 18	N	N	Y	N	N	N	Y	N	Y	N	N	N	N	N	N	N
BAND P 19	N	N	Y	N	N	N	Y	N	Y	N	N	N	N	N	N	N
BAND P 20	N	N	Y	N	N	N	Y	N	Y	N	N	N	N	N	N	N
BAND P 21	N	N	Y	N	N	N	Y	N	Y	N	N	N	N	N	N	N
BAND P 22	N	N	Y	N	N	Y	Y	N	Y	N	N	N	N	N	N	N
BAND P 23	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N
BAND P 24	N	N	Y	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y
BAND P 25	N	N	Y	N	N	N	N	N	Y	N	Y	N	N	N	N	Y
BAND P 26	N	N	Y	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y
BAND P 27	N	N	Y	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y
BAND P 28	N	N	Y	N	N	N	Y	N	Y	N	N	N	Y	N	N	N
BAND P 29	N	N	Y	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N
BAND P 30	N	N	Y	N	N	N	N	N	Y	N	Y	N	N	N	N	Y
BAND P 31	N	N	Y	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y
BAND P 32	N	N	Y	N	N	N	N	N	Y	N	Y	N	N	N	N	Y
BAND P 33	N	N	Y	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y
BAND P 34	N	N	Y	N	N	N	Y	N	Y	N	N	N	Y	N	N	N
BAND P 35	N	N	Y	N	N	N	N	N	Y	N	Y	N	N	N	N	N

Table 18 (continued). Plot sampling history at four ecosites in three National Parks (BAND, GRCA, MEVE). Data from [Figure 41](#). Data is represented by lettering: Y = the plot was sampled that year, and N = the plot was not sampled that year. Data from 2007 was dropped from analysis since only one site was sampled that year.

Plot Number	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
BAND P 36	N	N	Y	N	N	N	N	N	Y	N	Y	N	N	N	N	Y
BAND P 37	N	N	Y	N	N	Y	N	N	Y	N	Y	N	N	N	N	N
BAND P 38	N	N	Y	N	N	N	N	N	Y	N	Y	N	N	N	N	N
BAND P 39	N	N	Y	N	N	N	N	N	Y	N	Y	N	N	N	N	N
BAND P 40	N	N	Y	N	N	N	N	N	Y	N	Y	N	N	N	N	Y
BAND P 41	N	N	N	Y	N	N	N	N	Y	N	Y	N	N	N	N	N
BAND P 42	N	N	N	Y	N	N	N	N	Y	N	Y	N	N	N	N	Y
BAND P 43	N	N	N	Y	N	N	N	N	Y	Y	Y	N	N	N	N	N
BAND P 44	N	N	N	Y	N	Y	N	N	Y	N	Y	N	N	N	N	Y
BAND P 45	N	N	N	Y	N	N	N	N	Y	N	Y	N	N	N	N	N
BAND P 46	N	N	N	Y	N	N	N	N	Y	N	Y	N	N	N	N	Y
BAND P 47	N	N	N	N	N	N	Y	N	N	N	Y	N	Y	N	N	N
BAND P 48	N	N	N	N	N	N	Y	N	Y	N	N	N	Y	N	N	N
BAND P 49	N	N	N	N	N	N	N	N	Y	N	N	N	Y	N	N	N
GRCA P 1	N	N	N	Y	Y	Y	N	N	N	Y	N	Y	N	N	N	N
GRCA P 2	N	N	N	Y	Y	Y	N	N	N	Y	N	Y	N	N	N	N
GRCA P 3	N	N	N	Y	Y	Y	N	N	N	Y	N	Y	N	N	N	N
GRCA P 4	N	N	N	Y	Y	Y	N	N	N	Y	N	Y	N	N	N	N
GRCA P 5	N	N	N	Y	Y	Y	N	N	N	Y	N	Y	N	N	N	N
GRCA P 6	N	N	N	Y	Y	Y	N	N	N	Y	N	Y	N	N	N	N
GRCA P 7	N	N	N	Y	Y	Y	N	N	N	Y	N	Y	N	N	N	N
GRCA P 8	N	N	N	Y	Y	Y	N	N	N	Y	N	Y	N	N	N	N
GRCA P 9	N	N	N	Y	Y	Y	N	N	N	Y	N	Y	N	N	N	N
GRCA P 10	N	N	N	Y	Y	Y	N	N	N	Y	N	Y	N	N	N	N

Table 18 (continued). Plot sampling history at four ecosites in three National Parks (BAND, GRCA, MEVE). Data from [Figure 41](#). Data is represented by lettering: Y = the plot was sampled that year, and N = the plot was not sampled that year. Data from 2007 was dropped from analysis since only one site was sampled that year.

Plot Number	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
GRCA P 11	N	N	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y	N
GRCA P 12	N	N	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y	N
GRCA P 13	N	N	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y	N
GRCA P 14	N	N	N	N	N	Y	N	Y	N	Y	N	N	N	N	Y	N
GRCA P 15	N	N	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y	N
GRCA P 16	N	N	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y	N
GRCA P 17	N	N	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y	N
GRCA P 18	N	N	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y	N
GRCA P 19	N	N	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y	N
GRCA P 20	N	N	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y	N
GRCA P 21	N	N	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y	N
GRCA P 22	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
GRCA P 23	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
GRCA P 24	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
GRCA P 25	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
GRCA P 26	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
GRCA P 27	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
GRCA P 28	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
GRCA P 29	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
GRCA P 30	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
MEVE L 1	Y	Y	Y	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N
MEVE L 2	Y	Y	Y	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N
MEVE L 3	Y	Y	Y	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y
MEVE L 6	Y	Y	Y	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N

Table 18 (continued). Plot sampling history at four ecosites in three National Parks (BAND, GRCA, MEVE). Data from [Figure 41](#). Data is represented by lettering: Y = the plot was sampled that year, and N = the plot was not sampled that year. Data from 2007 was dropped from analysis since only one site was sampled that year.

Plot Number	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
MEVE L 7	Y	Y	Y	N	N	N	Y	N	N	N	Y	N	Y	N	N	N
MEVE L 8	Y	Y	Y	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N
MEVE L 9	Y	Y	Y	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y
MEVE L 10	Y	Y	Y	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y
MEVE L 11	N	N	N	Y	N	N	Y	N	N	Y	Y	N	Y	N	N	N
MEVE L 12	N	N	N	Y	N	N	N	N	Y	N	Y	N	N	N	N	Y
MEVE L 13	N	N	N	Y	N	N	Y	N	N	Y	Y	N	Y	N	N	N
MEVE L 14	N	N	N	Y	N	N	Y	N	N	N	N	N	Y	N	N	Y
MEVE L 15	N	N	N	Y	N	N	Y	N	Y	N	N	N	Y	N	N	Y
MEVE L 16	N	N	N	Y	N	N	N	N	Y	N	Y	N	N	N	Nn	Y
MEVE L 17	N	N	N	Y	N	N	Y	N	Y	Y	Y	N	Y	N	N	N
MEVE L 18	N	N	N	N	Y	N	N	N	N	N	Y	N	N	N	N	Y
MEVE L 19	N	N	N	N	Y	N	N	N	Y	N	Y	N	N	N	N	Y
MEVE L 20	N	N	N	N	Y	N	Y	N	Y	Y	N	N	Y	N	N	Y
MEVE L 21	N	N	N	N	Y	N	Y	N	Y	N	Y	N	Y	N	N	N
MEVE L 22	N	N	N	N	Y	N	Y	N	N	N	N	N	Y	N	N	Y
MEVE L 23	N	N	N	N	Y	N	N	N	Y	N	Y	N	N	N	N	Y
MEVE L 24	N	N	N	N	Y	N	N	N	Y	N	Y	N	N	N	N	Y
MEVE L 25	N	N	N	N	Y	N	N	N	Y	N	Y	N	N	N	N	Y
MEVE L 26	N	N	N	N	Y	N	N	N	Y	N	Y	N	N	N	N	Y
MEVE L 27	N	N	N	Y	N	N	Y	N	Y	N	N	N	Y	N	N	Y
MEVE L 28	N	N	N	Y	N	N	N	N	Y	N	N	N	Y	N	N	Y
MEVE L 29	N	N	N	Y	N	N	N	N	Y	N	Y	N	N	N	N	Y
MEVE L 30	N	N	N	N	Y	N	Y	N	N	Y	Y	N	Y	N	N	N

Table 18 (continued). Plot sampling history at four ecosites in three National Parks (BAND, GRCA, MEVE). Data from [Figure 41](#). Data is represented by lettering: Y = the plot was sampled that year, and N = the plot was not sampled that year. Data from 2007 was dropped from analysis since only one site was sampled that year.

Plot Number	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
MEVE L 31	N	N	N	N	N	N	Y	N	Y	N	Y	N	N	N	N	Y
MEVE L 32	N	N	N	N	N	N	Y	N	Y	N	N	N	Y	N	N	Y
MEVE S 1	N	N	N	N	N	Y	N	N	N	Y	N	Y	N	N	N	N
MEVE S 2	N	N	N	N	N	Y	N	Y	N	Y	N	Y	N	N	N	N
MEVE S 3	N	N	N	N	N	Y	N	N	N	Y	N	Y	N	N	N	N
MEVE S 4	N	N	N	N	N	Y	N	Y	N	Y	N	Y	N	N	N	N
MEVE S 5	N	N	N	N	N	Y	N	Y	N	Y	N	Y	N	N	N	N
MEVE S 6	N	N	N	N	N	Y	N	Y	N	N	Y	Y	N	N	N	N
MEVE S 7	N	N	N	N	N	Y	N	Y	N	Y	N	Y	N	N	N	N
MEVE S 8	N	N	N	N	N	Y	N	N	N	Y	N	Y	N	N	N	N
MEVE S 9	N	N	N	N	N	Y	N	N	N	Y	N	Y	N	N	N	N
MEVE S 10	N	N	N	N	N	Y	N	Y	N	Y	N	Y	N	N	N	N
MEVE S 11	N	N	N	N	N	N	N	Y	N	N	Y	Y	N	N	N	N
MEVE S 13	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
MEVE S 14	N	N	N	N	N	N	N	Y	N	N	Y	Y	N	N	Y	N
MEVE S 15	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
MEVE S 16	N	N	N	N	N	N	N	Y	N	Y	N	Y	N	N	Y	N
MEVE S 17	N	N	N	N	N	N	N	Y	N	N	Y	Y	N	N	Y	N
MEVE S 18	N	N	N	N	N	N	N	Y	N	N	Y	Y	N	N	Y	N
MEVE S 19	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	N	N
MEVE S 20	N	N	N	N	N	N	N	Y	N	N	Y	Y	N	N	Y	N
MEVE S 21	N	N	N	N	N	N	N	Y	N	Y	N	Y	N	N	Y	N
MEVE S 22	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
MEVE S 23	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N

Table 18 (continued). Plot sampling history at four ecosites in three National Parks (BAND, GRCA, MEVE). Data from [Figure 41](#). Data is represented by lettering: Y = the plot was sampled that year, and N = the plot was not sampled that year. Data from 2007 was dropped from analysis since only one site was sampled that year.

Plot Number	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
MEVE S 24	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
MEVE S 25	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
MEVE S 26	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
MEVE S 27	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	N	N
MEVE S 28	N	N	N	N	N	N	N	Y	N	N	Y	Y	N	N	Y	N
MEVE S 29	N	N	N	N	N	N	N	Y	N	N	Y	Y	N	N	Y	N
MEVE S 30	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N	Y	N
MEVE S 31	N	N	N	N	N	N	N	N	N	Y	N	Y	N	N	N	N

National Park Service
U.S. Department of the Interior



Science Report NPS/SR—2025/307
<https://doi.org/10.36967/2312771>

Natural Resource Stewardship and Science

1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525