



Southeast Utah Group Climate and Drought Adaptation Report

Exposure and Perennial Grass Sensitivity

Natural Resource Report NPS/NCPN/NRR—2022/2432



ON THE COVER

Grasslands in Canyonlands National Park
NPS/Amy Washuta

Southeast Utah Group Climate and Drought Adaptation Report

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Executive Summary

National Park Service (NPS) managers face growing challenges resulting from the effects of climate change. In particular, as temperatures rise in coming decades, natural resource management in the western United States must cope with expectations for elevated severity and frequency of droughts. These challenges are particularly pronounced for vegetation managers in dryland environments. Developing adaptive strategies requires specific information about the expected magnitude of change in climate and drought conditions as well as insights into how those changes will affect important vegetation resources. This report describes research focused on Southeast Utah Group (SEUG) park units designed to provide information about exposure and sensitivity of perennial grasses to aridification. Analyses at larger regional scales are also reported for context and comparison.

This report is a product of an ongoing climate adaptation collaboration between the U.S. Geological Survey (USGS), NPS, and Northern Arizona University. The study it summarizes contributes quantitative ingredients for vulnerability assessments that are needed in the Climate-Smart Conservation framework. As such, the results informed a series of climate adaptation workshops conducted between 2018 and 2021 for Colorado Plateau scientists and managers. This is a giant step forward in science-informed management. The information in this report can be used to craft management strategies that can be implemented at the right place and time for individual species of concern.

Climate Exposure

An ecosystem water-balance model was applied to evaluate the exposure of SEUG park units to climate change and drought. Integrated long-term climate projections drawn from a broad suite of climate models were used with the water-balance model to generate long-term projections of soil moisture and drought conditions within SEUG parks. The water-balance model includes increasing plant water-use efficiency under higher future atmospheric CO₂ levels and was applied to quantify the direction and magnitude of expected change and consistency of change among climate models for several variables related to ecologically relevant drought conditions.

The results clearly indicate increasing temperatures and associated increases in moisture demand from the atmosphere. Precipitation projections are much more variable, with median projections indicating potentially modest increases in precipitation during the spring and fall. These conditions, combined with elevated plant water-use efficiency, create variable projections for future soil moisture, including potentially small increases during some times of year. Overall, the findings indicate that while plants will be exposed to substantial increases in temperature, soil moisture availability is unlikely to increase commensurately, resulting in elevated plant moisture stress.

Grassland Sensitivity to Climate

To quantify grass sensitivity to future conditions, climatic niche models were created for 11 perennial grass species that are abundant on the Colorado Plateau and important to SEUG parks. These species included a mix of both C₄ (warm season) and C₃ (cool season) grasses. Overall, C₃ species habitat suitability declined, while C₄ species had mixed responses to variation in future climate conditions, and SEUG parks displayed modest variations in past and future habitat suitability. Among C₃

grasses, habitat suitability of *Hesperostipa comata* (needle and thread) was most negatively impacted throughout the Colorado Plateau, including SEUG parks, while *Achnatherum hymenoides* (Indian ricegrass) was the least affected and presumably most resilient. Among C₄ grasses, *Bouteloua gracilis* (blue grama) experienced spatially widespread declines in habitat suitability across the Colorado Plateau and SEUG parks, while *Aristida purpurea* (purple three awn), *Sporobolus airoides* (alkali sacaton), and *Bouteloua eriopoda* (black grama) experienced areas of habitat suitability increase. Those grass species that registered habitat suitability increases are generally adapted to warmer climates (e.g., more drought-adapted species with historical distributions in lower latitudes).

Management Opportunities

These results suggest that there may be management opportunities to “replace” potentially maladapted C₃ species with more heat- and drought-adapted C₄ perennial grasses in the future. The goal of this project is to create useful information for managers engaged in climate adaptation planning for SEUG parks and other grassland resources across the Colorado Plateau. Collaborative efforts between managers and researchers such as this one create opportunities to learn from one another and develop better adaptive strategies to address the ongoing effects of climate change. In particular, the results presented here may aid in the identification of specific management and experimental approaches designed to strengthen climate adaptation for SEUG parks and beyond.

Acknowledgments

We are grateful to all the NPS scientists and staff who contributed to this effort, particularly to all the staff who helped develop and confirm vegetation maps for the parks (see Table A.2.1 in Appendix 2). We are grateful to Sasha Stortz for playing a crucial role in developing and initiating this project, and to Martha Sample and Courtney Peterson, who are working with us to integrate these results into ongoing climate adaptation efforts for the SEUG parks. We appreciate the timely and professional assistance provided by Lara Schmit for editing and formatting the report.

Introduction

The Colorado Plateau is experiencing increasing temperatures, greater moisture deficits, and increasing aridification, or the gradual drying of the region resulting from climate change. Aridification is expected to include both long-term directional shifts in mean climate conditions, including consistent and substantial increases in temperature and enhanced short-term precipitation variability (Stocker et al. 2014). Increasing aridification presents considerable challenges to Southeast Utah Group (SEUG) park units: Arches National Park (ARCH), Canyonlands National Park (CANY), Hovenweep National Monument (HOVE), and Natural Bridges National Monument (NABR).

Southeast Utah has been in either severe, extreme, or exceptional drought much of the past 20 years. Climate models suggest that in the 21st century, projections for enhanced ecological drought are consistent across climate models and expected to grow over time (Bradford and Schlaepfer 2020). Reduced water availability in the 21st century is expected to cause widespread, frequent plant mortality (Breshears et al. 2018b, Law et al. 2018), failed plant regeneration (Petrie et al. 2017, Shriver et al. 2018), declines in plant growth (Gremer et al. 2015), and to create significant challenges for NPS staff tasked with sustaining plant communities.

In southeastern and southcentral Utah, NPS managers oversee more than 1.5 million acres of drylands included in the four SEUG park units, Capitol Reef National Park (CARE), and Glen Canyon National Recreation Area (GLCA). Vegetation in these parks is particularly sensitive to variability in drought conditions (Thoma et al. 2019). The SEUG parks are characterized by a high degree of physical and biotic heterogeneity. Vegetative heterogeneity is largely attributable to varying conditions of water availability resulting from complex patterns of geology and soils, and steep elevation gradients. The primary vegetation communities are perennial grasslands, shrublands, and pinyon pine-juniper woodlands. Open areas with deeper soils support grasslands. Rocky mesa tops and alluvial benches are dominated by shrublands. Higher elevation areas support woodlands. This range of species and soils provides an important opportunity to determine how different communities with varying edaphic conditions may respond to increased aridity.

The potential for widespread, frequent plant mortality is a recognized challenge for natural resource managers (Kemp et al. 2015), and it is of particular concern in dryland environments, where rising temperatures will alter climate conditions and create a “new normal.” This new normal will include typical years that have longer, hotter warm seasons; increased weather variability; and drought events that are more extreme and damaging to dryland plant and animal communities. Water is a primary resource limiting plant production, particularly in grasslands and shrublands. The dominant dependency of plant production on water availability is well-documented for Southwestern ecosystems (Sala et al. 1988, Huxman et al. 2004). Precipitation regimes, edaphic conditions, and temperature patterns are the primary controls on plant water availability, which directly influences photosynthesis, biomass production, plant mortality, and regeneration dynamics (Gremer et al. 2015, Thoma et al. 2016, Witwicki et al. 2016, Shriver et al. 2018). Shifting climate conditions will alter the suitability of SEUG parks to support plant functional groups. For example, changing ratios of

cool season and warm season perennial grasses, or increasing the extent of non-native invasive plant species, could have cascading effects on overall vegetation structure, habitat quality, and ecosystem services provided by SEUG parks (Witwicki et al. 2016).

This report describes results designed for a vulnerability assessment framework (proposed by Glick et al. (2011), Stein et al. (2014)), which involves characterizing a system's exposure, sensitivity, and adaptive capacity. Exposure refers to the magnitude of change in climate and drought conditions, including extreme events (Glick et al. 2011). Over the next century, substantial increases in temperature and shifts in drought regimes are projected for North American drylands, including the Colorado Plateau (Schlaepfer et al. 2017). Climate models consistently forecast increases in the frequency of extreme events such as severe storms and droughts (Dai 2013, Polade et al. 2014, Trenberth et al. 2015, Diffenbaugh et al. 2017, Pohl et al. 2017). Historical records show evidence of increasing rainfall variability (Groisman et al. 2005, Groisman and Knight 2008) with more intense rain events accompanied by more prolonged dry episodes. However, the implications of these changes for plant water availability remain unclear, in part because the impacts are mediated by soil conditions (Sperry and Hacke 2002). Through synthesis and modeling efforts, this effort can help clarify the relationships between these ecosystem controls and their responses.

Sensitivity represents the change in a process or state, such as plant community composition or productivity, caused by a given change in an environmental condition, such as drought. The greatest impacts of aridification will occur where both exposure and sensitivity are high. Insights into how and where effects are likely to be greatest can inform management decisions about how, where, and when to prioritize management action. These different sensitivities, which should have vastly different controls, together determine the vulnerability of SEUG plant communities to aridification.

Although our current understanding of how increasing aridification will affect NPS ecosystems is improving, we have insufficient integration of science to develop optimal management solutions. Excellent science exists; however, we need to mobilize and connect that science with park needs through real time applications that warn of change or threshold conditions. Research is needed to assess the vulnerability of cultural properties (e.g., National Register-eligible archeological sites) and natural resources (e.g., vegetation communities and wildlife species) to increasing moisture deficits. The focus here is on understanding plant water availability as a key component in the translation of climate to vulnerability in the SEUG parks.

A better understanding of both the vulnerability of SEUG park resources and the array of science-based tools available for developing management alternatives creates opportunities for managers to respond to the challenges created by climate change and drought. That knowledge, combined with the ability to capitalize on increasingly accurate weather forecasts and a suite of adaptive management actions (Bradford et al. 2018), will provide managers a framework within which optimal decisions can be made in responding to aridification.

Objectives

The Climate-Smart Conservation guide (Stein et al. 2014) recommends incorporating assessments of vulnerability into management planning and activities to advance effective climate adaptation (Figure

1). The Southeast Utah Group Climate Adaptation Working Group, a collaborative partnership of managers and scientists, agreed to advance climate adaptation planning through a series of workshops described below and in Appendix 1. As a first step, the project team worked with NPS staff at SEUG and nearby parks to develop consistent parkwide vegetation maps to be used in the subsequent analysis. The overall objectives of this report are to (1) characterize the climate and drought exposure of SEUG parks, and (2) assess the climate and drought sensitivity of important Colorado Plateau perennial grasses.

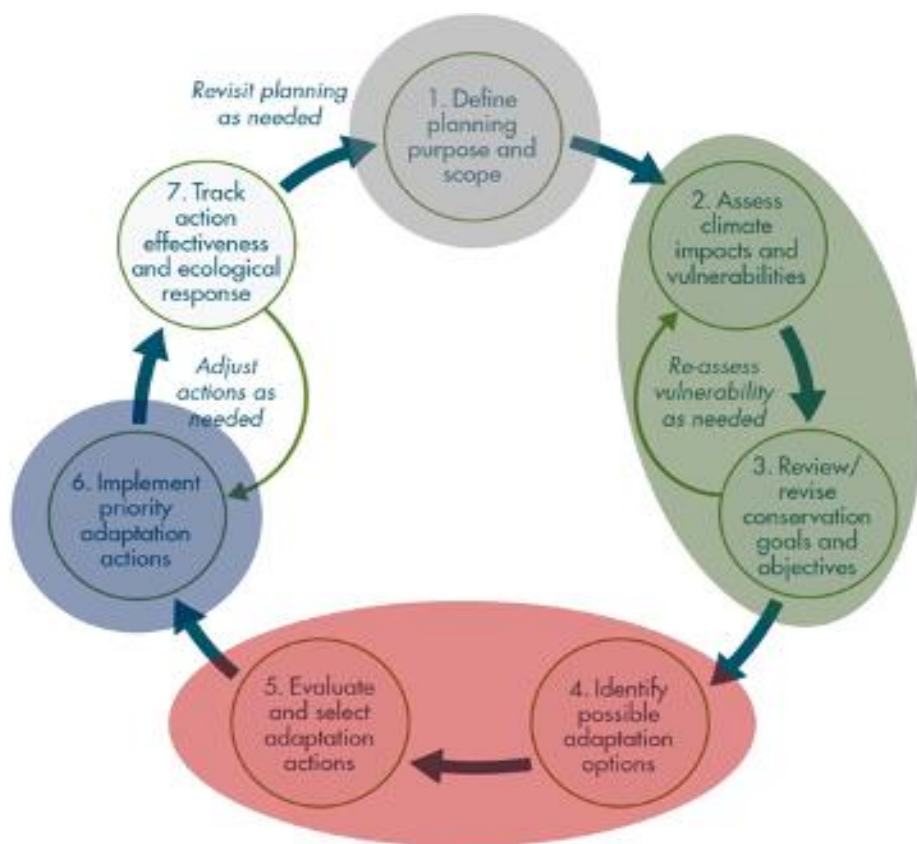


Figure 1. Climate-smart conservation cycle (from Stein et al. 2014), illustrating how the activities of this project will advance adaptive management. Planning efforts (shown in gray) have defined the overall goal of this project, which is conserving perennial grass communities in the context of rising aridity. This report describes outcomes from Objectives 1 and 2 of the project (green area above), focused on characterizing vulnerability and potential impacts on these plant communities. Results are being used to identify and evaluate potential management strategies (red area above, Appendix 1), and to work with NPS Southeast Utah Group resource managers to develop tools and strategies that aid in the implementation of the adaptive strategies (blue area above). This project is a first step in building long-term decision support relationships between resource managers and research scientists. These relationships can sustain the adaptive conservation approaches that are recognized as the best strategy for managing resources in a time of dramatic environmental change.

To assess climate and drought exposure (objective 1), we quantified past and expected future patterns of temperature, precipitation, and soil moisture across soil depths and seasons using an ecosystem

water-balance model. To quantify grass sensitivity to future conditions (objective 2), we developed climatic niche models for 11 perennial grass species that are abundant on the Colorado Plateau and important to SEUG parks. Climatic niche modeling provides a tool to identify climate conditions that are related to the species' distributions and quantify potential shifts in distribution in response to future changes in those conditions. These results indicate the locations and plant communities that may be sustained by changing management activities and those that may need to be replaced with climate-adapted plant species or genotypes. They contributed directly to the climate adaptation workshops, which were designed to guide resource managers through a process of identifying and evaluating various strategies, tactics, and actions for enhancing climate resilience in vegetation resources.

Study Areas

The study area for this report is primarily focused on the Southeast Utah Group park units, which include Arches National Park, Canyonlands National Park, Hovenweep National Monument, and Natural Bridges National Monument. The larger study area includes 19 national parks in the Four Corners region of the Southwestern United States, which encompasses the southwestern corner of Colorado, southeastern corner of Utah, northeastern corner of Arizona, and northwestern corner of New Mexico (Figure 2).

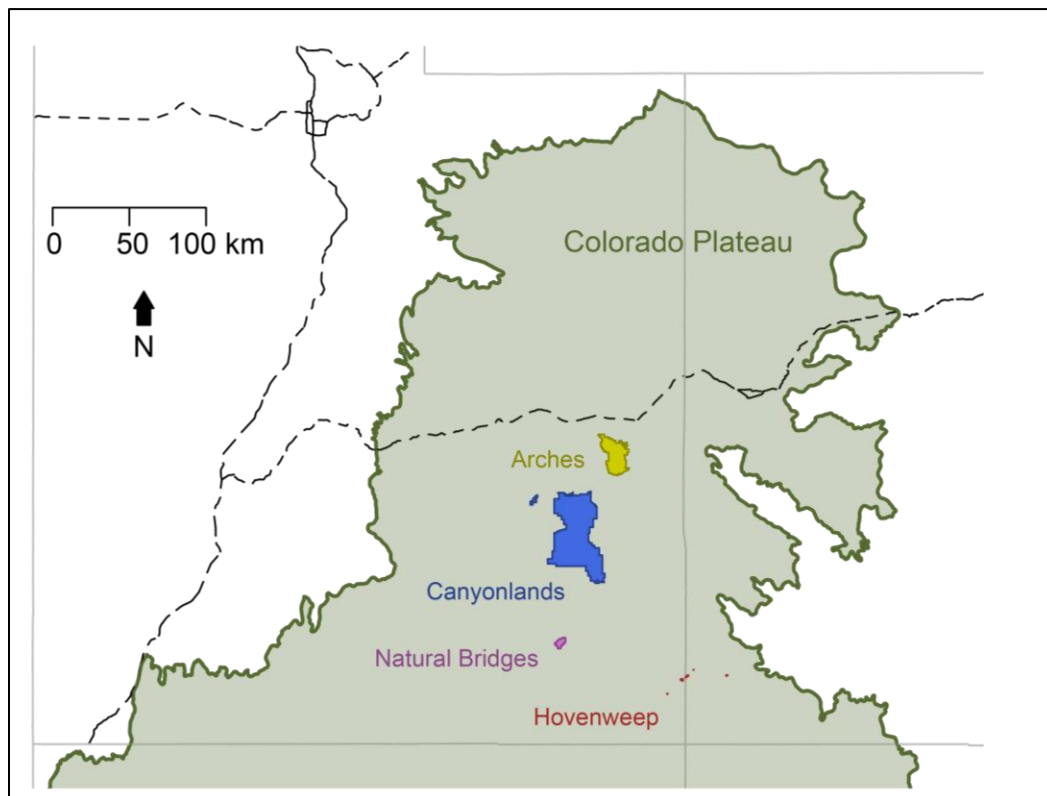


Figure 2. Map of the Southeast Utah Group of national park units that are the project's primary study area and focus of this report: Arches National Park, Canyonlands National Park, Hovenweep National Monument, and Natural Bridges National Monument.

Workshops

The sensitivity and exposure analyses presented in this report are integral to a series of climate adaptation workshops focused on the conservation of arid grasslands on the Colorado Plateau. These workshops were held by the Southeast Utah Group Climate Adaptation Working Group from 2018 to 2021. The first four working group meetings, from 2018 to 2020, were focused on identifying grasslands as the focal resource and synthesizing initial results about climate exposure and sensitivity. In the summer of 2021, a final series of four workshops was held that focused on applying the results about exposure and sensitivity to develop specific management strategies to sustain grassland resources. Appendix 1 provides a more detailed description of each workshop, including a resulting draft “Adaptation Menu of Strategies and Approaches for Colorado Plateau Arid Grasslands.”

Vegetation Mapping

To effectively evaluate the exposure and sensitivity of grasslands to climate change, it was necessary to identify and define the grassland locations in each SEUG park unit. A vegetation survey was done previously to map vegetation units across each SEUG park. The resulting vegetation units were then categorized into five vegetation classes: (1) grasslands, (2) shrublands, (3) woodlands, (4) forests, and (5) non-native vegetation. This vegetation mapping process allowed for the analysis of grassland communities separate from other vegetation communities.

Methods

The vegetation inventory maps in an ArcGIS geodatabase format were downloaded from <https://www.nps.gov/im/vmi-products.htm> for each SEUG park. These geodatabases were opened in ArcMap and exported as shapefiles with all ancillary data for each polygon within each park unit boundary. The vegetation map units correspond to the information in a report available for each park describing the vegetation map units in detail. These data were then pulled into R to ensure compatibility across each park. The park codes, column names, and attributes for each polygon were standardized across the parks. NPS staff (D. Witwicki and A. Wight) provided datasets of vegetation polygons grouped into alliances.

Map unit descriptions and descriptions from NatureServe were used to classify each vegetation polygon into the coarse classes of grasslands, shrublands, woodlands, forests, or non-native vegetation. These classifications were used to make preliminary vegetation maps for each SEUG park unit. The resulting maps and vegetation classification were shared with NPS vegetation specialists, Dana Witwicki (Northern Colorado Plateau Network, NCPN) and Megan Swan (Southern Colorado Plateau Network, SCPN), to adjust and confirm the classifications of each vegetation unit into the coarse classes.

The resulting maps (Figures 3–6) were presented to the SEUG stakeholders at the 2019 Biennial Conference for Science and Management on the Colorado Plateau and Southwest Region in Flagstaff, Arizona. Project staff had conversations with key vegetation personnel from the park units, who provided contact information. Twenty-nine NPS specialists (see Table A.2.1 in Appendix 2) were consulted on the accuracy of the preliminary vegetation maps and adjustments were made as necessary. The vegetation classifications were then finalized and a final vegetation map for each park unit was produced.

Vegetation Maps

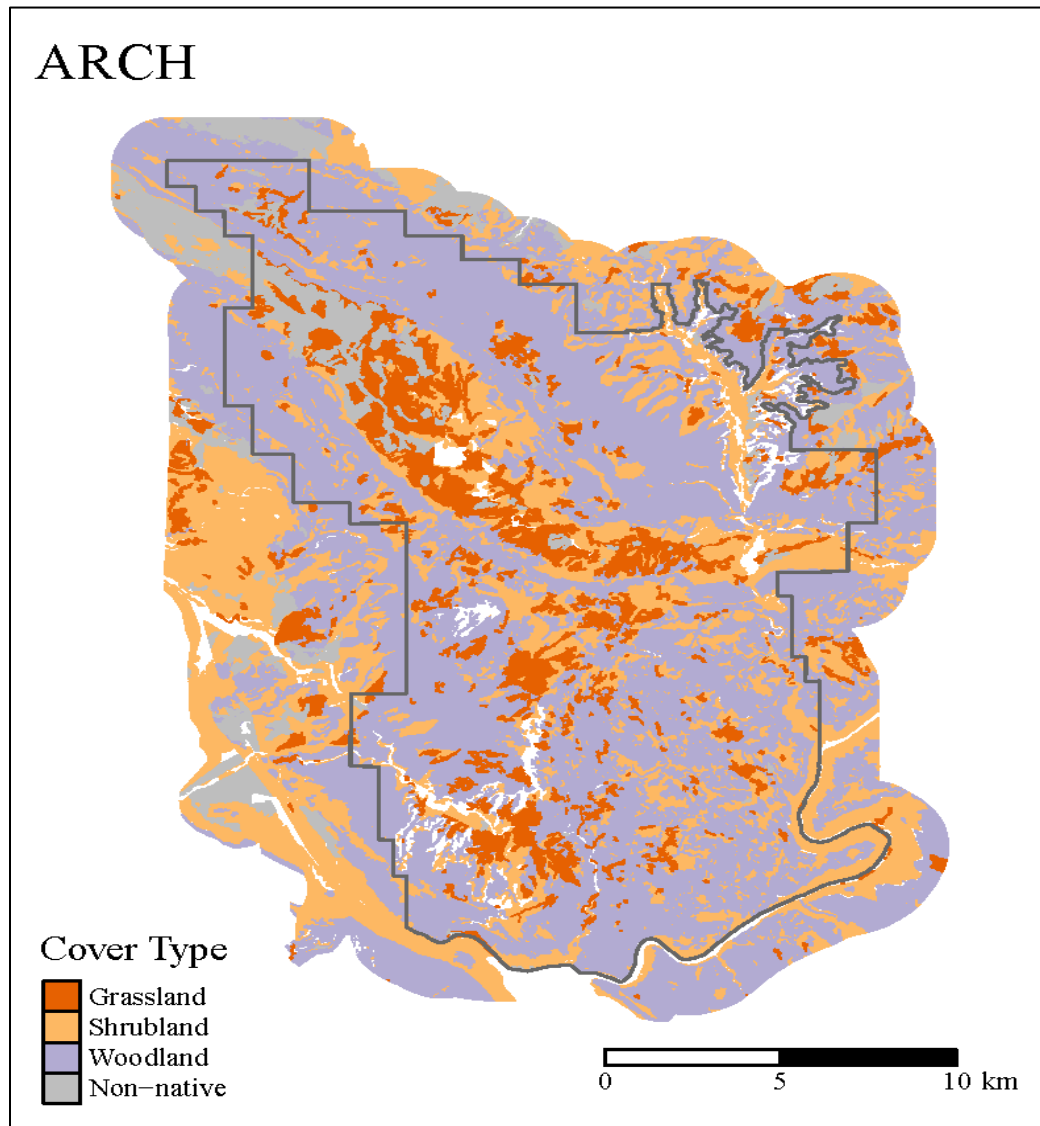


Figure 3. Arches National Park (ARCH) vegetation classes include grasslands (6%), shrublands (22%), woodlands (67%), and non-native vegetation (5%).

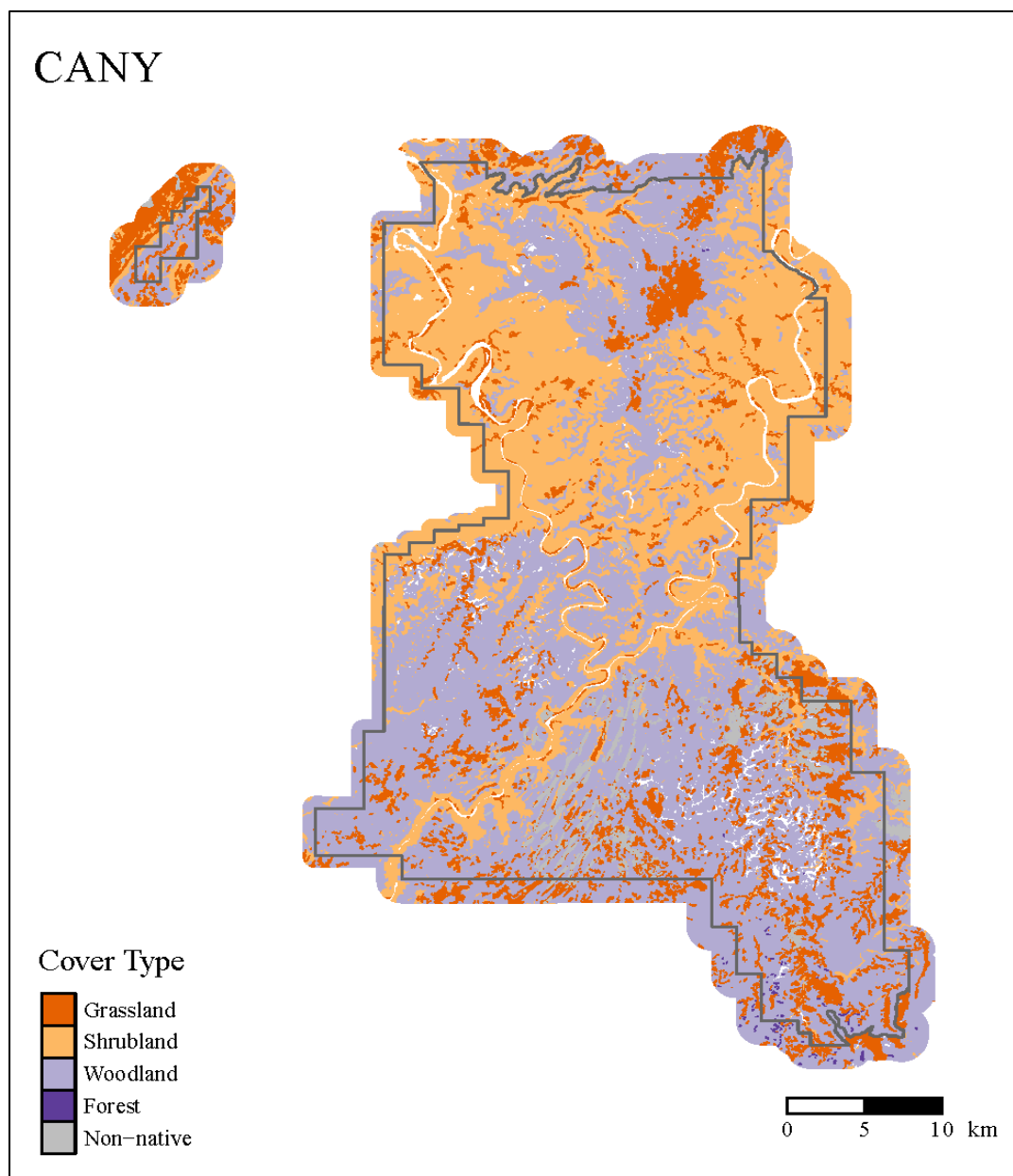


Figure 4. Canyonlands National Park (CANY) vegetation classes include grasslands (7%), shrublands (25%), woodlands (66%), forests (1%), and non-native vegetation (1%).

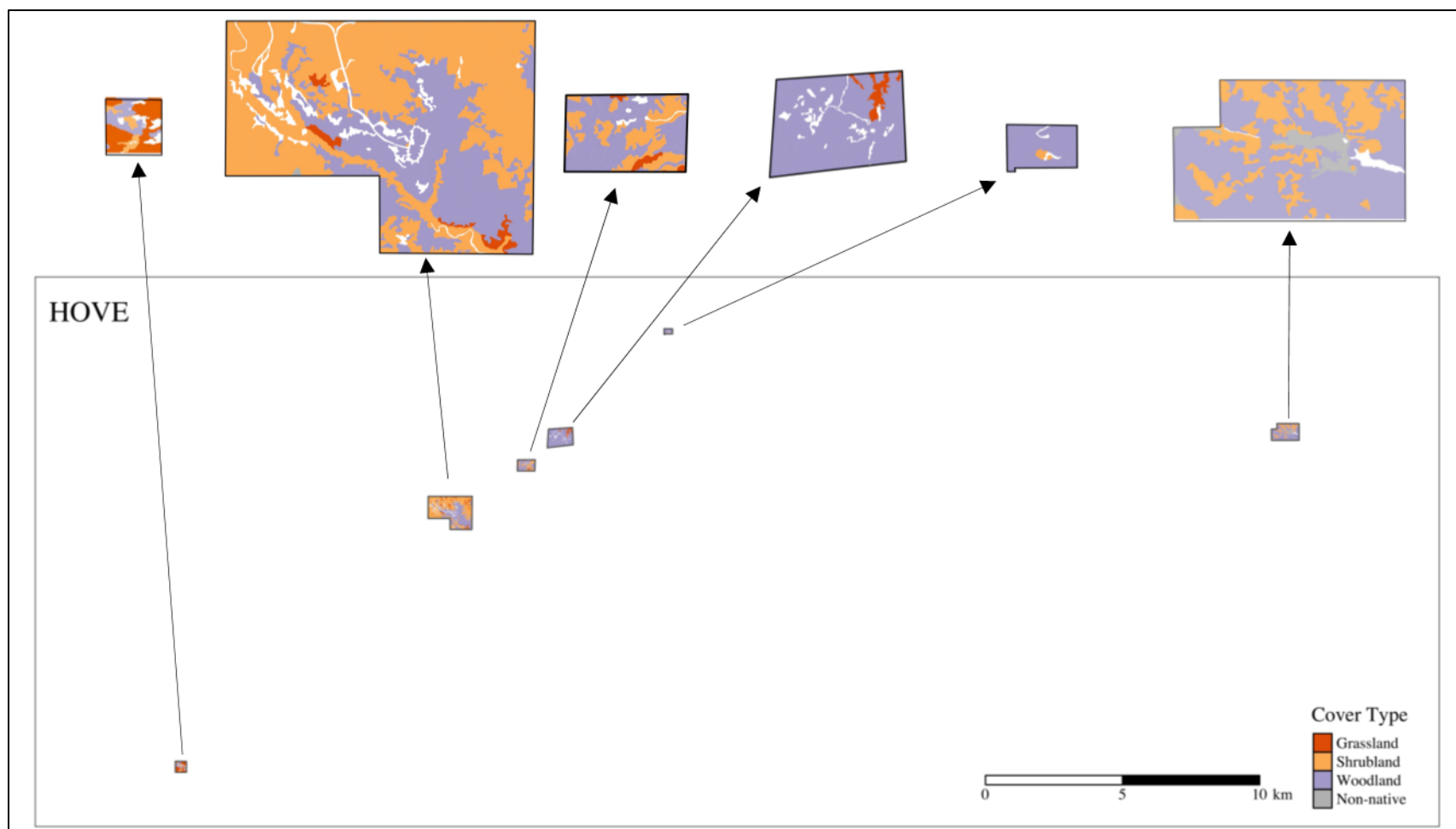


Figure 5. Hovenweep National Monument (HOVE) vegetation classes include grasslands (4%), shrublands (22%), woodlands (73%), and non-native vegetation (1%).

NABR

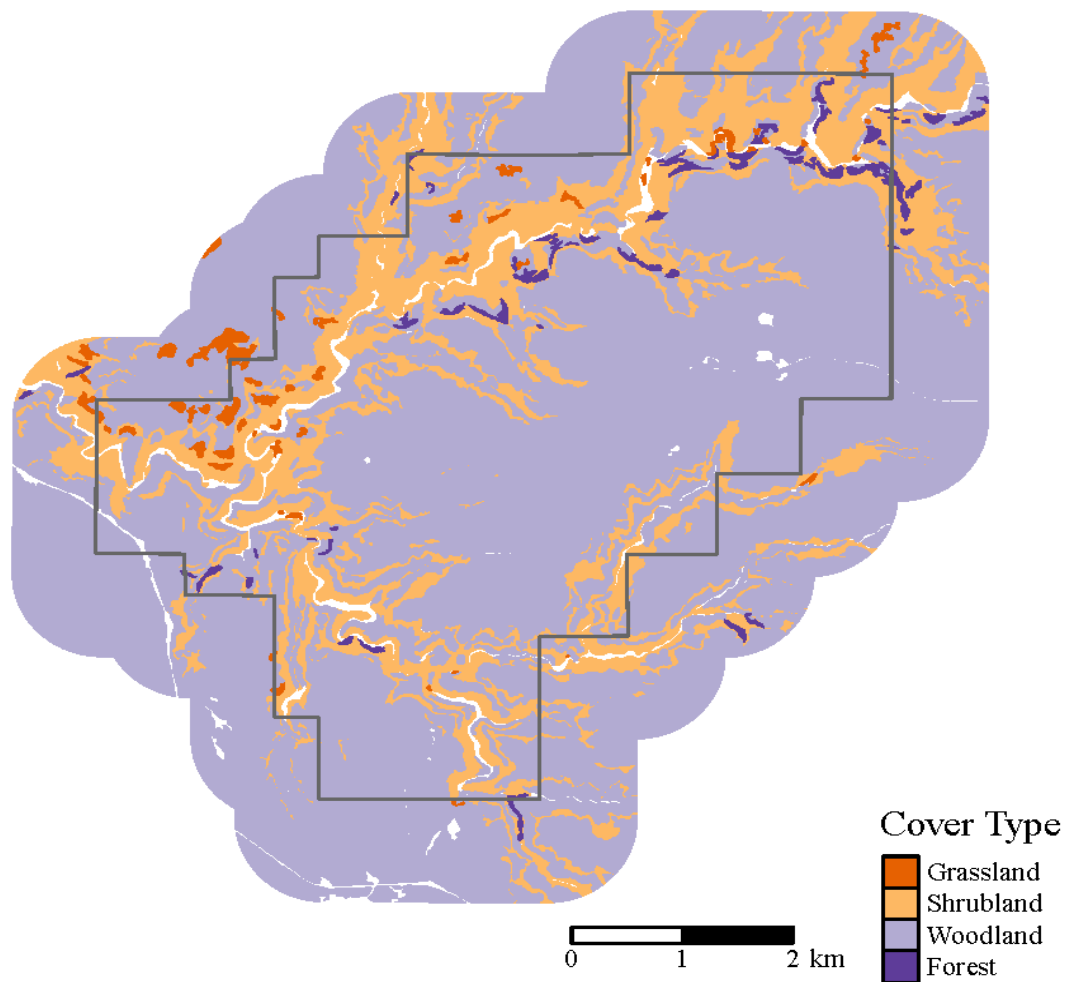


Figure 6. Natural Bridges National Monument (NABR) vegetation classes include grasslands (1%), shrubland (9%), woodlands (83%), and forest (7%).

Climate and Drought Exposure

Quantifying the magnitude and direction of change in climate and drought conditions for the Southeast Utah Group park units is one part of defining the overall vulnerability to climate change (Stein et al. 2014). Effectively estimating ecosystem response to climate change and developing appropriate adaptive strategies to sustain natural resources requires recognizing the potential direction and magnitude of future changes in both climate and ecologically relevant drought conditions. In this section, we present the exposure results in two parts: long-term monthly normals (e.g., long-term mean monthly conditions) and detailed information on specific climate metrics.

Long-term monthly normals of climate conditions show the seasonal variation in temperature, precipitation, and soil moisture at four soil depths under historical conditions and for the future for each month of the calendar year. Long-term monthly normals make it possible to identify trends and changes in the timing of temperature, precipitation, and soil moisture.

We also provide estimates for a large suite of detailed climate and drought variables under both historical and future conditions for each SEUG park unit in supplementary figures (Bradford et al. 2022). Results for each variable and park include a graphical representation of the changes forecast in the near-term (2020–2059) and long-term (2060–2099) time periods and for two representative concentration pathways (RCPs; representative concentration pathways are used by the United Nations Intergovernmental Panel on Climate Change to model climate forcing, primarily influenced by greenhouse gas concentration scenarios). The detailed information for each climate variable includes the range of predictions for each global circulation model (GCM), the departure from historical medians, and fine scale (30 m) maps of the geographic spread of predictions. Although including all these results in this report is not feasible (see Bradford et al. (2022) for full results), we present here results for four variables for illustration purposes: annual mean temperature, annual total precipitation, spring volumetric water content and fall available soil moisture. By quantifying the exposure of each park to 21st century changes in these climate variables, we hope to provide a strong background to empower future decision making and climate-smart planning by park managers.

Methods

Sample selection

Thirty-meter resolution rasters (Appendix 2) were obtained for elevation, percent sand, percent clay, percent rock fragment, depth to restrictive layer, slope, eastness, and southness (Nauman and Duniway 2020). Cells with slopes equal to or greater than thirty degrees and riparian vegetation types were filtered out. The conditioned Latin hypercube algorithm was used to select one point per square kilometer for each vegetation type, with a minimum of 25 points per vegetation type for each park (see Appendix 2). The conditioned Latin hypercube selection algorithm samples points representative of the distribution for each of the supplied attributes (Minasny and McBratney 2006).

SOILWAT2 data inputs and model outputs

Daily soil moisture and ecohydrological variables were simulated using the SOILWAT2 ecosystem water-balance model. SOILWAT2 is a process-based daily simulation model that represents upland

dryland ecosystems. It includes soils at multiple depths and vegetation as composed of multiple co-occurring plant types responsive to atmospheric CO₂ concentrations. The code is available open-source as a set of R packages including rSOILWAT2 v4.0.0 and rSFSW2 v4.3.0 (Schlaepfer and Murphy 2018, Schlaepfer and Andrews 2019). Previous model applications and model evaluations include global dryland ecosystems (e.g., Bradford et al. 2017, Schlaepfer et al. 2017, Tietjen et al. 2017), North American dry grasslands (e.g., Bradford et al. 2014b, Lauenroth et al. 2014), dry forests (Bradford et al. 2014a), and shrublands (e.g., Schlaepfer et al. 2012b, Palmquist et al. 2016a, Renne et al. 2019), as well as simulations under climate change projections (Schlaepfer et al. 2012c, a, Schlaepfer et al. 2015, Palmquist et al. 2016b, a, Bradford et al. 2019).

SOILWAT2 simulations were run for the 2,352 sites across all four SEUG park units for three time periods: 1980–2018, 1950–2005, and 2006–2099. Daily meteorological variables from the gridMET dataset (accessed from <http://www.climatologylab.org/gridmet.html>; Abatzoglou and Brown 2012) were used to force SOILWAT2 simulations for the “observed” time period 1980–2018. Also used in the model were climate projections derived for CMIP5 from 20 global circulation models (GCMs, Appendix 2) that were statistically downscaled to daily values with the multivariate adaptive constructed analog (MACA) method relative to the gridMET dataset (accessed from <http://www.climatologylab.org/maca.html>; Abatzoglou and Brown 2012). Projections from the historical runs were used to force SOILWAT2 simulations for the period 1950–2005. Projections under two representative concentration pathways (RCPs)—the medium mitigation and stabilization scenario RCP 4.5 and the high baseline, no-policy scenario RCP 8.5 (Van Vuuren et al. 2011)—were used as forcing for the period 2006–2099.

Additional inputs for SOILWAT2 include climate data, topographic information, soils information, and vegetation parameters. Monthly climate normals for wind speed, relative humidity, and sky cover were extracted from the National Centers for Environment Prediction/Climate Forecast System Reanalysis (NCEP/CFSR; Saha et al. 2010), which contribute to the estimation of evaporative demand following Penman (1948). Elevation, slope, and slope aspect at each site were extracted from Nauman and Duniway (2020) and contribute to the estimation of daily tilted irradiation using the anisotropic transposition model HDKR (Reindl et al. 1990) with updates for daily integrated terms (Allen et al. 2006).

Soil depth, bulk density, volume of coarse rock fragments, and the proportions of sand, clay, and silt were obtained from Nauman and Duniway (2020). The soil profiles were linearly interpolated to 5 cm increments and then averaged for soil layers of 0–10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 150, 200, and 250 cm depth unless soil depth was shallower. Vegetation cover was extracted based on National Land Cover Database Shrubland Components v12 (Rigge et al. 2020) for fractional cover of trees, shrubs, herbaceous, and annual herbaceous types. Estimates were made for each site and time period (i.e., depending on the daily meteorological forcing/downscaled climate projections) of the relative contribution of C₃ and C₄ grasses towards the herbaceous type. Estimates were also made for monthly biomass, litter, and root depth distributions from climate conditions for each vegetation type using methods described in Bradford et al. (2014b).

From daily SOILWAT2 output variables, including soil moisture at 13 soil layers, calculations were made for a range of time-series exposure metrics aggregated into four seasons (winter: December–February; spring: March–May; summer: June–August; fall: September–November) and two soil zones (top: 0–50 cm; whole profile: 0–soil depth).

The calculations were based on the following inputs:

- precipitation
- mean, minimum, and maximum air temperature
- days below -1 °C
- climate seasonality (monthly temperature-precipitation correlation)

and from simulated outputs:

- potential evapotranspiration (PET)
- transpiration (T)
- evaporation (E)
- soil volumetric water content (VWC)
- soil water availability (SWA, soil moisture above -3.9 MPa)
- wet soil days (soil water potential (SWP) in any soil layer greater than -1.5 MPa)
- dry soil days (SWP in all soil layers less than -3.9 MPa)
- SWA during not dry soil days (SWA on days with SWP in any soil layer greater than -3.9 MPa)
- extreme short-term dry stress (mean daily maximum air temperature of the 10 hottest day when SWP of all soil layers less than -3.9 MPa)
- semi-dry soil duration length (mean length of continuous days with SWP in all soil layers less than -1.5 MPa)

Additionally, we calculated mean monthly normals from the inputs mean air temperature and precipitation sum and from the output soil water potential for each simulated soil layer.

The output from SOILWAT2 for each of the stratified random points was then used to geographically represent the entire park unit. Mahalanobis distance from each stratified random point to other cells was found and the nearest neighbor was used to match each cell to a random point. For climate variables, the cell attributes of latitude, longitude, elevation, slope, and southness were used. For soil outputs, the variables latitude, longitude, elevation, percent sand, and percent clay were used to find cell similarity. The resulting maps provide parkwide predictions of future soil and weather conditions on the fine scale. All data are available through the United States Geological Survey data repository (Hartsell et al. 2022).

Exposure Results

Detailed methods, tables, and figures for the exposure analyses are accessible in Appendix 2 and in supplementary figures (Bradford et al. 2022). Underlying data are available from the US Geological Survey's digital repository, ScienceBase, at

<https://www.sciencebase.gov/catalog/item/61a6952fd34eb622f6978d9f>.

Long-term monthly normals

Long-term temperature projections include increases that are relatively consistent among climate models throughout the year. Temperature increases are greater under RCP 8.5 than RCP 4.5, and greater at the end of the 21st century than in the middle of the 21st century (Table 1, Figures 7–10).

By contrast, projected changes in precipitation are much more variable among climate models, although median projections indicate slight increases in precipitation during spring and fall. Annual seasonal variation in soil moisture is affected by interactions among temperature, winter moisture, and monsoonal rain. The SEUG parks experience wet winters and dry springs, with a replenishing of soil moisture during the summer monsoon period beginning in July. The soils become increasingly dry from April to June until summer monsoons begin. Deeper soil layers remain dry until the winter, but shallow levels are quickly replenished with summer rain (Figures 7–10). The seasonal pattern is similar for all four SEUG parks. This pattern is projected to continue, but projections are less certain during the monsoon season by the end of the century.

Table 1. Average annual temperature (Tavg), annual average precipitation (PPT), and seasonal soil volumetric water content (VWC) for each of the Southeast Utah Group national park units. Shown are the median global circulation models (GCM), change (delta) between historical and median GCM, and percent change (percent delta) from historical for each of the emission scenarios (RCP) and long-term (LT; 2060–2099) and near-term (NT; 2020–2059) time periods.

Var	Season	Time Period	RCP	Arches National Park			Canyonlands National Park			Hovenweep National Monument			Natural Bridges National Monument		
				Median	Delta	Percent Delta	Median	Delta	Percent Delta	Median	Delta	Percent Delta	Median	Delta	Percent Delta
Tavg (°C)	Annual	LT	4.5	15.5	2.9	NA	15.4	3.0	NA	13.6	2.9	NA	13.7	2.7	NA
	Annual	NT	4.5	14.5	1.9	NA	14.3	1.9	NA	12.6	1.9	NA	12.7	1.8	NA
	Annual	LT	8.5	17.6	5.0	NA	17.4	5.0	NA	15.6	4.9	NA	15.7	4.7	NA
	Annual	NT	8.5	14.9	2.3	NA	14.8	2.4	NA	13.1	2.4	NA	13.2	2.2	NA
	Annual	Historical	N/A	12.6	0.0	NA	12.4	0.0	NA	10.7	0.0	NA	10.9	0.0	NA
PPT (cm)	Annual	LT	4.5	26.3	0.9	0.04	23.1	1.6	0.07	32.8	1.8	0.06	31.3	2.9	0.10
	Annual	NT	4.5	25.8	0.4	0.02	22.7	1.2	0.06	32.4	1.3	0.04	30.6	2.2	0.08
	Annual	LT	8.5	26.4	1.0	0.04	23.1	1.6	0.07	32.3	1.3	0.04	30.8	2.4	0.09
	Annual	NT	8.5	26.5	1.0	0.04	22.9	1.4	0.07	32.4	1.4	0.04	31.5	3.1	0.11
	Annual	Historical	N/A	25.4	0.0	0.00	21.5	0.0	0.00	31.1	0.0	0.00	28.4	0.0	0.00
VWC (m³/m³)	Winter (Dec–Feb)	LT	4.5	0.096	0.007	0.077	0.104	0.005	0.048	0.220	0.016	0.078	0.140	0.008	0.061
	Winter (Dec–Feb)	NT	4.5	0.096	0.006	0.072	0.103	0.005	0.047	0.218	0.013	0.065	0.139	0.007	0.054
	Winter (Dec–Feb)	LT	8.5	0.096	0.007	0.076	0.104	0.005	0.050	0.223	0.018	0.089	0.143	0.011	0.083
	Winter (Dec–Feb)	NT	8.5	0.097	0.008	0.090	0.105	0.006	0.064	0.219	0.015	0.074	0.142	0.011	0.081
	Winter (Dec–Feb)	Historical	N/A	0.089	0.000	0.000	0.099	0.000	0.000	0.204	0.000	0.000	0.132	0.000	0.000
	Spring (Mar–May)	LT	4.5	0.068	-0.001	-0.018	0.075	-0.003	-0.038	0.209	0.008	0.041	0.115	0.005	0.050

Table 1 (continued). Average annual temperature (Tavg), annual average precipitation (PPT), and seasonal soil volumetric water content (VWC) for each of the Southeast Utah Group national park units. Shown are the median global circulation models (GCM), change (delta) between historical and median GCM, and percent change (percent delta) from historical for each of the emission scenarios (RCP) and long-term (LT; 2060–2099) and near-term (NT; 2020–2059) time periods.

Var	Season	Time Period	RCP	Arches National Park			Canyonlands National Park			Hovenweep National Monument			Natural Bridges National Monument		
				Median	Delta	Percent Delta	Median	Delta	Percent Delta	Median	Delta	Percent Delta	Median	Delta	Percent Delta
VWC (m³/m³) (cont.)	Spring (Mar–May)	NT	4.5	0.068	-0.002	-0.026	0.074	-0.005	-0.059	0.208	0.007	0.034	0.114	0.005	0.041
	Spring (Mar–May)	LT	8.5	0.070	0.000	0.001	0.076	-0.003	-0.034	0.212	0.011	0.054	0.116	0.007	0.060
	Spring (Mar–May)	NT	8.5	0.069	-0.001	-0.012	0.075	-0.003	-0.034	0.212	0.012	0.058	0.117	0.007	0.066
	Spring (Mar–May)	Historical	N/A	0.070	0.000	0.000	0.078	0.000	0.000	0.201	0.000	0.000	0.110	0.000	0.000
	Summer (Jun–Aug)	LT	4.5	0.037	0.000	0.006	0.048	0.000	-0.006	0.136	0.001	0.008	0.069	0.001	0.009
	Summer (Jun–Aug)	NT	4.5	0.036	0.000	-0.001	0.048	-0.001	-0.010	0.135	0.000	0.003	0.068	0.000	0.001
	Summer (Jun–Aug)	LT	8.5	0.037	0.001	0.018	0.049	0.000	0.007	0.137	0.003	0.019	0.069	0.001	0.018
	Summer (Jun–Aug)	NT	8.5	0.036	0.000	0.000	0.048	0.000	-0.009	0.136	0.001	0.007	0.069	0.000	0.007
	Summer (Jun–Aug)	Historical	N/A	0.036	0.000	0.000	0.049	0.000	0.000	0.135	0.000	0.000	0.068	0.000	0.000
	Fall (Sep–Nov)	LT	4.5	0.060	-0.002	-0.034	0.073	-0.001	-0.008	0.162	0.001	0.005	0.097	0.000	-0.004
	Fall (Sep–Nov)	NT	4.5	0.058	-0.004	-0.057	0.070	-0.003	-0.038	0.159	-0.003	-0.016	0.094	-0.003	-0.033
	Fall (Sep–Nov)	LT	8.5	0.058	-0.004	-0.066	0.070	-0.003	-0.039	0.161	-0.001	-0.005	0.097	-0.001	-0.006

Table 1 (continued). Average annual temperature (Tavg), annual average precipitation (PPT), and seasonal soil volumetric water content (VWC) for each of the Southeast Utah Group national park units. Shown are the median global circulation models (GCM), change (delta) between historical and median GCM, and percent change (percent delta) from historical for each of the emission scenarios (RCP) and long-term (LT; 2060–2099) and near-term (NT; 2020–2059) time periods.

Var	Season	Time Period	RCP	Arches National Park			Canyonlands National Park			Hovenweep National Monument			Natural Bridges National Monument		
				Median	Delta	Percent Delta	Median	Delta	Percent Delta	Median	Delta	Percent Delta	Median	Delta	Percent Delta
VWC (m³/m³) (cont.)	Fall (Sep–Nov)	NT	8.5	0.060	-0.002	-0.031	0.072	-0.001	-0.014	0.162	0.001	0.006	0.097	-0.001	-0.005
	Fall (Sep–Nov)	Historical	N/A	0.062	0.000	0.000	0.073	0.000	0.000	0.162	0.000	0.000	0.097	0.000	0.000

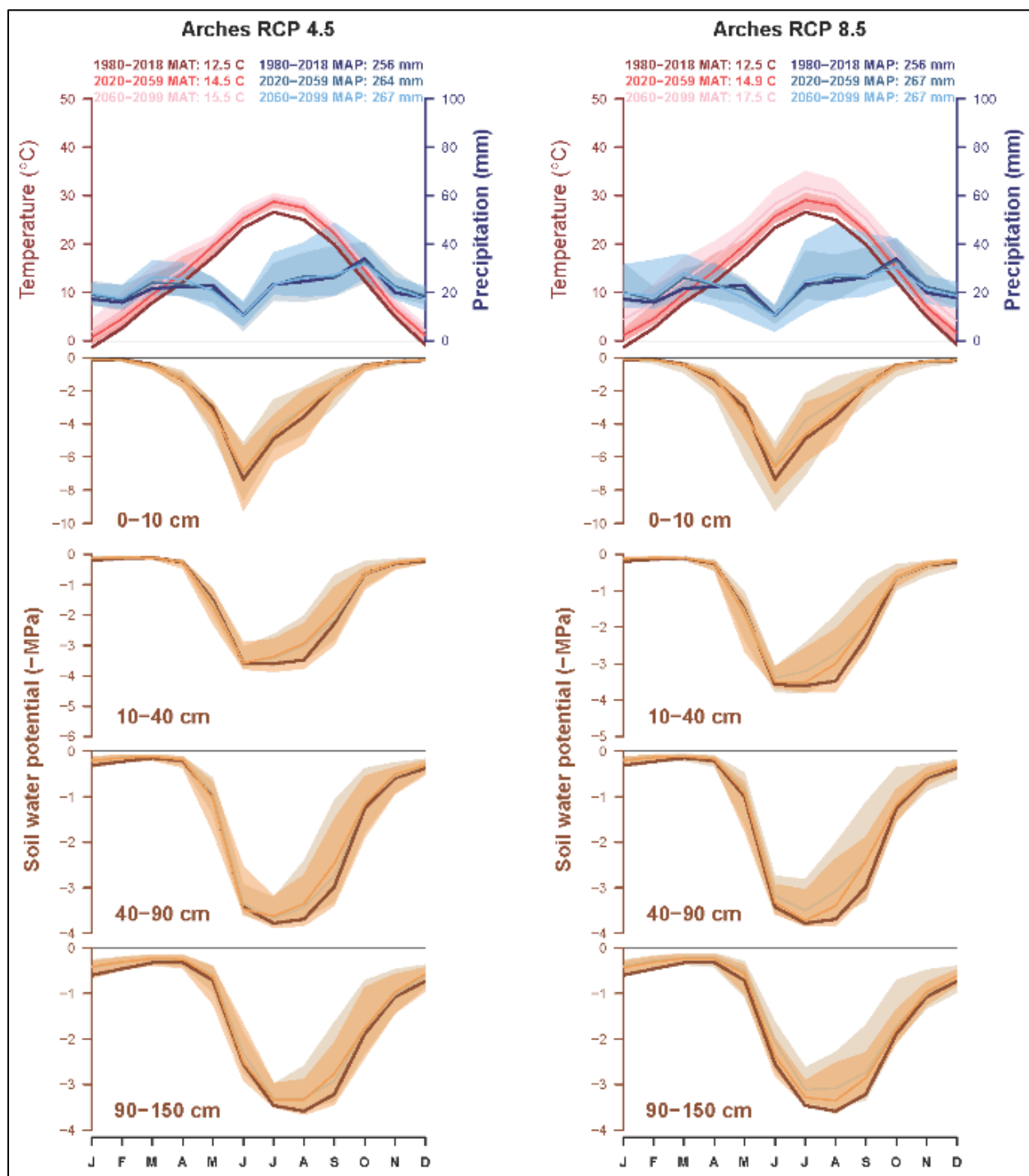


Figure 7. Climate and soil moisture exposure overview for Arches National Park (ARCH). Panels show historical and future long-term monthly normal values for precipitation, temperature, and soil moisture at four depths under representative concentration pathways RCP 4.5 and RCP 8.5. Solid lines denote median across global circulation models (GCMs) for each time period and shaded areas show the values between the minimum and maximum GCM showing variability across GCMs. MAT = mean annual temperature; MAP = mean annual precipitation.

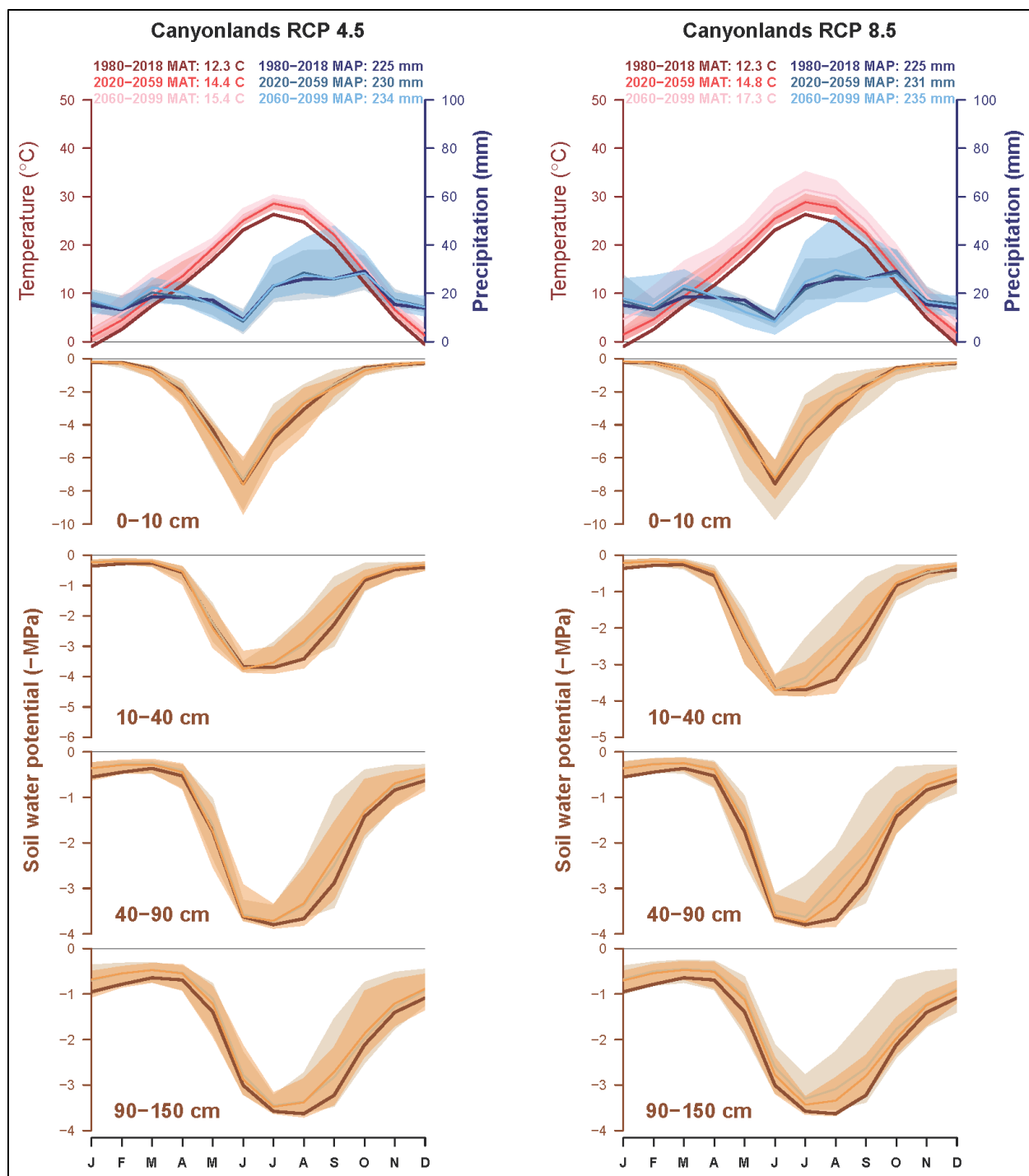


Figure 8. Climate and soil moisture exposure overview for Canyonlands National Park (CANY). Panels show historical and future long-term monthly normal values for precipitation, temperature, and soil moisture at four depths under representative concentration pathways RCP 4.5 and RCP 8.5. Solid lines denote median across global circulation models (GCMs) for each time period and shaded areas show the values between the minimum and maximum GCM showing variability between GCMs. MAT = mean annual temperature; MAP = mean annual precipitation.

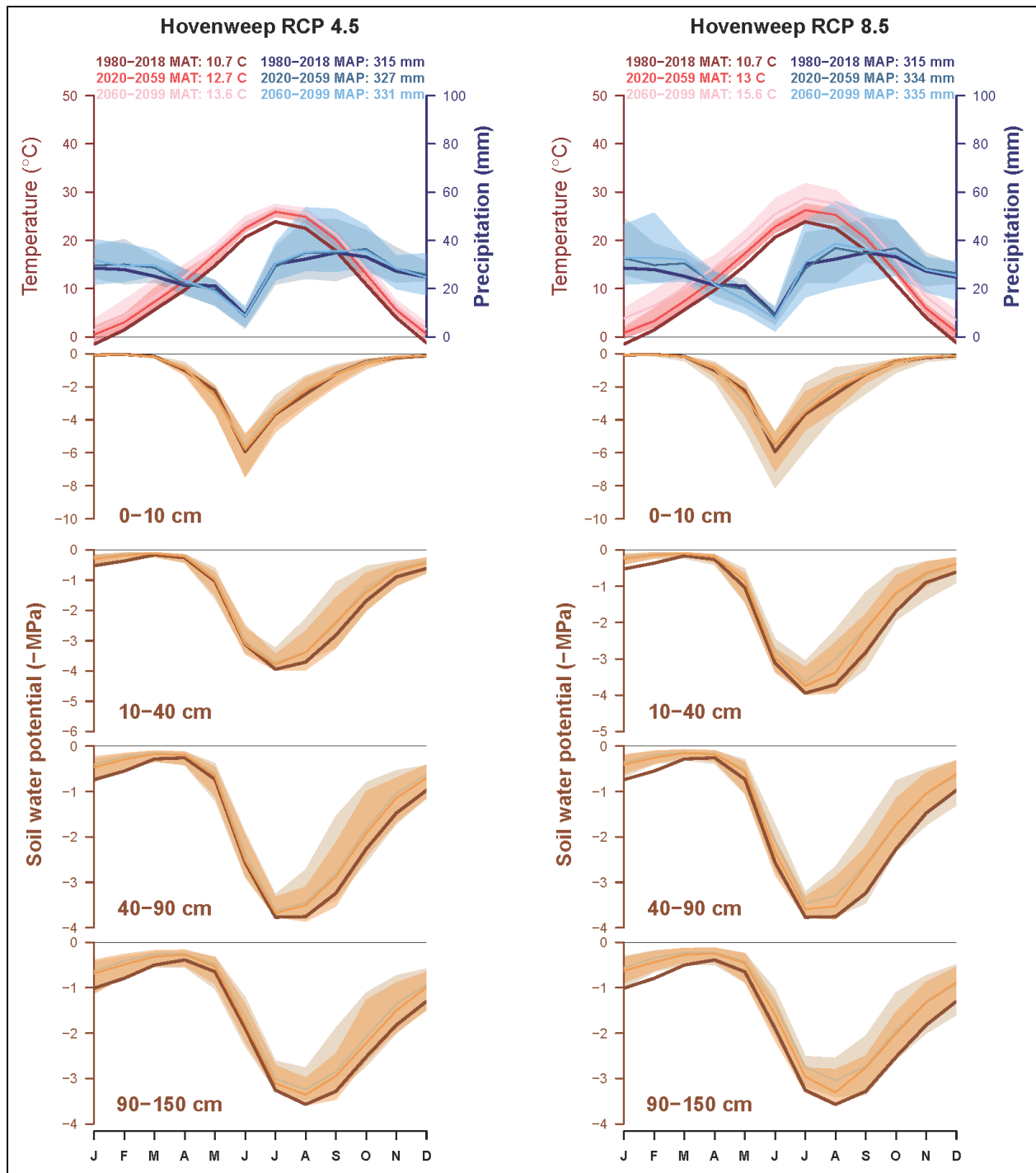


Figure 9. Climate and soil moisture exposure overview for Hovenweep National Monument (HOVE). Panels show historical and future long-term monthly normal values for precipitation, temperature, and soil moisture at four depths under representative concentration pathways RCP 4.5 and RCP 8.5. Solid lines denote median across global circulation models (GCMs) for each time period and shaded areas show the values between the minimum and maximum GCM showing variability among GCMs. MAT = mean annual temperature; MAP = mean annual precipitation.

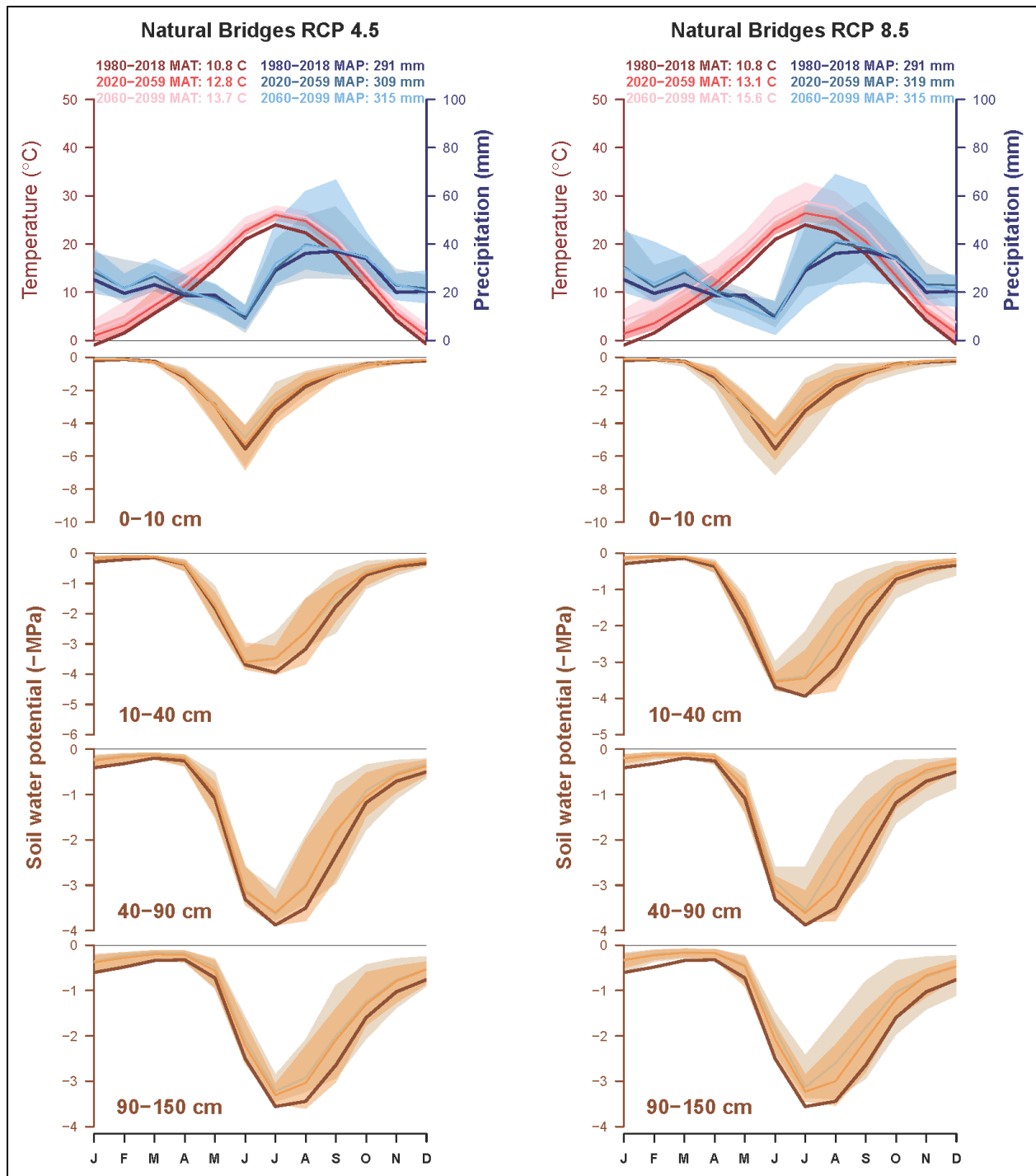


Figure 10. Climate and soil moisture exposure overview for Natural Bridges National Monument (NABR). Panels show historical and future long-term monthly normal values for precipitation, temperature, and soil moisture at four depths under representative concentration pathways RCP 4.5 and RCP 8.5. Solid lines denote median across global circulation models (GCMs) for each time period and shaded areas show the values between the minimum and maximum GCM showing variability among GCMs. MAT = mean annual temperature; MAP = mean annual precipitation.

Detailed climate and drought exposure results

The four variables described in the figures below (annual temperature, cumulative annual precipitation, volumetric soil water content, fall available soil moisture) are intended as a sample of the figures, maps, and data available from exposure analysis, using Arches National Park as an example. Complete figure series for the SEUG national park units (Arches, Canyonlands, Hovenweep, and Natural Bridges) can be found in Bradford et al. (2022) (supplementary figures). Variables include annual and/or seasonal value aggregations of mean temperature, minimum temperature, maximum temperature, frost days, potential evapotranspiration, precipitation, soil volumetric water content, soil water availability (soil moisture above -3.9 MPa), wet soil days (soil water potential in any soil layer greater than -1.5 MPa), dry soil days (soil water potential in all soil layers less than -3.9 MPa), soil water availability during not dry soil days (days with soil water potential in any soil layer greater than -3.9 MPa), extreme short-term dry stress (mean daily maximum air temperature of the 10 hottest days when soil water potential of all soil layers less than -3.9 MPa), semi-dry soil duration length (mean length of continuous days with soil water potential in all soil layers less than -1.5 MPa), transpiration, and evaporation (Table 2).

Table 2. Metrics available in the detailed climate and drought exposure results for Southeast Utah Group national parks.

Category	Variable	Definition
Meteorological conditions	Temperature (°C)	Mean annual temperature
	Minimum temperature (°C)	Lowest minimum temperature
	Maximum temperature (°C)	Highest maximum temperature
	Frost Days (days)	Count of days below -1 °C
	Potential evapotranspiration (PET) (cm/cm)	The amount of evaporation and transpiration that would occur with no moisture limitation
	Precipitation (cm)	Sum of precipitation received
	Monthly T-P correlation	Correlation (Pearsons) between monthly precipitation and average temperature across one (Dec–Nov) year
Soil moisture	Soil volumetric water content (VWC) top 50 cm (cm/cm)	Median seasonal VWC in the top 50 cm of soil
	Soil volumetric water content (VWC) entire profile (cm/cm)	Median seasonal VWC in the entire soil profile
	Available soil water (SWA) top 50 cm (cm)	Amount of water available in soil to plants (above -3.9 MPa) in the top 50 cm of soil
	Available soil water (SWA) entire profile (cm)	Amount of water available in soil to plants (above -3.9 MPa) in the entire soil profile
Ecological drought conditions	Days with wet soil (days)	Count of days with "wet" soil, defined as any soil layer being "wet" (greater than -1.5 MPa)
	Days with dry soil (days)	Count of days with "dry" soil, defined as all soil layers being "dry" (less than -3.9 MPa)

Table 2 (continued). Metrics available in the detailed climate and drought exposure results for Southeast Utah Group national parks.

Category	Variable	Definition
Ecological drought conditions	Extreme short-term drought stress (°C)	Maximum temperature of the 10 hottest days when all soil layers are "semi-dry" (less than -1.5 MPa)
	Duration of semi-dry soil spells (days)	Length of continuous days with all soil layers "semi-dry" (less than -1.5MPa)
Water balance	Evaporation (cm)	Sum of evaporation from soil, litter, canopy, surface water and snowpack
	Transpiration (cm)	Sum of transpiration from all soil layers

Annual temperature

Mean annual temperature between 1980 and 2018 for the four SEUG parks was 11.6 ± 0.8 °C, with NABR and HOVE having generally cooler mean annual temperatures than ARCH and CANY (Table 1). The climate is generally cold in the winter and warm in the summer, with winter temperatures ranging from a minimum -15.5 ± 0.6 °C to a maximum 15.7 ± 1.2 °C and summer temperatures from a minimum 5.4 ± 1.6 °C to maximum 37.7 ± 1.6 °C (Figures 7–10).

Mean annual temperature varies slightly within SEUG parks. ARCH is generally warmer in the southern and eastern portions of the park and cooler in the northwestern portion of the park (Figure 11). CANY is generally cooler in the higher elevation areas of the Island in The Sky district and above the Colorado and Green River drainages of the Needles and Maze districts. The easternmost portion of both NABR and HOVE are cooler than the other sections of these monuments.

The future mean annual temperature for the SEUG parks will be higher than the historical mean annual temperature (using Arches as an example, Figures 11–12). The large majority of future GCM medians project higher mean annual temperatures than the historical 90th percentile for each national park unit for the near-term period (2020–2059). There are no climate scenarios that project any overlap between the historical mean annual temperatures and the future long-term period (2060–2099). The deviation from the historical median is greatest in the RCP 8.5 scenarios in the long-term period, with a warming of 4.9 ± 0.1 °C and a mean annual temperature of 16.6 ± 1.1 °C across the SEUG parks.

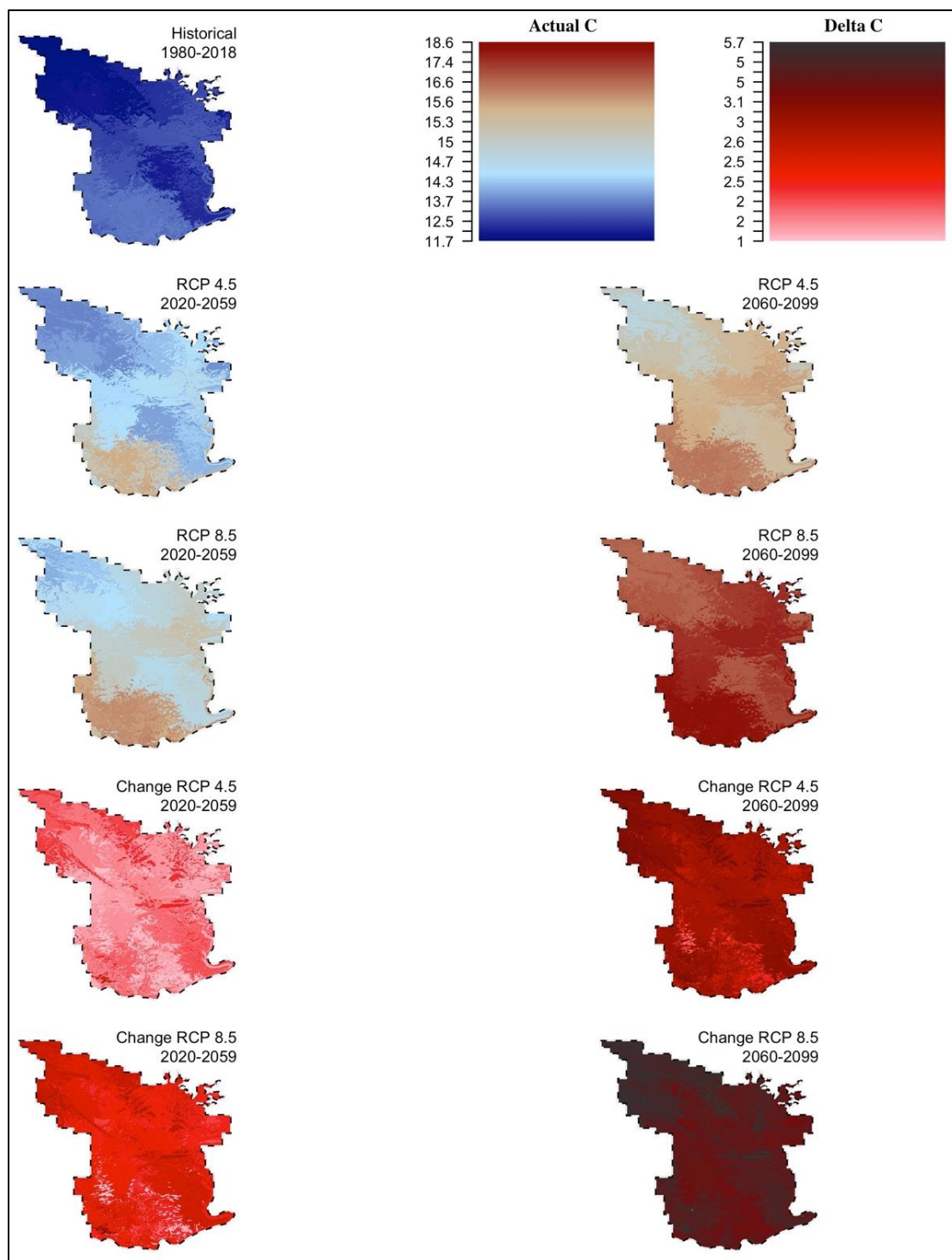


Figure 11. Arches National Park (ARCH) historical and future average annual temperatures: actual and delta for emission scenarios RCP 4.5 and RCP 8.5, and time periods. The average temperature is across global circulation models (GCMs). Delta values correspond to the change in average temperature from historical to future. Maps for other parks are available in Bradford et al. (2022). Topmost panel depicts the historical mean from 1980 to 2018. The next four panels show the emission scenarios of RCP 4.5 and RCP 8.5 at near-term (2020–2059) and long-term (2060–2099) time periods. Bottom four panels depict the change from the historical mean to near-term and long-term time periods.

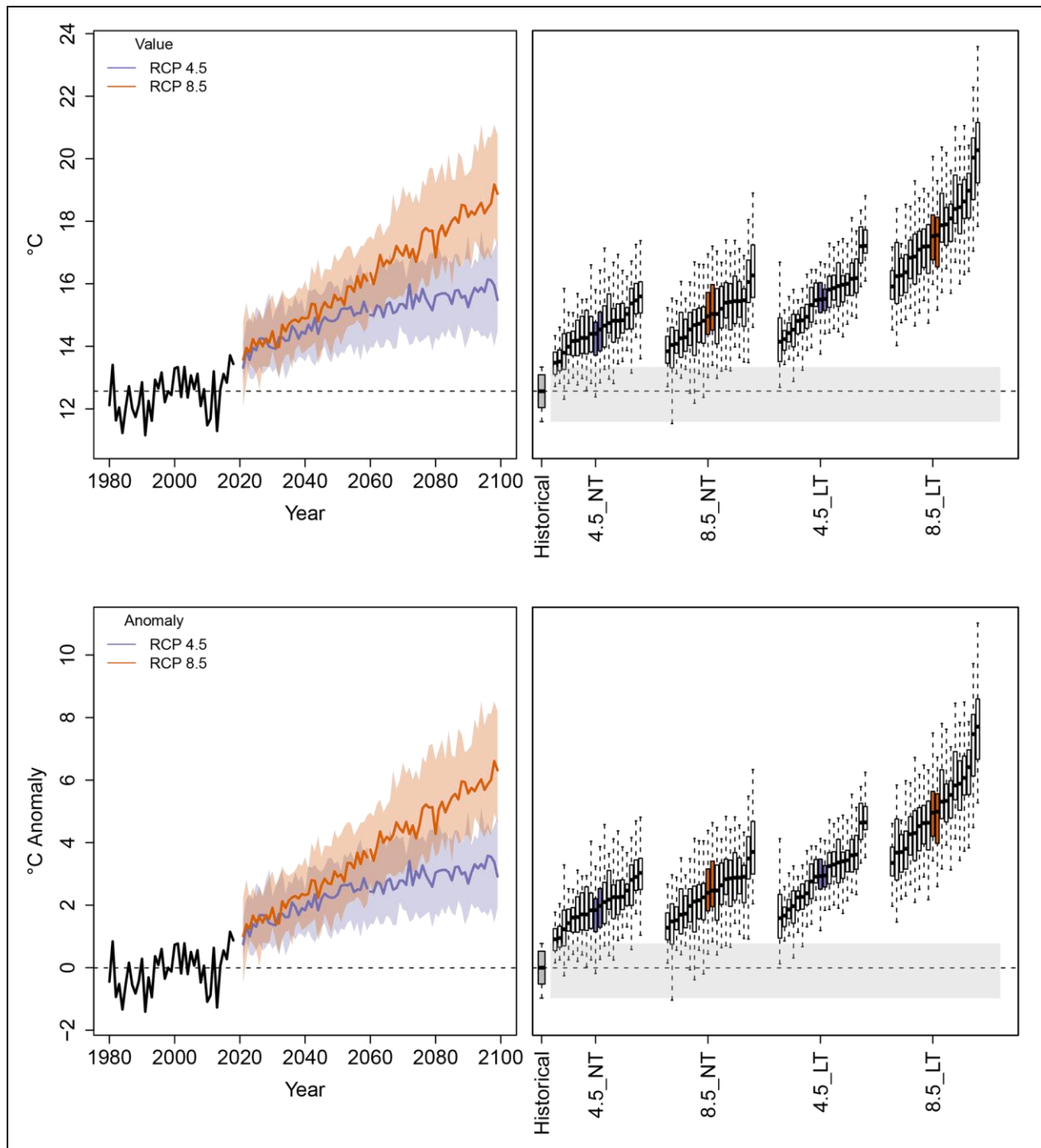


Figure 12. Arches National Park (ARCH) historical and future mean annual temperatures (°C) under emission scenarios RCP 4.5 and RCP 8.5. Red and blue shading show 10th and 90th percentiles among models within RCP 8.5 and RCP 4.5, respectively, and solid lines show median global circulation model, GCM. The right panels depict the quartile ranges for each GCM with the median GCMs shaded red or blue depending on the emission scenario for near-term (NT, 2020–2059) and long-term (LT, 2060–2099) time periods. Grey shading shows the historical range of temperature and the dotted line depicts the historical median. Lower panels show the deviation (anomaly) from the historical mean. Figures for other parks are available in Bradford et al. (2022).

Cumulative annual precipitation

The historical precipitation patterns are similar across SEUG park units, with a large amount of interannual variability (using Arches as an example, Figures 13–14). Most of the precipitation arrives in the summer and winter (Figures 7–10). HOVE has the greatest historical annual median precipitation with 31 cm, and CANY has the least historical annual median precipitation with 21 cm (Table 1).

Future models show a modest increase in median annual precipitation. NABR is projected to have an increase of 3 cm (11% increase) and ARCH an increase of 1 cm (4% increase) long-term with the highest emission scenario (Table 1). However, both emission scenarios show a high level of interannual variability and uncertainty (Figure 13). There is uncertainty in the seasonal timing of precipitation, with more uncertainty in the amount of precipitation received during the summer monsoon, especially in later years. Most of ARCH displays median projections for modest increases in precipitation under all emissions scenarios and time periods, with the exception of RCP 8.5 (high emissions) during the end of the 21st century, when portions of the park are projected to have very small decreases in precipitation (Figure 14).

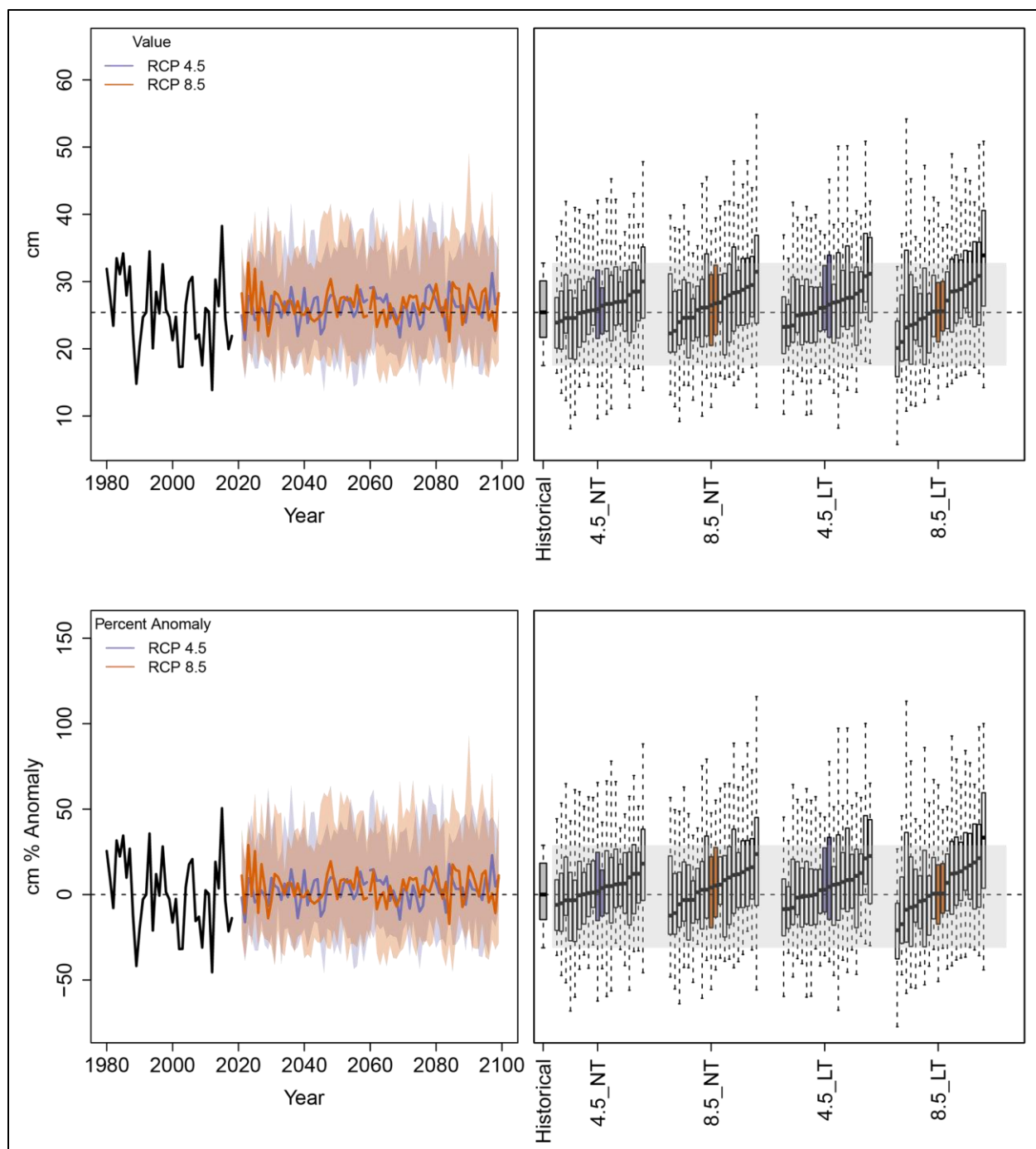


Figure 13. Arches National Park (ARCH) historical and future cumulative annual precipitation (cm) under emission scenarios RCP 4.5 and RCP 8.5. Red and blue shading show 10th to 90th percentiles for RCP 8.5 and 4.5, respectively, and sold lines show median global circulation model; GCM. The right panels depict the quartile ranges for each GCM with the median GCMs shaded red or blue depending on the emission scenario for near-term (NT, 2020–2059) and long-term (LT; 2060–2099) time periods. Grey shading shows the historical range and the dotted line depicts the historical median. Lower panels depict departures from the historical median. Figures for other parks are available in Bradford et al. (2022).

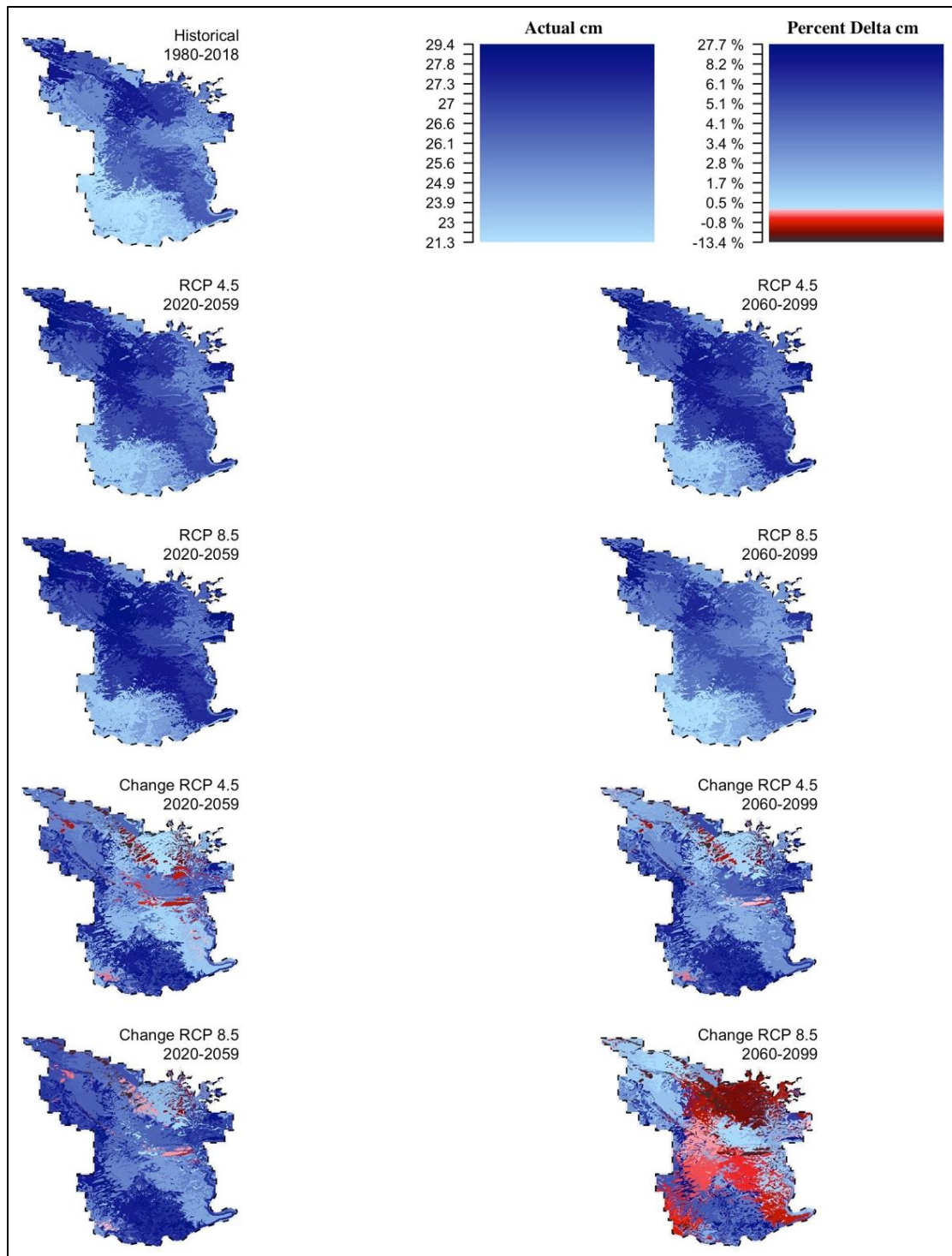


Figure 14. Arches National Park (ARCH) historical and future average annual precipitation actual and delta for emission scenarios RCP 4.5 and RCP 8.5 and time periods near-term (2020–2059) and long-term (2060–2099). The average annual precipitation is across global circulation models (GCMs). Delta values correspond to the change in average cumulative precipitation from historical to future. Maps for other parks are available in Bradford et al. (2022).

Volumetric soil water content

Historical soil moisture, as measured by volumetric water content, has similar seasonal patterns across SEUG park units. Seasonally, the winter season is the wettest, followed by the fall and spring seasons, and summer is the driest (Table 1). CANY has the driest soils, followed by ARCH, HOVE, and NABR.

Future projections show a modest increase in winter, spring, and summer soil volumetric water content in long-term projections under the high-emission scenario. Fall season soil volumetric water content is the only season to show a small decrease in the soil volumetric water content (Table 1). The spring volumetric water content is projected to be slightly lower in the near term, with a small increase in the long term (Figures 15–16), although there is not much agreement in the global circulation models on the direction of change.

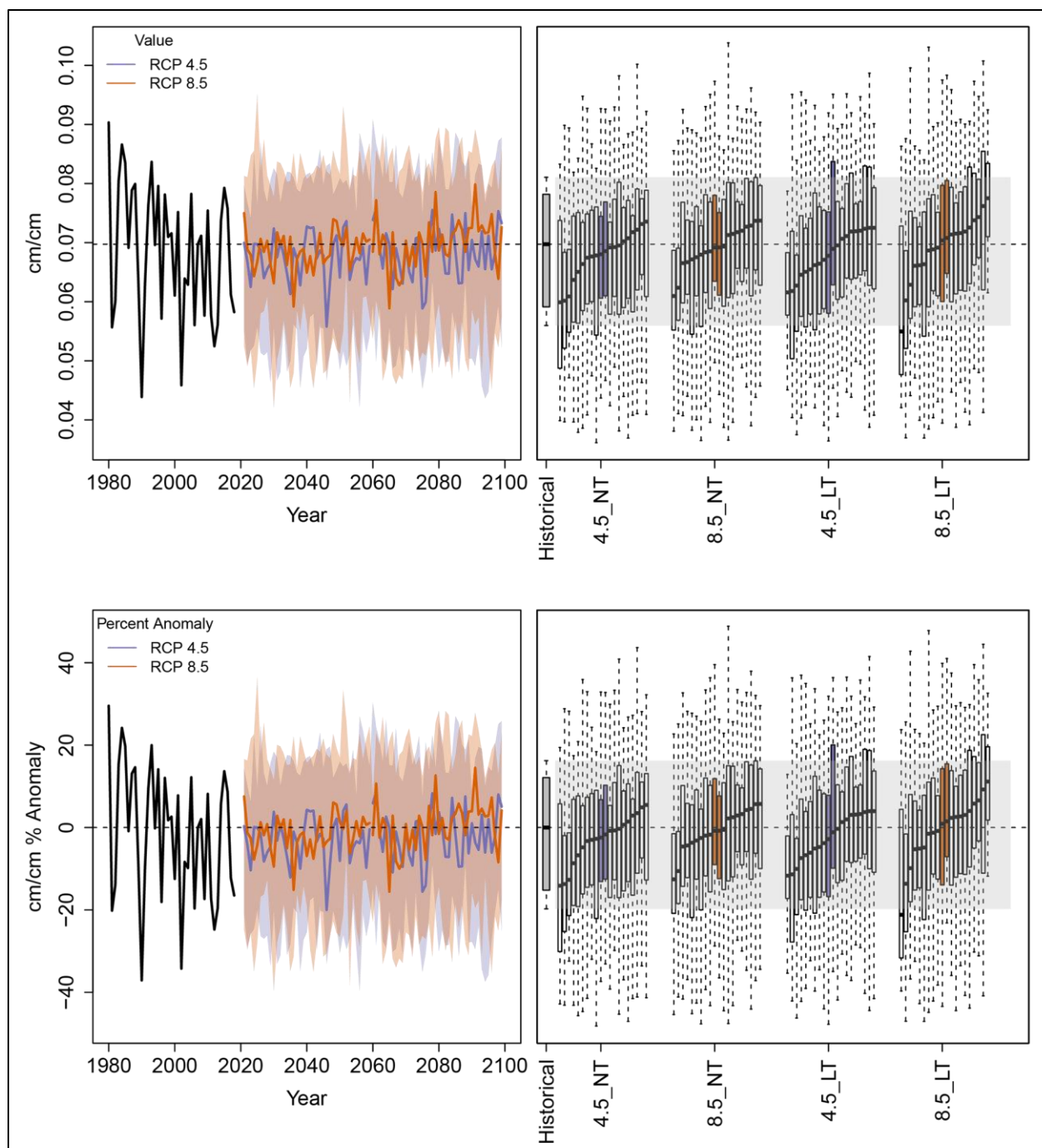


Figure 15. Arches National Park (ARCH) spring volumetric water content in the top 50 cm of soil, historical and future values. Red and blue shading show 10th and 90th percentiles and solid lines denote the median global circulation model (GCM). The right panels depict the quartile ranges for each GCM with the median GCMs shaded red or blue depending on the emission scenario for near-term (NT, 2020–2059) and long-term (LT, 2060–2099) time periods. Grey shading shows the historical range and the dotted line depicts the historical median. Lower panels depict the percent deviation (anomaly) from the historical median. Figures for other parks are available in Bradford et al. (2022).

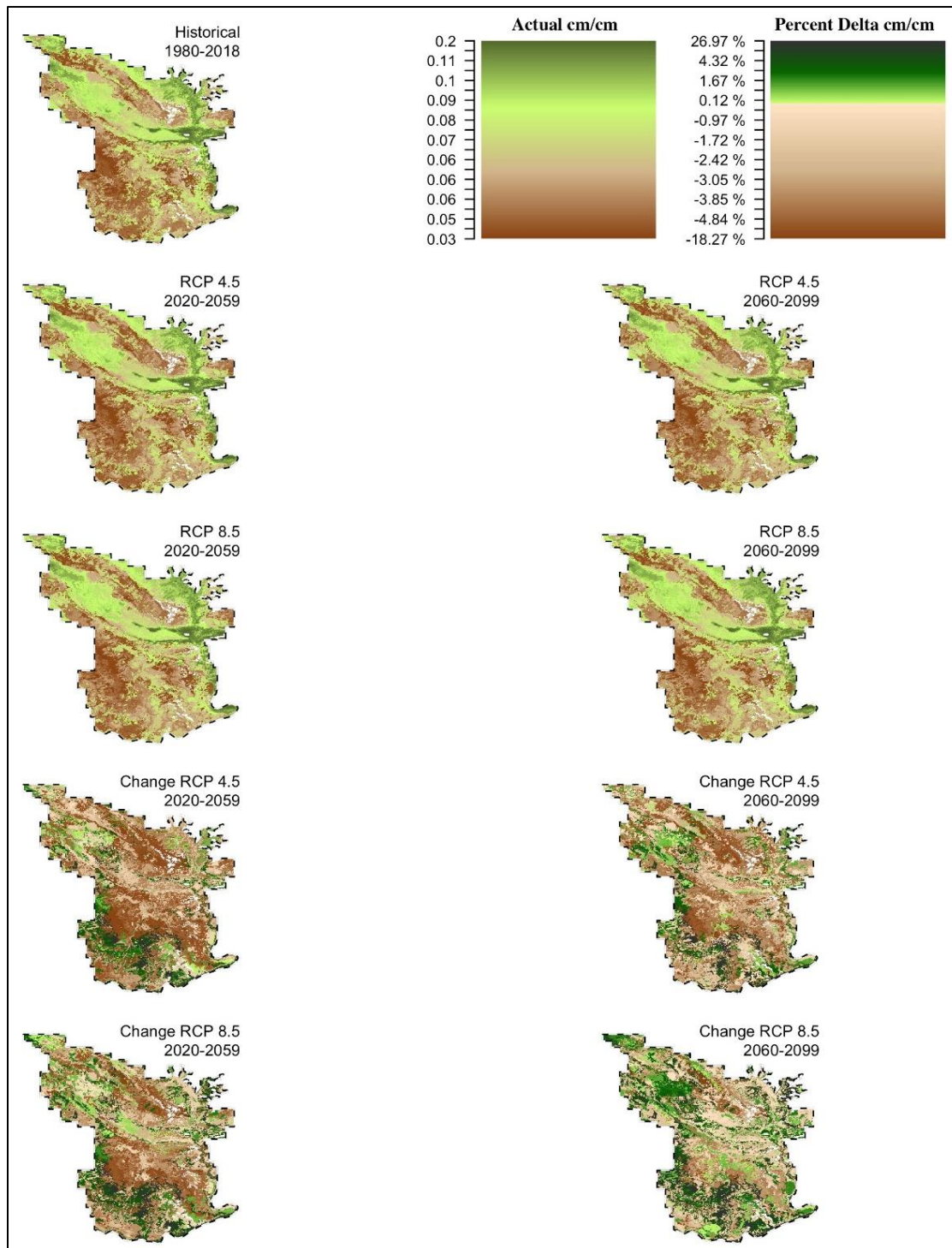


Figure 16. Past trends and future trajectories of parkwide mean values for spring soil water content in the top 50 cm of soil in Arches National Park. Topmost panel depicts the historical mean from 1980 to 2018. Next four panels show the emission scenarios of RCP 4.5 and RCP 8.5 at near-term (2020–2059) and long-term (2060–2099) time periods. The bottom four panels depict the change from the historical mean to the respective time periods. Maps for other parks are available in Bradford et al. (2022).

Fall available soil moisture

Soil water availability (SWA) is calculated as the amount of moisture that can be extracted from the soil until the soil water potential drops to -3.9 MPa (a level at which many dryland plants have difficulty accessing moisture). This metric shows how much soil moisture is available to plants.

Future projections suggest declines in SWA during the fall season that are reasonably consistent among climate models and emission scenarios (Figure 17). Most of the global circulation models show a decline in soil water availability. Spatial patterns suggest most areas will experience declines in fall soil moisture, but a few small areas may have slight increases (Figure 18).

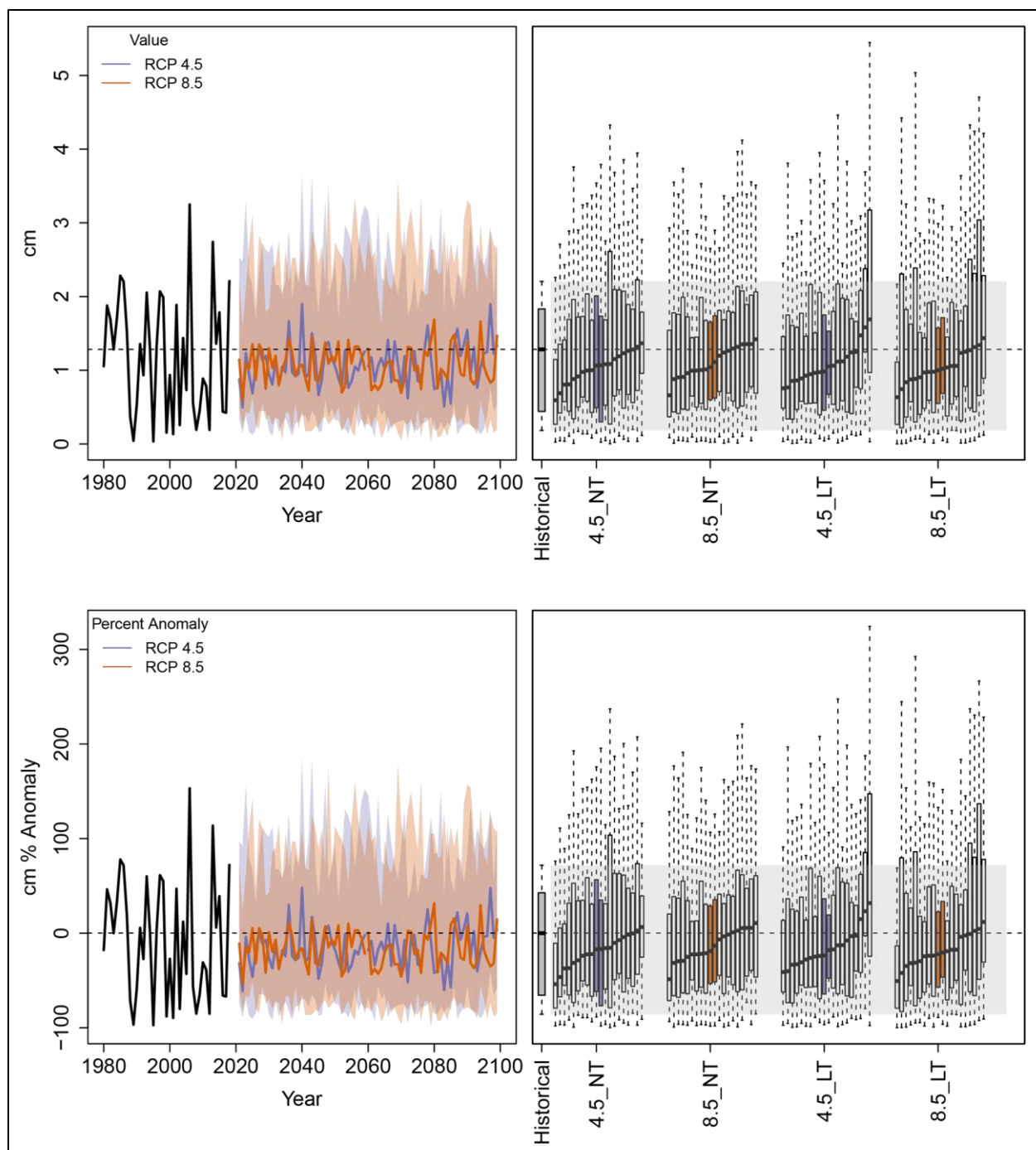


Figure 17. Past trends and future trajectories of parkwide mean values for fall available soil moisture in Arches National Park. Top panels show values, while bottom panels show the departure from the historical mean. Left panels depict the time series of historical (black) and future projections for emission scenarios RCP 4.5 (blue) and RCP 8.5 (red). Shaded areas show spread among climate models. Right panels depict boxplots of temporal variability over 40-year periods under historical (left-most box) and individual climate models. Figures for other parks are available in Bradford et al. (2022).

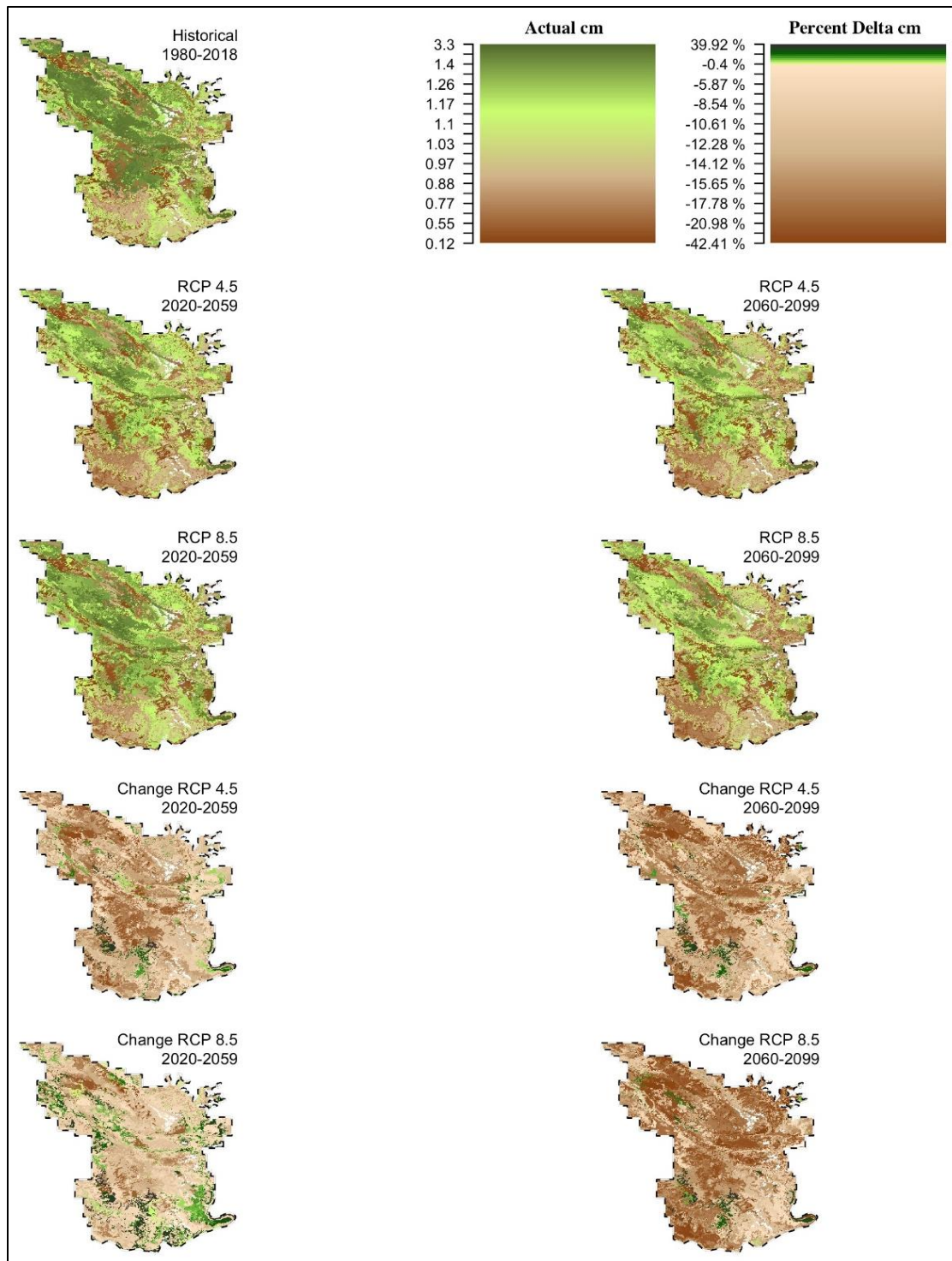


Figure 18. Parkwide mean values for fall available soil moisture in Arches National Park. Topmost panel depicts the historical mean from 1980 to 2018. Next four panels show the absolute means for emission scenarios of RCP 4.5 and RCP 8.5 at near-term (2020–2059) and long-term (2060–2099) time periods. Bottom four panels depict the change from the historical mean to the respective time periods. Maps for other parks are available in Bradford et al. (2022).

Exposure Discussion

The future climate of SEUG parks will see increases in overall temperature, uncertain changes in precipitation amounts and timing, and either unchanged or modestly increasing soil moisture (assuming increases in plant water use efficiency). The impacts of high-confidence large increases in temperature will be accompanied by increasing vapor pressure deficit (VPD) and potential evapotranspiration (PET) and decreased relative humidity. These changes represent elevated atmospheric demand for moisture that has strong potential to negatively affect plant growth and survival since soil moisture is not expected to increase commensurately. Increased VPD and PET negatively impact plant growth by increasing the moisture demand of plant tissues, requiring plants to close the pores in leaves that allow gas exchange to reduce moisture loss. This closure of the pores slows or halts photosynthesis and the production of carbon which is essential for plant growth. Plants can become desiccated or suffer carbon starvation through whichever strategy its species employs. The SOILWAT model simulations include plant acclimation to higher CO₂ levels, which acts to moderate the potential impact of increased VPD and PET, allowing soil moisture to persist even when conditions are warm, and moderating impacts of high temperature conditions on plant growth and survival. Thus, soil moisture will be only modestly impacted, responding primarily to changes in total and seasonal precipitation, which, along with the added increases of VPD through temperature, will likely create an increasingly arid climate across SEUG parks.

Although overall SEUG parks will see increasing aridity, the effect of limited soil moisture is not uniform across the national park units and is mediated by soil type. Fine textured soils near the surface hold moisture in conditions where it can be lost to evaporation, whereas coarse textured soils and deep soils allow for moisture to percolate to depths where evaporative losses are modest.

Exposure Conclusion

The results of the exposure analysis reveal certain and uncertain climate impacts for SEUG parks. For annual temperature, there are no climate scenarios that project any overlap between the historical mean annual temperatures and the future long-term period (2060–2099). Park units in SEUG are projected to have hotter climates, and longer periods of warm seasons. Precipitation timing and amount is uncertain, especially during the monsoon period, but small increases are projected in soil moisture. These soil moisture patterns are mediated on the small scale by soil conditions, notably texture and depth. Although a small and uncertain increase in precipitation is projected, the certain increase in temperatures will increase the physiological stress on plants and may cause an increase in plant mortality.

Exposure Implications for Managers

The exposure results offer both large-scale and small-scale impacts for management in SEUG park units. Large-scale precipitation patterns are uncertain but are likely to stay the same or have a modest increase, while temperature is projected to have a large increase by the end of the century. Projects focused on reclamation and restoration can be focused in areas that are projected to be buffered by soil conditions. Likewise, areas can be avoided that will have an increase in aridity. Areas projected to be refugia or have a large amount of climate exposure can be examined in supplementary figures (Bradford et al. 2022). Likewise, park-specific maps of changes in drought metrics provided in

Bradford et al. (2022) can be used to recognize existing geographic patterns in drought within and across parks. These patterns provide perspective on the implications of future changes in climate and drought conditions provided in Bradford et al. (2022).

Climate Sensitivity of Important Perennial Grass Species

Predicting ecosystem responses to climate change is one of the greatest challenges of the 21st century. Global climate change threatens biodiversity and ecosystem productivity worldwide, particularly in ecosystems in which species cannot respond quickly enough to adapt to rapidly changing environmental conditions. Anticipating plant species responses to climate change is key to predicting how ecosystems will respond to global change. When faced with rapid climate change, a species' climatic niche may no longer occur within its current geographical range. In this scenario, a species may respond by shifting its geographical range to remain within its climatic niche, such as moving to suitable habitats (e.g., Le Roux and McGeoch 2008), shifting its climatic niche to encompass the new environmental conditions through evolutionary and/or plastic responses (e.g., Ackerly 2003), or, in extreme cases, extinction (e.g., Cahill et al. 2013).

Arid and semi-arid grasslands account for 30% of global landmass and provide critical ecosystem services, including forage for livestock and wildlife, biodiversity, and carbon sequestration (Bahre 1995, McClaran and McPherson 1995, Sala and Paruelo 1997, Shuman et al. 2002, Asner et al. 2004). Grasslands are expected to be particularly vulnerable to climate change since they contain relatively shallow-rooted, short-lived species (Peters et al. 2012, Petrie et al. 2014) whose productivity is highly sensitive to variation in annual precipitation (Knapp and Smith 2001, Throop et al. 2012). In recent decades, grass-dominated ecosystems in the western United States have experienced significant warming and drying, or aridification, and have been identified as a hotspot for future aridification (Seager et al. 2007, Diffenbaugh et al. 2008, Stocker et al. 2014).

Aridification can have major consequences for plant productivity and mortality (Munson 2013, Breshears et al. 2018a) and has been linked to widespread forest and grassland die-offs in this region in recent decades (McAuliffe and Hamerlynck 2010, Munson et al. 2011b, Larter et al. 2015). Grass cover losses can contribute to destabilization of soils, which in turn results in reduction of nutrient availability and water-holding capacity and increases soil erosion and dust storm activity (Schwinning et al. 2008, Munson et al. 2011a). Moreover, declines in perennial grass cover can trigger ecological state transitions that can feed back into cascading declines in vegetation and ecosystem functioning. Similar patterns of grass mortality have been reported globally, but the ability to predict which grass species will respond to aridification and where remains limited.

Predicting changes in perennial grass species habitat suitability under future aridification will be key to understanding how grasslands respond to climate change. Ecological niche modeling, specifically species distribution modeling (Peterson 2001), is a common tool that allows ecologists and conservation practitioners to predict the vulnerability of ecosystems to changing environmental conditions. Species distribution models (SDMs) seek to describe the set of conditions (typically climatic) that best predict a species' occurrence at broad spatial scales. The location of these conditions can then be projected under different climate scenarios to estimate how and where suitability for the species will change.

Methods

To assess long-term impacts of climate change on perennial grass species distributions in the western United States, SDMs were used to identify current environmental drivers of habitat suitability and predict changes in future habitat suitability in response to predicted climate change for 11 high-priority native, perennial grass species. A group of NPS conservation experts were consulted to identify the 11 perennial grass species selected for evaluation (Table 3). Roughly half of the species have a C₃ (cool season) photosynthetic pathway, while half are C₄ (warm season) species. For each species, a SDM strategy was developed that combined presence-only (PO) and presence-absence (PA) records based on an integrated species distribution model derived from Koshkina et al. (2017).

Table 3. Eleven perennial grass species included in this study. Source: species occurrence (presence only; PO) data, SEINet data portal (<http://swbiodiversity.org/seinet/>); species presence-absence (PA) data, 2020 Bureau of Land Management Assessment, Inventory, and Monitoring (BLM AIM) TerraDat species and inventory dataset.

Species	Common name	Carbon fixation pathway	Species occurrence records (PO; SEINet)	Species presence-absence records (PA; BLM AIM)
<i>Achnatherum hymenoides</i>	Indian ricegrass	C ₃	1,311	1,868 / 12,430
<i>Elymus elymoides</i>	squirreltail	C ₃	1,768	3,382 / 12,186
<i>Hesperostipa comata</i>	needle and thread	C ₃	1,206	878 / 12,226
<i>Pascopyrum smithii</i>	western wheatgrass	C ₃	999	517 / 13,781
<i>Poa secunda</i>	sandberg bluegrass	C ₃	1,315	7,649 / 6,649
<i>Aristida purpurea</i>	purple three awn	C ₄	1,364	434 / 15,134
<i>Bouteloua eriopoda</i>	black grama	C ₄	170	120 / 15,448
<i>Bouteloua gracilis</i>	blue grama	C ₄	928	1,577 / 12,721
<i>Pleuraphis jamesii</i>	James' galleta	C ₄	397	267 / 15,301
<i>Sporobolus airoides</i>	alkali sacaton	C ₄	391	80 / 15,488
<i>Sporobolus cryptandrus</i>	sand dropseed	C ₄	608	86 / 15,482

Using these SDMs of *a priori* identified important grass species, three main research objectives were addressed: (1) describe patterns of drivers of historical habitat suitability in dominant grass species, (2) quantify the direction and magnitude of changes in grass species habitat suitability in response to future climate (aridification), and (3) identify species and areas with projected changes in habitat suitability that are robust across climate models. Robust is defined as locations where 90% of tested climate models agree in the direction of change in future habitat suitability relative to historical suitability. Given that previous work has shown grass biogeography is often largely determined by the correlation between temperature and photosynthetic pathway (e.g., Batanouny et al. 1988), exploring differences in C₃ versus C₄ species niches was of particular interest.

These results will provide useful insights for anticipating the impacts of climate change on grass-dominated and co-dominated ecosystems. More broadly, this approach of identifying robust changes

in species habitat suitability may be useful for other assessments of climate impacts in grasslands and provide a more rigorous foundation for making long-term strategic resource management decisions. Predicting how species habitat suitability may shift spatially, for example, could help land managers select more resilient species in grassland revegetation efforts and identify habitat refugia for priority grass species under global change.

Data inputs

Species occurrence and absence records

Data for fitting species distribution models take two forms: species occurrence or presence only data, in which a species was observed to be present at a particular location (but no search was performed to confirm that the species is not present if not observed), and presence-absence data, in which all present species are tabulated in a search over a specified ground area or time and absences indicate that the species was not found. Species occurrence records, or presence only (PO) data, for the 11 grass species were extracted for the western United States (latitude = 25°N to 50°N, longitude = 130°W to 100°W) from the SEINet data portal (<http://swbiodiversity.org/seinet/>). Only records collected since 1980 with reliable associated georeferencing data (i.e., those records with a GPS georeferencing source, coordinate uncertainty <2000 m, or UTM coordinates) were retained. Species presence-absence (PA) data were acquired from the 2020 Bureau of Land Management Assessment, Inventory, and Monitoring (BLM AIM) TerraDat species inventory dataset; these data were collected using the line-point intercept method at 15,568 sites situated on BLM-managed lands throughout the western United States. For *A. hymenoides*, *P. secunda*, *P. smithii*, and *B. gracilis*, a subset of BLM AIM sites (n = 14,556) were used. For these species, sites within the state of Wyoming were removed because the dataset reported zero occurrences of these species even though they are common species in this region. Maps of species PO and PA records can be found in Appendix 3, Figures A.3.1–A.3.11).

Climate data

Gridded weather data were used to represent historical climate conditions (1970–2000). These historical data were downloaded from the WorldClim2 version 2.0 database (Fick and Hijmans 2017) for the western United States at a resolution of 30 arc-seconds, or ~900 m at the equator, including data for minimum, mean, and maximum temperature, precipitation, solar radiation, wind speed, water vapor pressure, and total precipitation. Monthly mean, minimum, and maximum temperatures and total precipitation data were converted to decadal mean bioclimatic variables for further analysis. A standard set of 19 bioclimatic variables, which represent annual and seasonal combinations of temperature and precipitation that have potential to be biologically important, were calculated from WorldClim2 data using the “dismo” package in R (Hijmans et al. 2017). WorldClim2 data were also used to calculate a monthly aridity index (Trabucco and Zomer 2018) dataset to quantify precipitation deficit over atmospheric water demand as:

$$\text{Aridity Index (AI)} = \text{MAP/PET} \quad , \quad (\text{Equation 1})$$

where MAP is the mean annual precipitation and PET is the mean annual potential evapotranspiration.

PET was estimated based on the global modeling of potential evapotranspiration (Trabucco et al. 2008) using the Hargreaves (1994) evapotranspiration equation. Monthly aridity values were then used to calculate gridded average seasonal aridity datasets for spring (“Spring Aridity” March–May), summer (“Summer Aridity” June–August), fall (“Fall Aridity” September–November), and winter (“Winter Aridity” December–February), respectively. Lower aridity index values indicate greater aridity. In addition, mean monthly temperature and precipitation values were used to calculate a variable representing the Pearson correlation between monthly precipitation and monthly temperature values (PTcorr). This correlation is high in places where precipitation occurs during the warm season, and low in places where precipitation occurs during the cool season.

In total, 24 candidate climatic variables were considered for inclusion in the development of ecological niche models (Appendix 3, Table A.3.1). To reduce the number of candidate climatic predictor variables included in model selection for ecological niche models, Pearson correlations were assessed among all candidate environmental variables. This assessment excluded variables that were highly correlated ($|r| < 0.70$) to others, retaining those variables that have been shown to influence plant species niches in the western United States and that are relatively independent dimensions of climate variability (Butterfield and Munson 2016). This process resulted in the selection of a suite of six climatic variables representing relatively orthogonal dimensions of climate for the region for development of ecological niche modeling to provide a good characterization of species' current realized climate niches. These six variables were mean annual temperature (MAT), mean annual precipitation (MAP), precipitation timing (PTcorr; correlation between monthly mean precipitation and temperature), precipitation seasonality (PSeas; the coefficient of variation in monthly mean precipitation), annual temperature range (TRange; temperature difference between the warmest and coldest month), and summer aridity index. See Appendix 3 for candidate covariate details.

Soil and species sampling effort data

Gridded soil composition (i.e., percent clay, silt, and sand) and depth data were acquired from the SoilGrids application (<https://www.isric.org/explore/soilgrids>) and resampled for the western United States at spatial resolution of 250 m using a bilinear resampling function. Soil composition data were averaged over the top 0–100 cm of the soil profile after removing pixels from layers that fell below the total predicted soil depth in that average computation. To account for potential differences in sampling effort in the PO data, a sampling effort dataset was calculated to account for potential differences in grass species sampling intensity across the western United States. Occurrence records and associated map coordinates for the family *Poaceae* were downloaded from the SEINet data portal (Gilbert et al. (2019); <http://swbiodiversity.org/seinet/>) for the region using the same time period and georeferencing criteria as outlined above for SEINet species occurrence data.

Species distribution modeling

PO and PA data were combined in an integrated species distribution model derived from Koshkina et al. (2017) by assuming detection probability equal to one during PA surveys. This is a reasonable assumption given that every grass species on the transect is identified. In the model, the expected abundance of individuals, λ , is linked to covariates, X , by the following relationships:

$$\lambda = e^{\alpha + \beta X} \quad , \quad (\text{Equation 2})$$

where α represents an intercept and β represents a vector of slopes associated with each covariate in X . The probability of a count, C , greater than 0 (i.e., the probability of a species is present, ψ) during a PA survey can then be predicted according to:

$$\psi = P(C > 0) = 1 - e^{-\lambda} = 1 - e^{-e^{\alpha + \beta X}} \quad , \quad (\text{Equation 3})$$

This equation is equivalent to a Bernoulli generalized linear model GLM with a complementary log-log link (McCullagh and Nelder 1989). Predictions of presence or absence (PO) is estimated by the product of λ and the probabilities that both a particular area is sampled and that an individual is detected in the sampled area (Yackulic et al. 2013). This leads to thinning (loss of records) and frequently sampling bias (i.e., uneven thinning with respect to environmental covariates). The process of thinning, b , was modeled using a logit-linear link, based on covariates W that are hypothesized to represent the thinning process:

$$b = \frac{e^{\gamma + \delta W}}{(1 + e^{\gamma + \delta W})} \quad , \quad (\text{Equation 4})$$

where γ represents an intercept and δ represents a vector of slopes associated with each covariate in W . The expected density of PO data in a region is then given by the product of b and λ . For more details, see Koshkina et al. (2017).

The *a priori* assumption was that it seemed reasonable that λ for different species might respond as either a linear or quadratic function of the three soil and six climate covariates of interest to this study, and that interactions between covariates might be expected. This implied a large number of potential models ($>10^{16}$ models) and necessitated development of a model selection strategy (Morin et al. 2020). The model selection strategy used consisted of two stages. Model comparison was based on a fourfold cross-validation process. Specifically, in each fold, three of four groups were used to fit a model (leaving out one quarter of the data) and the results were used to predict values for the 4th (out of sample) group. Those estimates were compared with observations in the out of sample group to estimate model performance, quantified by negative log-likelihood. The four negative log-likelihoods were summed to assign a score to each model. Groups were determined geographically by splitting gridded data for the western United States into four quadrants.

The first stage consisted of a modification to typical backwards stepwise variable selection in which linear and quadratic effects for a given covariate were dropped or maintained simultaneously. This effort began with a model that included quadratic and linear effects of all nine covariates, which was compared to the nine models formed by dropping both the linear and quadratic effect for a given covariate. If the more complex model had a lower fourfold negative log-likelihood stage, then the process was stopped, but if otherwise, the best of the simpler models was selected and removing additional covariates was considered. The second stage involved adding interactions among all covariates that remained after the first stage and performing a more traditional backwards stepwise variable selection in which each linear effect, quadratic effect, or interaction was evaluated independently. While traditional backwards stepwise selection can lead to overfitted models when

used with in-sample metrics of fit, the fourfold cross-validation process should lower the probability that an overly complex model is identified because it is a more conservative approach to assessing fit.

The model identified at the end of this second stage for each species was then evaluated based on out-of-sample area under the curve (AUC) values using a similar process to the fourfold cross-validation process to calculate log-likelihood in which data were fit to approximately three-quarters of the data and predictions were made for the other one-quarter of the data. AUC values were derived independently for the PO and PA data held out in each fold.

For future climate forecasts, future monthly temperature and precipitation data were extracted over two time periods. Data were extracted for mid- (average for 2041–2060, “2050”) and late- (average for 2061–2080, “2070”) 21st century from a suite of 17 GCMs and two representative concentration pathways (RCPs; 4.5 and 8.5), producing a total of 68 future climate spaces (17 GCMs $\times$ 2 RCPs $\times$ 2 time periods = 68 climate spaces). Future monthly temperature and precipitation data were extracted from all climate models from the Coupled-Model Intercomparison Project, phase 5 (CMIP5; Taylor et al. 2012), calibrated (bias-corrected), and downscaled to approximately 1/8-degree spatial resolution (Maurer et al. 2010, Brekke et al. 2013). Two relative concentration pathways from the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment report (Stocker et al. 2014) were also assessed. The RCP 4.5 scenario (4.5 W/m² radiative forcing by 2100 relative to preindustrial levels) predicts stabilizing emissions around the mid-21st century (Thomson et al. 2011), while RCP 8.5 (Riahi et al. 2011) predicts high emissions through 2100 (8.5 W/m²). Initial results showed similar changes in habitat suitability until mid-century for both emissions scenarios, after which these changes tapered off for RCP 4.5, corresponding with the decrease in CO₂ emissions at mid-century in this emission scenario. These initial results confirm sensitivity to emissions scenarios.

Using future climate data, SDMs were geographically projected for all future climate scenarios (17 GCMs $\times$ 2 RCPs) for both near- (2050) and longer-term (2070) future time periods yielding 68 future SDM projections per species. SDM projections were ensembled by taking the 50th quantile of the 17 GCMs for each RCP $\times$ time-period combination yielding four future projection scenarios per species. Then, change in habitat suitability was calculated for each species as the difference in lambda between historical and the ensembled future climate scenarios divided by the maximum historical suitability value for that species:

$$\Delta\lambda = (\lambda_{future} - \lambda_{historical}) / (\max(\lambda_{historical})). \quad , \quad \text{(Equation 5)}$$

Values for delta lambda (Equation 5) can range between -1, representing a location where lambda changed from its maximum value historically to zero in the future, 0, representing an area of no change, to values hypothetically greater than 1, representing an increase in suitability greater than the difference between zero and the historical maximum.

Finally, to provide a perspective on the magnitude of variation due to uncertain future climate conditions, we also identified areas expected to experience robust changes in future habitat suitability in which a robust change was defined as areas where 90% of GCMs agreed on the direction of

change in lambda for each RCP × time period combination. The longer-term (2070) results for the RCP 8.5 emissions scenario are presented in the body of this report because global emissions are currently tracking slightly above RCP 8.5. Results for the remaining three RCP × time-period scenarios can be found in Appendix 3 (future climate: Figures A.3.13–A.3.18, Table A.3.3.; future habitat suitability: Figures A.3.19–A.3.34, and Table A.3.4).

Historical (1960–2000) environmental conditions

From 1960 to 2000, the western United States study region had a MAP of 461.2 mm/year and a mean annual temperature (MAT) of 9.3 °C (Table 4). The average correlation between monthly temperature and precipitation (PTCorr) was 0.04, coefficient of variability in monthly precipitation (PSeas) was 49.0, and the average temperature difference between the warmest and colder months (TRange) was 37.2 °C. Mean summer aridity index was 0.23, mean soil depth was 195.1 cm, and mean percent sand and clay were 45.5% and 20.9%, respectively. Spatially, MAP and summer aridity indexes were lowest, while MAT was highest in the southwest portion of the western United States, indicating drier conditions in this region (Appendix 3). PTCorr generally increased from west to east, and PSeas was lowest in the intermountain area in the center of the study region (Appendix 3). Soils were deep across most of the western United States with some areas of lower soil depth in the southern areas of the study region. Soil composition was heterogeneously patterned across the western United States.

Table 4. Past and future values for the climatic covariates utilized, summarized for the western United States. Climate covariates include: (1) mean annual precipitation (MAP; mm/yr), (2) mean annual temperature (MAT; °C), (3) the correlation between monthly precipitation and temperature (PTCorr), (4) precipitation seasonality (PSeas; coefficient of variation in monthly precipitation), (5) annual temperature range (TRange; difference between maximum and minimum monthly temperature; °C), and (6) summer aridity index for the western United States. Mean values for these six covariates are shown under historical conditions (1970–2000) and future conditions (values shown are the median from 17 climate models for RCP 8.5 between 2070–2100). Percent area increasing and decreasing show the percent of the western United States where 90% of climate models agree that the covariate is robustly increasing (magenta) or decreasing (orange). Pos and Neg mean are the mean magnitude of change in those areas, respectively.

Environmental covariate	Historical (1970–2000)	Future median model (2070–2100)	Percent area increasing	Pos mean	Percent area decreasing	Neg mean	Robust change mean	Direction of change
<i>MAP</i>	461.24	465.45	57.43	71.90	42.57	-79.15	7.60	Increasing
<i>MAT</i>	9.32	13.43	100.00	4.13	0.00	-3.65	4.13	Increasing
<i>PTCorr</i>	0.036	-0.11	15.39	0.07	84.61	-0.30	-0.24	Decreasing
<i>PSeas</i>	48.98	54.43	92.04	10.28	7.96	-8.35	8.80	Increasing
<i>TRange</i>	37.24	39.40	84.86	5.21	15.14	-2.97	3.97	Increasing
<i>Summer_Aridity</i>	0.23	0.15	0.38	0.01	99.62	-0.08	-0.08	Decreasing

Inclusion of covariates in species distribution models

Inclusion of environmental covariates in final species distribution models varied between functional types (C₃ versus C₄) and among species (Figure 19; Appendix 3, Tables A.3.1, A.3.2, A.3.15). Temperature-related covariates were included more often in C₃ versus C₄ species SDMs (Figure 19). For example, MAT was included in most (80%) C₃ species SDMs but was included in fewer (50%) C₄ species models, and TRange was included in all C₃ species SDMs but only half of C₄ species models. Exclusively precipitation-related environmental covariates were included in a similar proportion of C₃ and C₄ species SDMs (Figure 19). MAP was included in 60% of SDMs for C₃ species and 67% for C₄ species. Similarly, PSeas was included in 60% of C₃ and 63% of C₄ SDMs. The PTCorr was similarly included in most SDMs for both C₃ (80%) and C₄ (83%) species. Summer aridity index (higher values are less arid) was included in more C₄ versus C₃ SDMs (67% and 40% of SDMs, respectively). Inclusion of soil covariates into SDMs also varied between plant functional types and across species. Soil compositional covariates were more commonly included in SDMs of C₄ species. Soil percent clay was included in SDMs for all C₄ species but only 60% of C₃ species. Percent soil sand was included in 83% of SDMs of C₄ species and 60% of C₃ species. Soil depth was included in 80% of C₃ and 50% of C₄ species SDMs. Full model results including model coefficients can be found in Appendix 3.

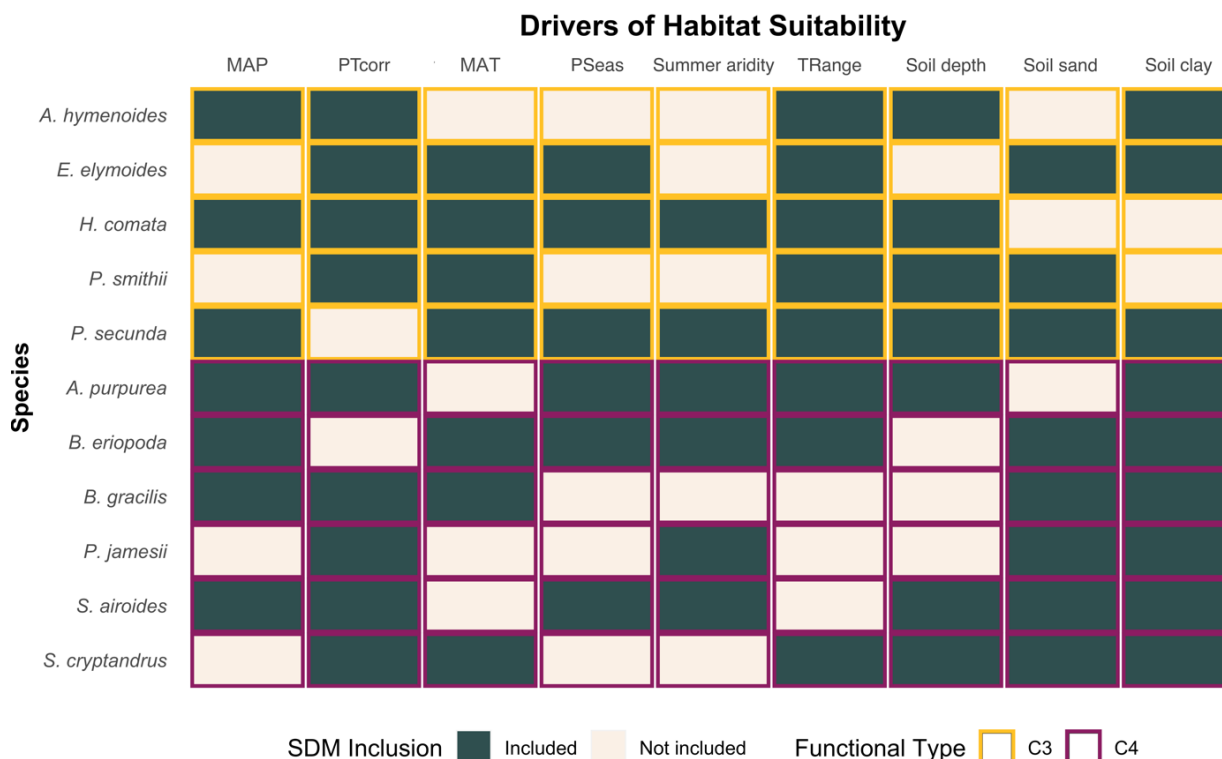


Figure 19. Environmental covariates included in the final species distribution models (SDMs) for 11 grassland species in the western United States. C₃ species are the top 5 rows; C₄ species are the bottom six rows. MAP = mean annual precipitation; PTcorr = correlation between monthly mean precipitation and temperature; MAT = mean annual temperature; PSeas = coefficient of variation in monthly precipitation; TRange = difference between maximum and minimum monthly temperature. A more accessible tabular version of this figure is provided in Table A.3.15 in Appendix 3.

Sensitivity Results

We focused our examination of perennial grass climate sensitivity on RCP 8.5; results about RCP 4.5 are available in Appendix 3. We present our results about climate sensitivity of perennial grasses at multiple spatial scales, including the western U.S., as well as the Colorado Plateau and specific SEUG parks.

Sensitivity results for the western United States

All models performed moderately well (AUC for in-sample, training data: mean = 0.87, range = 0.82 to -0.96; Appendix 3, Table A.3.2). Grasses showed different responses to variation in environmental covariates included in each SDM depending on functional type and species (Figures 19 and 20). Temperature-related covariates consistently played an important role in structuring grass species habitat suitability as evidenced by their inclusion in final species SDMs. C₃ and C₄ species alike had unimodal responses to variation in MAT with C₃ species tending to occupy cooler climatic niches with lower MAT relative to C₄ species (Figure 20, C₃ average = 4.9 °C, C₄ average = 13.2 °C). Both C₃ and C₄ grasses had species-specific responses to TRange, with species optima ranging from 26.2 °C (*P. secunda*) to 42.6 °C (*P. smithii*). Though, in some species (*A. hymenoides* (C₃), *B. eriopoda* (C₄)), habitat suitability increased linearly with increasing TRange. C₃ species had variable responses to the strength of the PTCorr, while C₄ species habitat suitability tended to increase as PTCorr increased (Figure 20).

For precipitation-related covariates, variation in MAP resulted in greater variation in habitat suitability in C₃ relative to C₄ species, with C₃ species projected to occupy niches with higher MAP values relative to C₄ species (Figure 20). The average MAP optimum for C₃ species was 681.9 mm/yr (ranging from 305.6 for *A. hymenoides* to 1058.3 mm/year for *H. comata*) and 472.2 mm/year for C₄ species (ranging from 338.9 for *B. gracilis* to 605.6 mm/year for *B. eriopoda*). Increasing PSeas (greater seasonal variability in precipitation) generally corresponded to increased C₃ species habitat suitability, while C₄ species showed unimodal responses to variation in PSeas with optimal values ranging from 31.2 (*B. eriopoda*) to 75.1 (*S. airoides*) (Figure 20). Among C₃ grasses, only *P. secunda* was influenced by summer aridity index, experiencing decreasing suitability with increasing aridity index. C₄ species responses to variation in summer aridity index were more variable. Some species (*P. jamesii* and *S. airoides*) experienced decreased habitat suitability with increasing summer aridity index (decreasing aridity) while other species (*A. purpurea* and *B. eriopoda*) had unimodal responses to aridity index, with species optima at AI = 0.12 and 0.31, respectively.

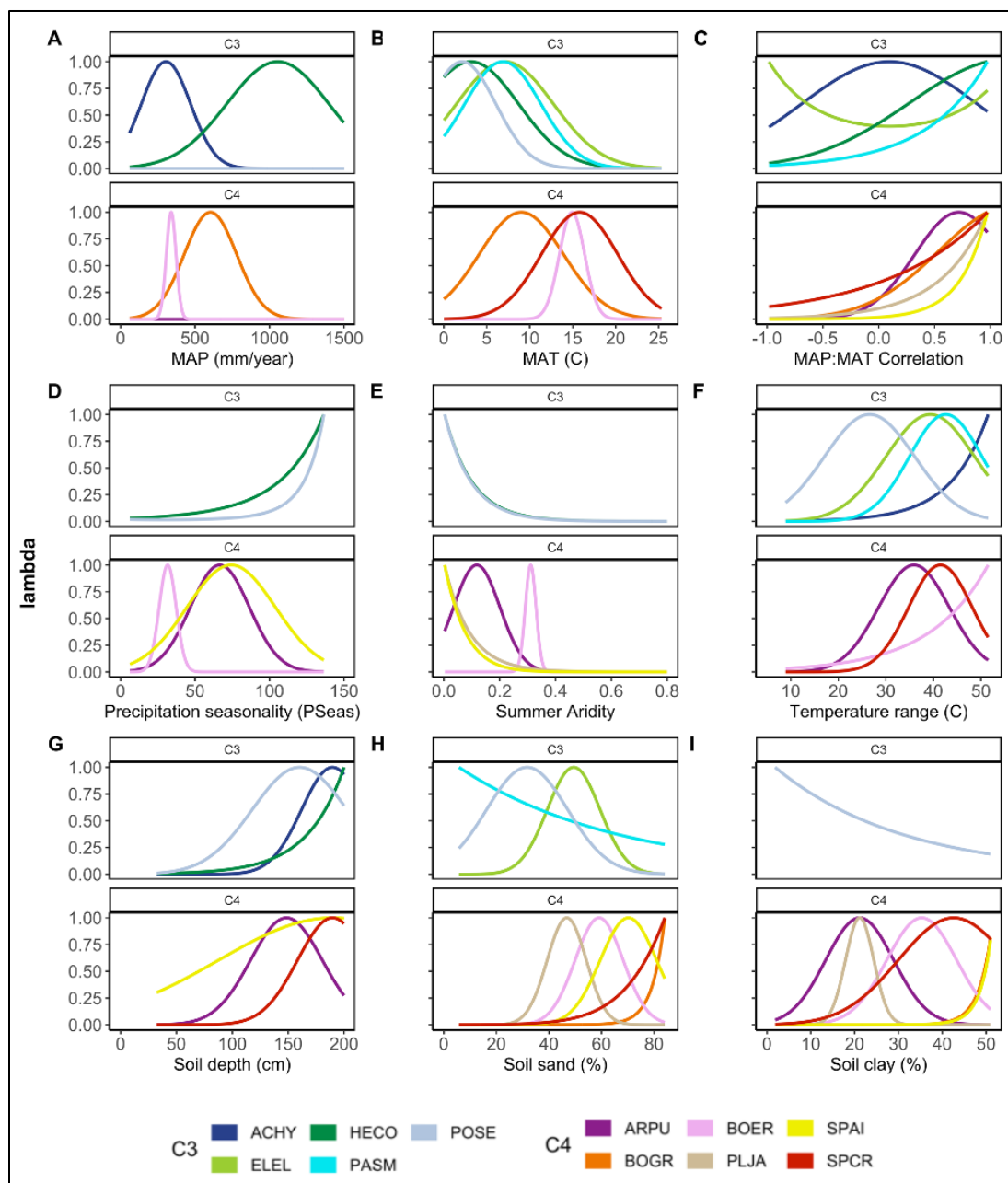


Figure 20. Historical (1970–2000) habitat suitability (λ) responses of C₃ and C₄ grasses to environmental covariates for the western United States. Lines represent response curves fitted to 1000 predicted habitat suitability (λ) values for a species to single environmental covariates when all other covariates included in the species SDM are set to their means for the following characteristics: (A) mean annual temperature (MAP), (B) mean annual precipitation (MAT), (C) PTCorr (monthly temperature-precipitation correlation), (D) precipitation seasonality (PSeas), (E) summer aridity index, (F) temperature range (TRange), (G) soil depth (cm), (H) soil sand (%), and (I) soil clay (%). Responses are only shown for a given species-covariate combination if the given covariate was included in the final SDM for a species. ACHY = *Achnatherum hymenoides*, HECO = *Hesperostipa comata*, POSE = *Poa secunda*, ELEM = *Elymus elymoides*, PASM = *Pascopyrum smithii*, ARPU = *Aristida purpurea*, BOER = *Bouteloua eriopoda*, SPAI = *Sporobolus airoides*, BOGR = *Bouteloua gracilis*, PLJA = *Pleuraphis jamesii*, SPCR = *Sporobolus cryptandrus*.

Soil covariates also consistently played a role in determining species habitat suitability. Both C₃ and C₄ species responded similarly to variation in soil depth, with niche optima in deeper relative to shallower soils (Figure 20). Overall, C₄ species were more sensitive to variation in soil composition relative to C₃ species (i.e., more C₄ species SDMs included percent soil sand and clay than C₃ species). C₃ species tended to occupy soils with lower sand relative to C₄ species. Soil sand optima for C₃ species *P. secunda* and *E. elymoides* were 31.6% and 49.3%, respectively. Optima for C₄ species *P. jamesii*, *B. eriopoda*, and *S. airoides* were 46.6%, 59.1%, and 70.2%, respectively. Habitat suitability in C₃ species *P. smithii* decreased with increasing soil sand content, while habitat suitability in C₄ species *B. gracilis* and *S. cryptandrus* increased with increasing soil sand content. Among C₃ species, only *P. secunda* responded to variation in soil clay content, decreasing as soil clay increased. Conversely, C₄ species had variable, unimodal responses to variation in soil clay, with species optima ranging from 21.1% in *A. purpurea* and *P. jamesii* to 42.7% in *S. cryptandrus* (Figure 20).

Forecasted perennial grass niche responses to future climatic conditions

On average, the western United States is forecast to experience variable changes in annual precipitation, increased temperatures, and greater aridity under RCP 8.5 by the end of the 21st Century (2070) (Appendix 3, Figures A.3.13–A.3.18; Table A.3.3). About half (57.4%) of all areas in the West that experienced both robust changes in MAP had increasing MAP, while 42.6% of areas experienced decreasing MAP (Table 4), with a mean increase of +7.60 mm across the region. In general, MAP increased in more northern latitudes and decreased in more southern latitudes of the region (Appendix 3, Figure A.3.13). The entire western United States also experienced increased MAT, with an average increase in MAT of +4.1 °C relative to historical averages, with greatest increases occurring in the Great Plains (Appendix 3, Figure A.3.14). The PTCorr decreased across 84.6% of areas experiencing robust change by an average of -0.24 overall. In general, the areas of greatest declines in PTCorr occurred in the Great Basin, while some areas in Southwest deserts experienced slight increases in PTCorr (Appendix 3, Figure A.3.15). PSeas increased across most (92.0%) of the region by an average of +8.80, with increases greatest in the Great Plains (Appendix 3, Figure A.3.16). TRange increased in most (84.9%) of the West by an average range of +2.8 °C annually, with areas of increase occurring mostly in northern latitudes. Southern deserts experienced declines in TRange, especially in the Mojave and Sonoran Deserts (Appendix 3, Figure A.3.17). Summer AI decreased by an average of -0.08 across nearly all (99.6 %) areas experiencing robust change in AI, indicating increasing aridity across the western United States by the late 21st century (Appendix 3, Figure A.3.18).

Plant functional group and species-level responses to future aridification

Overall, most C₃ grasses (80.0%) experienced robust decreases in habitat suitability, while most C₄ species (66.7%) experienced robust increases in habitat suitability under RCP 8.5 by the end of the 21st century (2070–2100) across the western United States (Table 5, Figures 21 and 22). The magnitude of habitat suitability declines in C₃ grasses varied by species, with *P. secunda* > *H. comata* > *P. smithii* >> *E. elymoides*. Among C₃ species, only *A. hymenoides* experienced slightly increased habitat suitability under future conditions. Increases in habitat suitability in C₄ species varied in magnitude among species, with *A. purpurea* > *S. airoides* > *P. jamesii* >> *S. cryptandrus*.

The two C₄ *Bouteloua* species, *B. eriopoda* and *B. gracilis*, conversely experienced decreased habitat suitability under future conditions with these negative effects greater in *B. gracilis* over *B. eriopoda*.

Table 5. Habitat suitability (lambda) values for the 11 grass species for the western United States. Shows historical (1970–2000) lambda, future (2070) lambda for the 50th quantile of the ensemble of 17 GCMs for RCP 8.5, the percent area (pixel-wise) where lambda is robustly increasing and decreasing, the mean lambda values for regions of robust increase (magenta) and decrease (orange), and the overall mean robust change in lambda. Historical and future lambda values should not be compared among species. However, since robust change in habitat suitability was adjusted by the maximum historical habitat suitability for each species, mean changes in lambda values can be compared across species and can be used to infer relative changes in habitat suitability among species.

Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ median model (2070–2100)	Percent area increasing (% $+\lambda$)	Pos ($+\lambda$)	Percent area decreasing (% $-\lambda$)	Neg ($-\lambda$)	Robust change λ	Direction of change
C ₃	<i>A. hymenoides</i>	0.140	0.150	77.16	0.037	22.84	-0.042	0.019	Increasing
	<i>E. elymoides</i>	0.187	0.144	15.36	0.010	84.64	-0.006	-0.004	Decreasing
	<i>H. comata</i>	0.076	0.054	19.71	0.067	80.29	-0.052	-0.029	Decreasing
	<i>P. smithii</i>	0.068	0.029	12.54	0.008	87.46	-0.027	-0.023	Decreasing
	<i>P. secunda</i>	0.566	0.211	3.22	0.021	96.78	-0.032	-0.030	Decreasing
C ₄	<i>A. purpurea</i>	0.087	0.141	91.77	0.044	8.23	-0.055	0.036	Increasing
	<i>B. eriopoda</i>	0.019	0.012	34.50	0.017	65.50	-0.024	-0.010	Decreasing
	<i>B. gracilis</i>	0.198	0.094	21.76	0.001	78.24	-0.022	-0.017	Decreasing
	<i>P. jamesii</i>	0.020	0.021	93.29	0.021	6.71	-0.109	0.012	Increasing
	<i>S. airoides</i>	0.019	0.032	81.13	0.040	18.87	-0.002	0.032	Increasing
	<i>S. cryptandrus</i>	0.027	0.028	75.71	0.052	24.29	-0.146	0.004	Increasing

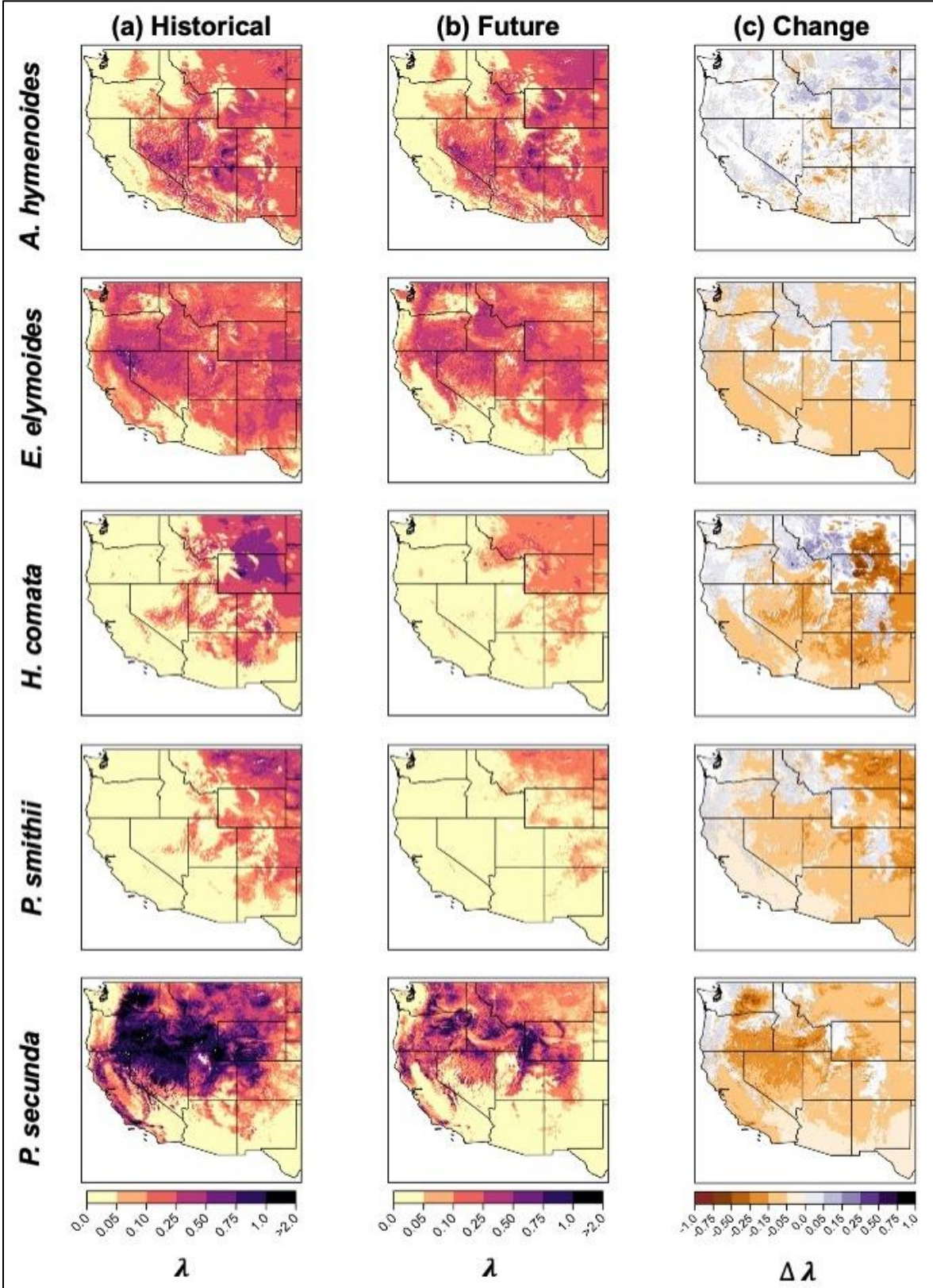


Figure 21. Projections of habitat suitability (λ) of C_3 (*A. hymenoides*, *E. elymoides*, *H. comata*, *P. smithii*, *P. secunda*) grass species included in this study. For each of these species, the figure shows (a) historical habitat suitability (λ) based on 1970–2000 WorldClim2 data; (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for the representative concentration pathway (RCP) 8.5, 2070 climate scenario; and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Change in habitat suitability was calculated as $\frac{\lambda_{future} - \lambda_{historical}}{\max(\lambda_{historical})}$ for the 50th quantile of ensembled GCMs for RCP 8.5, 2070 climate scenario, adjusted by the maximum historical lambda for that species. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 8.5, 2070. All areas in panel “c” are robust except for white shaded areas.

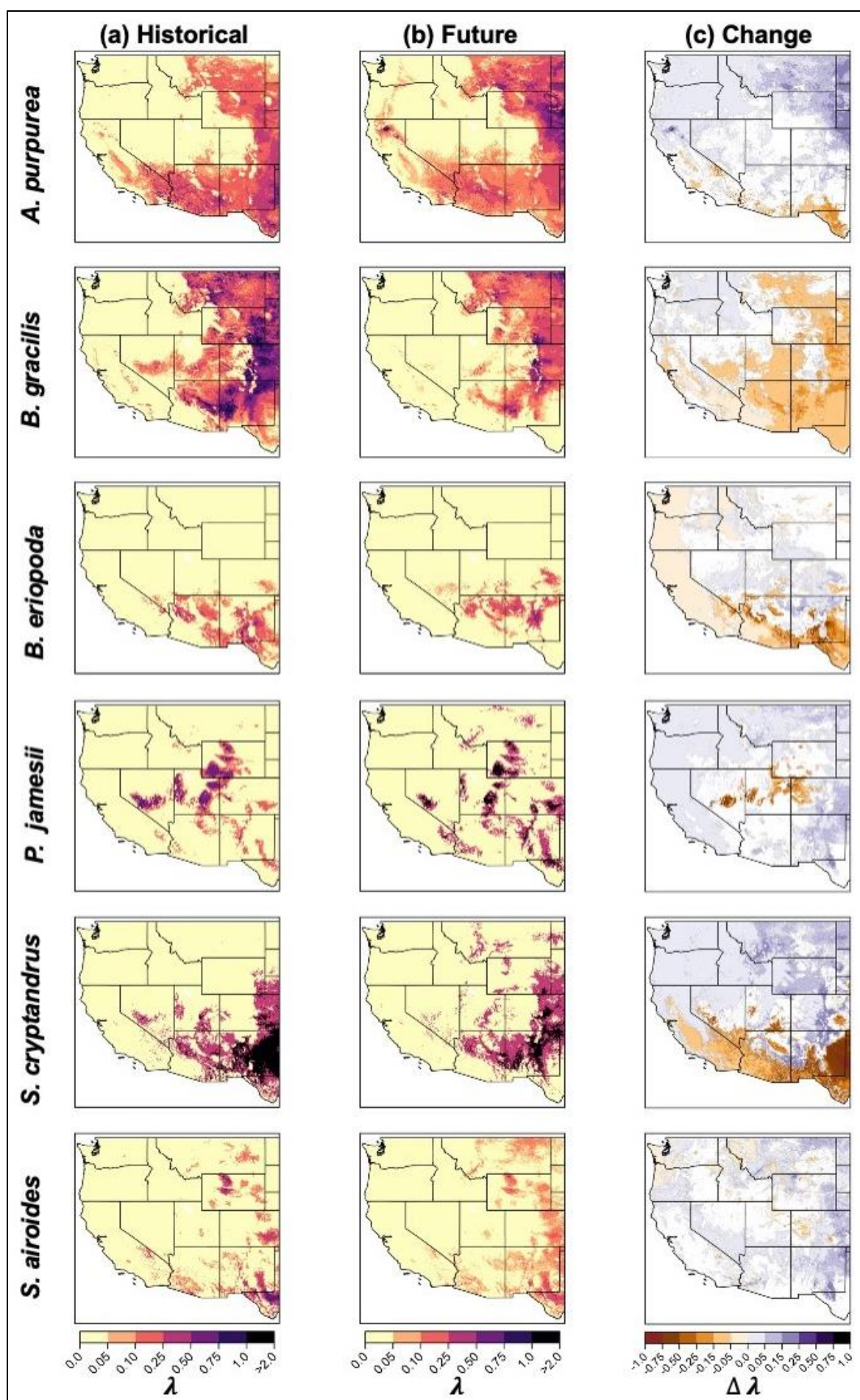


Figure 22. Projections of habitat suitability (λ) of C₄ (*A. purpurea*, *B. gracilis*, *B. eriopoda*, *P. jamesii*, *S. cryptandrus*, *S. airoides*) grass species included in this study. For each of these species, the figure shows (a) historical habitat suitability (λ) based on 1970–2000 WorldClim2 data; (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for the representative concentration pathway (RCP) 8.5, 2070 climate scenario; and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Change in habitat suitability was calculated as $\frac{\lambda_{future} - \lambda_{historical}}{\max(\lambda_{historical})}$ for the 50th quantile of ensembled GCMs for RCP 8.5, 2070 climate scenario, adjusted by the maximum historical lambda for that species. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 8.5, 2070. All areas in panel “c” are robust except for white shaded areas.

Spatial patterns in future changes

Strong spatial patterns existed in the projected robust changes in future habitat suitability that differed between C₃ and C₄ functional types. Areas of decrease in C₃ grass species habitat suitability were spatially widespread across the western portion of the region and varied in intensity across space, while declines in C₄ species habitat suitability were more localized, occurring mainly in lower latitude Southwestern deserts (Figures 21 and 22). In C₃ grasses, most species experienced consistent spatial patterns in declines of future habitat suitability that may reflect spatial patterns in future climate change. *Elymus elymoides*, *H. comata*, *P. smithii*, and *P. secunda* all experienced widespread declines in Southwestern deserts, the Great Basin, and the Great Plains, although the magnitude of these declines was spatially nuanced depending on species. For example, decreases in habitat suitability in *H. comata* and *P. smithii* were greatest in magnitude ($\Delta\lambda = -0.15$ to -0.50) in the Northern Great Plains in parts of Wyoming and Montana (Figures 21 and 22). This region is slated to experience substantial increases in MAT (Appendix 3, Figure A.3.14) and TRange (Appendix 3, Figure A.3.17) and decreased PTCorr (Appendix 3, Figure A.3.15) by the end of the 21st century, which were all influential environmental covariates in these species' SDMs. *Poa secunda* is projected to experience its most dramatic declines in habitat suitability in the Great Basin (Figures 21 and 22), which is projected to experience dramatic declines in PTCorr in the future in addition to increased MAT, decreased TRange, and decreased summer AI. In contrast to the other C₃ grasses, areas of robust decreases in *A. hymenoides* habitat suitability were heterogeneously distributed across the western United States (Figures 21 and 22).

Several C₄ grass species (i.e., *A. purpurea*, *B. eriopoda*, and *S. cryptandrus*) experienced their greatest declines in habitat suitability in southern deserts, areas which are projected to experience strong future aridification. Among C₄ species, *B. gracilis* experienced the most widespread decreases in future habitat suitability across southern deserts, and much of the Great Plains region in areas experiencing increased MAT and decreased PTCorr. In contrast to the other C₄ species, *P. jamesii* only experienced robust declines in habitat suitability in mid-latitude semiarid regions across parts of western Colorado, Utah, and Nevada in areas aligning spatially to projected future decreases in PTCorr (Appendix 3, Figure A.3.15). *Sporobolus airoides* is projected to experience few areas of localized declines in habitat suitability under future climate (Figures 21 and 22).

There were also some generalizable spatial patterns in areas of increase in habitat suitability for C₃ and C₄ species. Habitat suitability for C₃ species did not increase in many areas in the western United States except in some areas occupied by northwestern mountains and forests (Figures 21 and 22). In contrast, C₄ grasses experienced modest increases in habitat suitability across much of the western United States under future climate (Figures 21 and 22). Unlike other C₄ grasses examined by this study, *A. purpurea* and *S. cryptandrus* experienced more spatially localized increases in habitat suitability. In particular, *A. purpurea* experienced strongest increases in habitat suitability across much of the Northern Great Plains ($\Delta\lambda = -0.05$ to -0.25), as did *S. cryptandrus* ($\Delta\lambda = -0.05$ to -0.25) across a majority of the Great Plains region (Figures 21 and 22).

Sensitivity results for the Colorado Plateau and Southeast Utah Group park units

Colorado Plateau Ecoregion

Patterns of habitat suitability changes for the 11 perennial grasses studied within the Colorado Plateau Ecoregion (CPE) followed trends similar to the entire western United States. Under future climate projections (RCP 8.5, 2070; Appendix 3, Table A.3.5), all C₃ grasses experienced robust overall decreases in habitat suitability with declines greatest in *H. comata* ($\Delta\lambda = -0.057$). Other species with more modest projections for decline include *P. smithii* ($\Delta\lambda = -0.019$) and *P. secunda* ($\Delta\lambda = -0.010$). Two C₃ species displayed relatively small declines in suitability: *E. elymoides* ($\Delta\lambda = -0.007$) and *A. hymenoides* ($\Delta\lambda = -0.006$) (Appendix 3, Table A.3.6). Habitat suitability declines in most C₃ species were geographically widespread across the CPE, with the percent area decreasing from 98.9 to 100.0% of historical habitat. Although suitability declines for C₃ grasses over virtually the entire Colorado Plateau, suitability does not decrease to zero on the plateau as a whole or within particular park units (see park-specific results below and in Appendix 3). *Achnatherum hymenoides* was the only exception to this pattern. This species instead experienced patchy instances of habitat decline (50.5% of area) alongside areas of slightly increased habitat suitability (49.5% of area) across the CPE (Appendix 3, Figures A.3.27–A.3.34, Table A.3.6).

C₄ grass species' responses to variation in future climate on the CPE were more variable (Appendix 3, Figures A.3.27–A.3.34, Table A.3.6). Some C₄ grasses experienced overall robust declines in habitat suitability across the CPE. The magnitude of declines was greatest for *P. jamesii* ($\Delta\lambda = -0.107$) and *B. eriopoda* ($\Delta\lambda = -0.103$), and less for *B. gracilis* ($\Delta\lambda = -0.030$). *Bouteloua gracilis* was an outlier among C₄ grasses in terms of the spatial extent of its habitat declines. While the magnitude of robust habitat suitability decreases for *P. jamesii* and *B. eriopoda* were greater than that of *B. gracilis* (Appendix 3, Table A.3.6), declines in *B. gracilis* habitat were more spatially widespread. Habitat declines in *P. jamesii* and *B. eriopoda* accounted for only 33.3% and 34.9% of all CPE area, respectively, while declines in *B. gracilis* habitat occurred in 99.6% of areas (Appendix 3, Figures A.3.27–A.3.34; Table A.3.6). In contrast, other C₄ grasses displayed increasing suitability under future climate, including *S. cryptandrus* ($\Delta\lambda = 0.148$), *A. purpurea* ($\Delta\lambda = 0.054$), and *S. airoides* ($\Delta\lambda = 0.003$). Overall, spatial patterns in changes in habitat suitability in C₄ species across the CPE varied considerably by species (Figures A.3.27–A.3.34). For example, although *S. cryptandrus* experienced increased habitat suitability overall, this species experienced areas of high-magnitude habitat suitability increases (60.9% of area) and decreases (39.1% of areas) across the CPE (Appendix 3). *Aristida purpurea* and *S. airoides* overall experienced only minor robust changes in habitat suitability under future climate projections (Appendix 3; Table A.3.6), although both species experienced minor increases in suitability across mid-latitudes of the CPE (Appendix 3).

Arches National Park (ARCH)

Under future climate (RCP 8.5, 2070; Appendix 3, Table A.3.7), ARCH experienced overall robust declines in all habitat suitability for all C₃ perennial grass species. Suitability declines in ARCH ranged from *A. hymenoides* ($\Delta\lambda = -0.130$) to *H. comata* ($\Delta\lambda = -0.026$) to *E. elymoides* ($\Delta\lambda = -0.005$) to *P. smithii* ($\Delta\lambda = -0.002$) and *P. secunda* ($\Delta\lambda = -0.002$) (Table A.3.8). All areas where C₃ grasses experienced robust changes in future habitat suitability experienced habitat suitability decreases (Appendix 3, Table A.3.8).

C₄ grasses in ARCH experienced mixed changes in future habitat suitability, with habitat declines in *S. cryptandrus* ($\Delta\lambda = -0.065$), *B. eriopoda* ($\Delta\lambda = -0.032$) and *B. gracilis* ($\Delta\lambda = -0.012$). By contrast, *S. airoides* had slightly increased habitat suitability ($\Delta\lambda = 0.009$; Appendix 3, Table A.3.8). *Aristida purpurea* and *P. jamesii* did not experience robust changes in future habitat suitability, although future projections suggested *A. purpurea* habitat suitability trended up, while *P. jamesii* habitat suitability trended down under future climate (Appendix 3, Table A.3.8).

Canyonlands National Park (CANY)

Under future climate (RCP 8.5, 2070; Appendix 3, Table A.3.9), CANY experienced overall robust declines in habitat suitability across four of five C₃ perennial grass species (all except *A. hymenoides*). The magnitude of these changes was greatest for *H. comata* ($\Delta\lambda = -0.030$), followed by *E. elymoides* ($\Delta\lambda = -0.006$), *P. secunda* ($\Delta\lambda = -0.005$) and *P. smithii* ($\Delta\lambda = -0.004$) (Appendix 3, Table A.3.10). In contrast to other C₃ grasses, *A. hymenoides* experienced increased habitat suitability ($\Delta\lambda = 0.030$; Appendix 3, Table A.3.10) under future climate in CANY.

C₄ grasses in CANY experienced mixed change in future habitat suitability with robust habitat declines in *S. cryptandrus* ($\Delta\lambda = -0.107$) and *B. gracilis* ($\Delta\lambda = -0.011$), but increased habitat suitability in *A. purpurea* ($\Delta\lambda = 0.036$), *S. airoides* ($\Delta\lambda = 0.015$), and *B. eriopoda* ($\Delta\lambda = 0.009$; Appendix 3, Table A.3.10). *Pleuraphis jamesii* did not experience robust changes in future habitat suitability, but suitability projections suggested its habitat suitability trended down under future climate (Appendix 3, Table A.3.10).

Natural Bridges National Monument (NABR)

Under future climate (RCP 8.5, 2070; Appendix 3, Table A.3.11), NABR experienced overall robust declines in habitat suitability across four of the five C₃ perennial grass species (except *A. hymenoides*). The magnitude of these changes was greatest in *H. comata* ($\Delta\lambda = -0.056$) followed by *P. secunda* ($\Delta\lambda = -0.009$), *E. elymoides* ($\Delta\lambda = -0.008$) and *P. smithii* ($\Delta\lambda = -0.006$) (Appendix 3, Table A.3.12). In contrast to other C₃ grasses, *A. hymenoides* experienced no robust changes in habitat suitability (Appendix 3, Table A.3.12) under future climate in NABR.

C₄ grasses responses in NABR were mixed. Among C₄ species, only *B. gracilis* experienced robust decreases in habitat suitability under future climate ($\Delta\lambda = -0.010$; Appendix 3, Table A.3.12). Half of C₄ species included in this analysis experienced increased habitat suitability, with increases greatest for *B. eriopoda* ($\Delta\lambda = 0.065$), *A. purpurea* ($\Delta\lambda = 0.027$), and *S. airoides* ($\Delta\lambda = 0.018$) (Appendix 3, Table A.3.12). Neither *P. jamesii* nor *S. cryptandrus* experienced robust changes in habitat suitability under future climate, but habitat suitability trended downward for both species (Appendix 3, Table A.3.12).

Hovenweep National Monument (HOVE)

HOVE is a small park unit consisting of only six pixels. Given the scale and structure of this analyses, it was difficult to calculate robust changes in habitat suitability for HOVE because of its size. However, findings indicate that four of the five C₃ species experienced decreased habitat suitability under future climate (RCP 8.5, 2070; Appendix 3, Table A.3.13) in HOVE. Declines were greatest for *H. comata* ($\Delta\lambda = -0.038$), followed by *P. secunda* ($\Delta\lambda = -0.011$), *E. elymoides* ($\Delta\lambda = -$

0.010), and *P. smithii* ($\Delta\lambda = -0.006$) (Appendix 3, Table A.3.14). *Achnatherum hymenoides* did not experience robust changes in habitat suitability.

Under future climate in HOVE, C_4 species *A. purpurea* and *S. airoides* experienced habitat suitability increases of $\Delta\lambda = +0.021$ and $+0.018$, respectively (Appendix 3, Table A.3.14). Neither *B. eriopoda* nor *S. cryptandrus* experienced robust changes in habitat suitability under future climate.

Sensitivity Discussion

Temperature and precipitation timing drive historical habitat suitability across the western United States

Perennial grass species had nuanced responses to variation in historical environmental conditions. Across species, SDMs more consistently included temperature-related covariates (i.e., MAT, TRange) relative to precipitation-related covariates (i.e., MAP, PSeas). This result is consistent with previous studies that have shown temperature to be a dominant driver of perennial grass species niches (Butterfield and Munson 2016, Gremer et al. 2018). Grass habitat suitability responses to MAT differed depending on species and photosynthetic pathway. Unsurprisingly, C_3 grasses generally displayed greater habitat suitability in cooler (i.e., lower MAT) habitats at higher latitudes relative to C_4 species examined by this study, which on average occupied hotter, drier habitats at lower latitudes. This result is consistent with previous studies showing C_4 taxa generally occupy warmer, drier niches relative to C_3 species (e.g., Pau et al. 2013). The C_4 pathway is a morphological and biochemical trait complex that can confer a strong competitive advantage over the C_3 pathway in warm, drought-prone regions (Sage 2004). Since the C_4 pathway is more energetically expensive than the C_3 pathway, it is competitively dominant only in hot, dry environments under high light intensity, while the C_3 pathway is favored in cooler, wetter habitats (Sage 2004).

Precipitation can also play a strong role in determining grass biogeography (e.g., Bocksberger et al. 2016). Overall, the findings indicate variation in MAP had variable effects on historical grass distributions. In contrast, variables that reflect temporal variation in precipitation (i.e., PSeas, PTCorr) resulted in patterned effects on grass species distributions. This finding suggests that precipitation timing, rather than total annual amount, may determine habitat suitability across these species. Habitat suitability for C_3 species *H. comata* and *P. secunda* increased with increasing PSeas, suggesting dependence on short-term temporal concentration of precipitation events. A tendency for C_4 species *A. purpurea*, *B. eriopoda*, and *S. airoides* to have greatest habitat suitability in habitats with intermediate PSeas values may suggest species responses to longer duration seasonal precipitation events. Grass species habitat suitability was positively associated with the PTCorr, which suggests species rely on habitats with warm-season precipitation patterns, such as the North American monsoon during warm, summer months (Adams and Comrie 1997). This result agrees with previous work showing perennial grasses in dry regions of the western United States are known to rely heavily on summer monsoonal precipitation for recruitment, growth, and survival (Peters et al. 2012).

Future aridification is associated with robust declines in habitat suitability

Model results predict widespread, robust declines in native, C_3 perennial grass habitat suitability across the western United States by the late 21st century. These results align with spatial patterns of

future aridification in the region and are consistent with studies that have linked intensifying aridity to native perennial grass declines across the region (Munson et al. 2011b, Gremer et al. 2015, Gremer et al. 2018, Winkler et al. 2019). Habitat suitability losses for C₃ species (*E. elymoides*, *H. comata*, *P. smithii*, and *P. secunda*) were greatest in the Great Plains, especially Northern Great Plains, and Great Basin. Species distribution models indicated these C₃ species were particularly sensitive to temperature-related environmental covariates. Scrutiny of spatial patterns of niche declines and climate change in these regions suggests future decreases in habitat suitability were likely driven by increased MAT, decreased PTCorr, and increased TRange in the Great Plains and Great Basin ecoregions. This result agrees with previous experimental studies that link increasing temperature and increased C₃ grass mortality (Wertin et al. 2015, Winkler et al. 2019). Among the C₃ grasses in this study, only *A. hymenoides* deviated from these patterns. *Achnatherum hymenoides*, whose SDM did not display sensitivity to variation in MAT or PTCorr, did not experience similar declines in habitat suitability in these regions. Instead, projections indicate patchy distributions of habitat suitability increases and decreases for *A. hymenoides* across the western United States. This result conflicts with previous studies showing consistent negative impacts of drought on *A. hymenoides* (Winkler et al. 2019).

Most C₄ grasses (i.e., *A. purpurea*, *B. gracilis*, *S. cryptandrus*, and *B. eriopoda*), experienced habitat suitability declines in arid, low-latitude desert regions across southern California, Arizona, and Texas. This result suggests these C₄ species in Southwestern deserts may already be at the edge of their ecological temperature tolerances, meaning aridification in this area may result in steep declines in habitat suitability for these species. In contrast, increasing habitat suitability for most C₄ species was observed across much of the western United States at mid- to higher latitudes, suggesting expansion of C₄ species habitat suitability under future climate.

Study limitations

While this analysis revealed general declines in perennial grass species suitability under future climate scenarios, the study design is limited in several ways. First, models were developed only for 11 common species across the western United States. Future work could explore the responses of a broader range of species, including species with functional traits that may be suitable for future hotter, drier conditions across the region. Secondly, the SDMs predict species potential niches but may not reflect their realized niches. The SDM model-selection process only included *a priori* environmental covariates. There may be other abiotic factors controlling species distributions, including disturbance and/or land management history. In addition, biotic interactions also affect species' realized niches and are not included in these models. Finally, while great care was taken to account for uncertainty in future climate projections—modeling both RCP scenarios, across 17 GCMs per climate scenario, and calculating robust change where 90% of GCMs agreed—there is inherent uncertainty in all projections.

Implications for land managers

Perennial grass losses associated with aridification can serve as pivot points for ecological regime shifts, including grassland to shrubland state transition (Briggs et al. 2005, Báez et al. 2013, Bestelmeyer et al. 2018) and invasive annual grass state transition (Abatzoglou and Kolden 2011,

Munson et al. 2011b). A recent long-term study of drought effects on native plant communities on the Colorado Plateau conducted by Winkler et al. (2019) showed that in response to increased experimental drought, perennial grasses *A. hymenoides*, *P. jamesii*, and *S. cryptandrus* experienced mortality, while shrubs were more resistant to drought, likely owing to their ability to access deeper soil water. Grassland to shrubland state transition is often accompanied by ecosystem service losses, including decreased forage for livestock and wildlife (McKeon et al. 2009, Izaurrealde et al. 2011), increased bare ground cover and soil erosion rates (Okin et al. 2009), and decreased soil nutrient availability (Schlesinger et al. 1996).

While it could be predicted that perennial grasses with warmer, drier niche requirements might shift into higher-latitude habitats historically occupied by cooler, wetter adapted species under future climate scenarios, C₄ habitat expansion was modest relative to C₃ suitability declines. However, two C₄ grasses, *A. purpurea* and *S. cryptandrus*, did experience relatively strong increases in habitat suitability in the Northern Great Plains where most of the C₃ species experienced their greatest declines in habitat suitability under future climate. This may suggest that some C₄ species could become more prevalent in regions where C₃ species experience habitat losses under future climate. Such changes could have important implications for wildlife and livestock grazing because C₄ species tend to be of lesser forage quality relative to C₃ species (Barbehenn et al. 2004). Moreover, an overall shift from C₃ to C₄ habitat suitability could coincide with temporal mismatches between forage availability and herbivore grazing and habitat needs if cool-season (C₃) species cover declines and warm-season (C₄) grass cover increases.

Management interventions can be used to promote grass recovery within shrubland states to produce novel ecosystems that are unlike historical grasslands but support important ecosystem services (Bestelmeyer et al. 2018). Given predicted shifts in habitat suitability for perennial grasses under future climate scenarios demonstrated by this study, revegetation management practices will likely need to adapt to the challenges of a hotter, drier future. Predicted declines in perennial grass species habitat suitability across the western United States also have implications for resource managers selecting native plant species to use for restoration and reclamation purposes (Doherty et al. 2017, Winkler et al. 2018) as restoration efforts using perennial grasses may have limited success in increasingly dry climates.

Sensitivity Summary

Arid and semi-arid grasslands cover 30% of Earth's surface and support critical ecosystem functions but are expected to be particularly vulnerable to global change. In recent decades, grasslands in the western United States have experienced widespread native, perennial grass die-offs that have been linked to aridification. Yet, predicting geographic patterns in species-level responses to aridification remains a major challenge. In this sensitivity component of the study, species distribution modeling is used to assess drivers of habitat suitability for 11 dominant, perennial grass species in the western United States. Based on this information, the sensitivity analysis (1) describes patterns of drivers of historical habitat suitability in dominant C₃ and C₄ grass species, (2) quantifies the direction and magnitude of changes in grass species habitat suitability in response to aridification, and (3) identifies species and areas with projected changes in habitat suitability that are robust across climate

models. The findings indicate that grass species habitat suitability was structured by nuanced combinations of climatic and edaphic factors, with C₃ species distributions more consistently structured by temperature-linked covariates relative to C₄ species.

Future species distribution modeling projections predict widespread declines in grass habitat suitability under future climate projections. These declines occur particularly in the Great Plains and Great Basin ecoregions, potentially as a result of increasing annual temperatures and aridity and declines in monsoonal precipitation across the western United States. C₄ species experienced habitat declines mainly in southernmost latitudes of Southwestern deserts, but they experienced moderate northward habitat expansion. Overall, the results suggest future aridification may result in declines in C₃ perennial grass species habitat suitability across the western United States in the coming decades, while some C₄ species may experience potential habitat expansion. These results have implications for predicting grassland responses to climate change and developing climate-adaptive land management strategies (e.g., see draft grassland adaptation menu in Appendix 1), including identifying habitat refugia for priority grass species and selecting more resilient species in grassland revegetation efforts under global change.

Conclusions

This report provides a quantitative assessment of 21st century climate and drought exposure in Southeast Utah Group (SEUG) parks, and an evaluation of the sensitivity of perennial grass species to those changes. These exposure and sensitivity results provide foundational information for developing management strategies that adapt to anticipated climate change and sustain valuable grassland resources in these parks.

The results for both exposure and sensitivity were generally consistent among the SEUG parks, which is not surprising given the geographic proximity of the four parks. However, soil texture and depth, which can vary substantially over small areas, exerts important control over soil moisture dynamics and overall moisture holding capacity. As a result, soil differences within and among SEUG parks create local variation in many of the drought metrics that are based on soil moisture dynamics.

Several general expectations for changing conditions and impacts on grassland resources have emerged from this work. These expectations may provide a useful synthetic overview for initiating discussion of next steps and adaptation strategies (e.g., building upon ideas in Appendix 1, draft grassland adaptation menu).

General expectations for climate change and grassland impacts in Southeast Utah Group park units:

1. Warmer temperatures throughout the year (high confidence)
2. Temperature increases greatest during cool times (e.g., nighttime lows and winter) (high confidence)
3. More days with extreme heat and fewer days with extreme cold (high confidence)
4. Earlier spring thaw and later fall frost (high confidence)
5. Modest (~approximately 10%) increase in mean annual precipitation (low confidence)
6. Potential decline in precipitation during fall, with a general shift toward cool-season precipitation (medium confidence)
7. Longer and hotter summer dry soil period (high confidence)
8. Increased percentage of precipitation falling as rain (high confidence)
9. Uncertain shifts in monsoon activity
10. Elevated atmospheric demand for moisture (high confidence)
11. Soil moisture slightly higher in winter, relatively unchanged in spring and summer, lower in fall (medium confidence)
12. Increasing plant activity in winter (high confidence)
13. Increasing plant physiological stress in summer driven by high atmospheric demand and low soil availability of water (high confidence)
14. Less frequent occurrence of conditions favorable for seedling survival (medium confidence)

15. Potential declines in overall viability of perennial grasses (medium confidence)
16. General decrease in viability of cool-season C3 perennial grasses (medium confidence)
17. General modest increase in viability of warm-season C4 perennial grasses (low confidence)
18. More frequent and intense storms (other sources)
19. Enhanced potential for wildfires and exotic plant invasion (other sources)

In addition to these general expectations, an important outcome of this work is the detailed data generated in the vegetation mapping, exposure, sensitivity, and similarity analyses. The results presented here, including in Appendices 2 and 3 and in the supplementary figures (Bradford et al. 2022), provide detailed evaluation of those data, and much more can be done with the data to address specific questions or resource management needs. All of these datasets will be provided to SEUG and Northern Colorado Plateau I&M Network staff, and we look forward to engaging in the subsequent stages of this project to help utilize these rich datasets as needed. As a whole, this report provides a starting point for understanding how climate is likely to change in SEUG parks, and what those changes may mean for grassland resources.

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Appendix 1: Climate Adaptation Workshops on Arid Grassland Conservation

To begin climate adaptation planning, the Southeast Utah Group Climate Adaptation Working Group held four working group meetings from 2018 to 2020, and a final series of workshops in the summer of 2021. The meetings progressed from initial planning of the strategy and data needs to a synthesis of findings and resulting management options. The meetings produced a draft “Adaptation Menu of Strategies and Approaches for Colorado Plateau Arid Grasslands” (Table A1-1) for conserving arid grasslands in a changing climate (see Summer 2021 workshop).

Winter 2018

In December of 2018, the Southeast Utah Group Climate Adaptation Working Group met for the first time in Moab, Utah, for a 3-day workshop. Thirty-six people attended, representing the U.S. Geological Survey’s (USGS) Southwest Biological Science Center, seven national park units, two NPS inventory and monitoring networks (I&M), and one university. The workshop objectives were to (1) build a shared vision for climate adaptation management strategies and research needs; (2) refine targets for focus of climate adaptation planning and research; (3) generate an initial set of management options that could be implemented in affected areas, either given current knowledge or contingent on additional information; (4) identify existing data, tools, and research that can support management needs; (5) identify high priority information gaps and how they can be filled; and (6) agree on a path forward and a strategy to stay coordinated.

Workshop participants learned about the Climate-Smart Conservation framework as a method of climate adaptation planning and worked through an example of planning for grassland resources (Stein et al. 2014). Participants also shared current research on climate trajectory for the region, discussed existing information and data gaps, and explored ideas for using forecasting to develop tools for restoration and adaptation planning. Outcomes of the workshop included committing to move forward on several next steps to further climate adaptation planning efforts, using an adaptive management approach to experiment with seed sources for restoration, developing partnerships, and cultivating Tribal involvement in climate adaptation planning. Participants expressed an interest in meeting again, potentially at the next Northern Colorado Plateau I&M Network meeting, in order to further knowledge sharing, continue climate adaptation planning efforts, and explore ways to implement adaptation strategies across multiple park units and jurisdictions.

Fall 2019

The second workshop was held in October 2019 in Flagstaff, Arizona. The half-day workshop was held in conjunction with the Biennial Conference for Science and Management on the Colorado Plateau and Southwest Region. The meeting objectives were to share updates and provide feedback on several ongoing projects, including the following: (1) a project funded by the Natural Resource Preservation Program, which is a collaboration between NPS and USGS; (2) Southeast Utah Group (SEUG) and partner adaptation planning efforts; and (3) related projects and information. The workshop was attended by 15 NPS staff, eight USGS research scientists, one academic, two ranchers, and two Tribal environmental professionals. Participants were provided updates on this exposure and

sensitivity analysis, and they were asked to give feedback on the process to make it more relevant for management needs. Specifically, this included feedback on vegetation maps and species for the NPS restoration species list. All participants gave updates on projects relevant to southwestern dryland climate adaptation and management.

Winter 2019

The third workshop was held in December 2019 in Moab, Utah, as a half-day gathering. Attendees included 45 people representing 10 NPS units, two NPS I&M networks, the USGS, and two universities. The meeting was held in conjunction with the NPS Northern Colorado Plateau I&M Network annual meeting. The objectives of the meeting were to (1) share project updates and get feedback on current products and future decision points, (2) exchange knowledge and updates about related projects and research, (3) discuss outreach and engagement strategies with Tribes and other partners, and (4) conduct a related workshop focused on pinon-juniper woodlands. Participants received updates on ongoing exposure, sensitivity, and vulnerability modeling; identified products that could be useful for management decisions; discussed related projects; and developed a list of partners who may be interested in this project.

Winter 2020

The fourth workshop took the form of a 2-hour working group meeting held virtually in December 2020. This meeting involved 15 participants representing SEUG, NPS Northern and Southern Colorado Plateau I&M networks, USGS, Northern Arizona University, and Colorado State University. The objectives of the meeting were to develop a suite of management strategies and tactics for SEUG grasslands, called a management menu. Representatives from the [Northern Institute of Applied Climate Science](#) (NIACS) joined the group to introduce and help facilitate the creation of a climate adaptation management menu. The climate adaptation menu builds capacity for management actions by offering resource managers possibilities that they may not have considered for managing ecosystem transitions and transformations. The menu is a key tool in the NIACS framework, which combines climate science, resource vulnerabilities, and management options into one centralized resource that can be quickly and simply used to make quick and effective decisions across scales. The menu process connects broad ideas to specific actions, makes actions intentional, helps managers and scientists communicate ideas, and boosts creativity in the process (Swanston et al. 2016). The menu contains six strategies, or broad adaptation responses, that consider ecological conditions and overarching management goals, each with their own set of site-level approaches and tactics, or management actions.

Summer 2021

The NPS Southeast Utah Group, U.S. Geological Survey, Northern Arizona University, and the Northern Institute of Applied Climate Science held a Climate Adaptation Workshop focused on tangible management actions to address climate challenges. This workshop series was a continuation of the climate adaptation workshops held over the past three years that included assessing vulnerabilities to climate change and developing management options. The workshop was held virtually over four days on June 17 from 10–11 AM (PST), August 23 from 9 AM–12 PM (PST), August 25 from 9 AM–12 PM (PST), and August 30 from 1–4 PM (PST).

The June meeting was a science webinar where researchers synthesized climate change impacts from exposure and sensitivity analyses on Colorado Plateau grasslands. Attendees included 83 natural resource managers and scientists from across the Colorado Plateau.

The final workshop held in August was an active hands-on training where participants used their management goals and knowledge of climate change impacts as a guide to identify potential adaptation actions for specific projects inside a national park on the Colorado Plateau.

The goals of that workshop were to

- discuss information on the current and anticipated effects of climate change on grasslands in national parks across the Colorado Plateau,
- describe resources and tools that can be used to integrate climate change into resource conservation and management,
- test a new “Adaptation Menu of Strategies and Approaches for Colorado Plateau Arid Grasslands,” and
- identify adaptation actions that can be incorporated into current and future NPS projects.

This final workshop brought together a breadth of park managers from across the Colorado Plateau interested in incorporating climate change adaptation into their on-the-ground planning. The 45 participants worked in groups on specific projects in these parks: Cedar Breaks NM, Southeast Utah Group parks, Capital Reef NP, Grand Canyon NP, Pipe Spring NM, Zion NP, and Chaco Culture NHP. The group followed steps outlined in Chapter 5 (pp. 74–89) of *Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers*, 2nd Edition (Swanston and others, 2016: www.nrs.fs.fed.us/pubs/52760). An online version of the workbook is available at www.adaptationworkbook.org. This process included: defining the area of interest, program, goals and objectives, and timeframes (step 1); identifying climate change impacts at the regional and local levels (step 2); identifying management challenges and opportunities from climate change (step 3); identifying arid grassland adaptation approaches and tactics (step 4); and identifying metrics for monitoring and evaluating effectiveness (step 5). In the final day of the workshop, each group presented on their project and the climate change-informed management actions they were going to take. Overall, workshop participants walked away armed with new information, resources, and an adaptation menu for thinking about climate change impacts and climate-adaptive management strategies for arid grasslands in their national parks across the Colorado Plateau.

Table A1-1. Draft Adaptation Menu of Strategies and Approaches for Colorado Plateau Arid Grasslands

Strategy	Approaches
Strategy 1: Sustain fundamental ecological functions of grasslands	Approach 1.1: Maintain or increase perennial vegetation
	Approach 1.2: Maintain or enhance soil stability
	Approach 1.3: Maintain or restore hydrologic function
Strategy 2: Reduce the impacts of stressors and disturbances	Approach 2.1: Prevent the introduction, establishment, and spread of invasive plants
	Approach 2.2: Limit and selectively apply land use activities that increase stress to the ecosystem
	Approach 2.3: Reduce impacts and risk of climate-driven disturbances
Strategy 3: Protect and restore priority communities from local to landscape scale	Approach 3.1: Identify and maintain low-vulnerability sites
	Approach 3.2: Identify, maintain, and prioritize grassland refugia and unique sites
	Approach 3.3: Manage grassland communities across diverse sites and conditions
	Approach 3.4: Reduce landscape fragmentation
Strategy 4: Promote climate change resilient plant species and genotypes	Approach 4.1: Promote species and genotypes currently performing well in response to change
	Approach 4.2: Expand seed sources to incorporate genotypes adapted to future conditions
	Approach 4.3: Facilitate the movement of species expected to be adapted to future conditions
Strategy 5: Realign severely disrupted ecosystems in accordance with expected future conditions	Approach 5.1: Allow and facilitate community transitions in some areas
	Approach 5.2: Consider environmental engineering solutions where conventional restoration is insufficient
Strategy 6: Promote adaptable organizations and human communities	Approach 6.1: Maintain a co-developed research agenda to inform adaptation management
	Approach 6.2: Explicitly consider current and future effects of climate change during the planning process and adaptive management
	Approach 6.3: Promote social awareness and increase education about anticipated effects of climate change in arid grasslands

Appendix 2: Climate and Drought Exposure Methods

This appendix contains supplementary material for the exposure section of the report. These materials include tables of park personnel contacted (Table A.2.1), a list of global circulation models used, and counts of stratified random points by vegetation type across each of the park units (Arches NP, Canyonlands NP, Hovenweep NM, and Natural Bridges NM) (Table A.2.2). This appendix also includes maps depicting elevation and soil characteristics for each park (Figures A.2.1–A.2.4) and maps of the geographic spread of the stratified random points for all parks, except Hovenweep NM, that were used to develop long-term climate and drought projections (Figures A.2.5–A.2.7). See the ScienceBase dataset referenced below for stratified random point locations at Hovenweep NM.

A more complete set of supplementary figures for climate and drought exposure is available from Bradford et al. (2022).

Underlying data are available from the US Geological Survey (USGS) digital repository, ScienceBase, at <https://www.sciencebase.gov/catalog/item/61a6952fd34eb622f6978d9f>.

Table A.2.1. List of specialists consulted on the vegetation maps and their respective park units.

Name	Park
Laura Trader	Bandelier NM
Sarah Milligan	Bandelier NM
Scott McFarland	Bandelier NM
Dangwole Bockus	Black Canyon of the Gunnison NP/Curecanti NRA
Kim Hartwig	Black Canyon of the Gunnison NP/Curecanti NRA
Jessica Frey	Black Canyon of the Gunnison NP/Curecanti NRA
Eric Vasquez	Bryce Canyon NP
Sarah Karinen	Bryce Canyon NP
Carolyn Livensperger	Capitol Reef NP
Sandra (Sandy) Borthwick	Capitol Reef NP
Bryan Larsen	Cedar Breaks NM
Kathleen Gonder	Cedar Breaks NM
Dana Hawkins	Chaco Culture NHP
Laura Jones	Colorado NM
Molly Murphy	Colorado NM
Jessica Resnki	Colorado NM
Emily Spencer	Dinosaur NM
John Spence	Glen Canyon NRA

Table A.2.1 (continued). List of specialists consulted on the vegetation maps and their respective park units.

Name	Park
Daniel Boughter	Grand Canyon NP
Lonnie Pilkington	Grand Canyon NP
Tova Spector	Mesa Verde NP
Aneth Wight	Northern Colorado Plateau Inventory and Monitoring Network
Dana Witwicki	Northern Colorado Plateau Inventory and Monitoring Network
Josh Doucette	Northern Colorado Plateau Inventory and Monitoring Network
Kelli Quinn	Northern Colorado Plateau Inventory and Monitoring Network
Liz Ballenger	Northern Colorado Plateau Inventory and Monitoring Network
Tonnie Casey	Petrified Forest NP
Brian Black	Pipe Spring NM
Megan Swann	Southern Colorado Plateau Inventory and Monitoring Network
Laura Schrage	Zion NP, Pipe Spring NM

List of global circulation models (GCMs) used in the study for each of the emission scenarios (RCP 4.5 and RCP 8.5):

bcc-csm1-1

bcc-csm1-1-m

BNU-ESM

CanESM2

CCSM4

CNRM-CM5

CSIRO-Mk3-6-0

GFDL-ESM2G

GFDL-ESM2M

HadGEM2-CC365

HadGEM2-ES365

inmcm4

IPSL-CM5A-LR

IPSL-CM5A-MR

IPSL-CM5B-LR

MIROC-ESM

MIROC-ESM-CHEM

MIROC5

MRI-CGCM3

NorESM1-M

Table A.2.2. Stratified random point counts for each national park unit and vegetation type.

Park unit	Vegetation class	Count points
Arches National Park	Grassland	42
	Non-native	27
	Shrubland	201
	Woodland	232
	Total	502
Canyonlands National Park	Forest	25
	Grassland	119
	Non-native	21
	Shrubland	762
	Woodland	711
	Total	1638
Hovenweep National Monument	Grassland	24
	Non-native	25
	Shrubland	25
	Woodland	25
	Total	99
Natural Bridges National Monument	Forest	25
	Grassland	25
	Shrubland	25
	Woodland	38
	Total	113

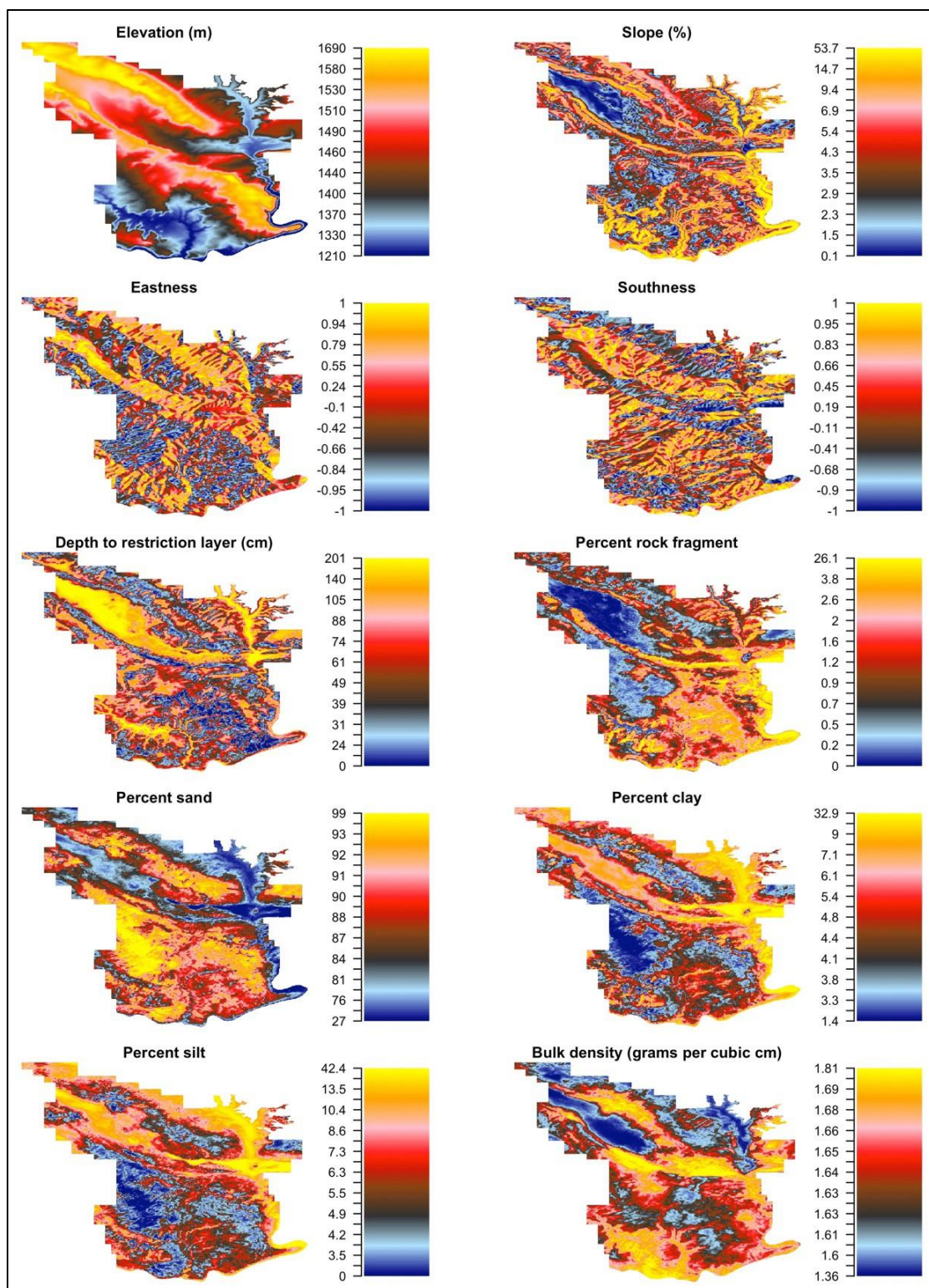


Figure A.2.1. Arches National Park elevation and soil characteristics. From top left, elevation, slope, eastness, southness, depth to restriction layer, percent rock fragment, percent sand, percent clay, percent silt and bulk density.

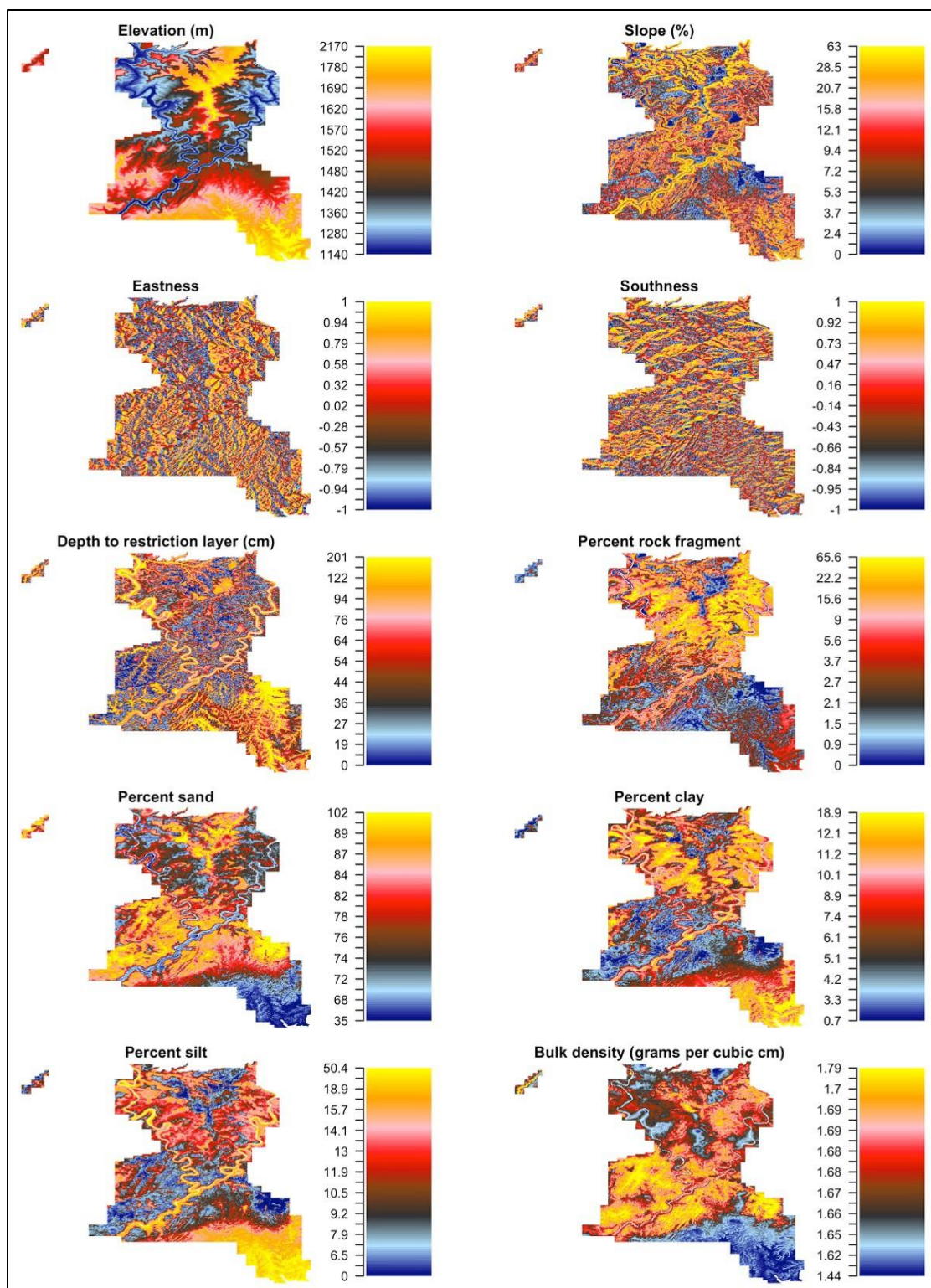


Figure A.2.2. Canyonlands National Park elevation and soil characteristics. From top left, elevation, slope, eastness, southness, depth to restriction layer, percent rock fragment, percent sand, percent clay, percent silt and bulk density.

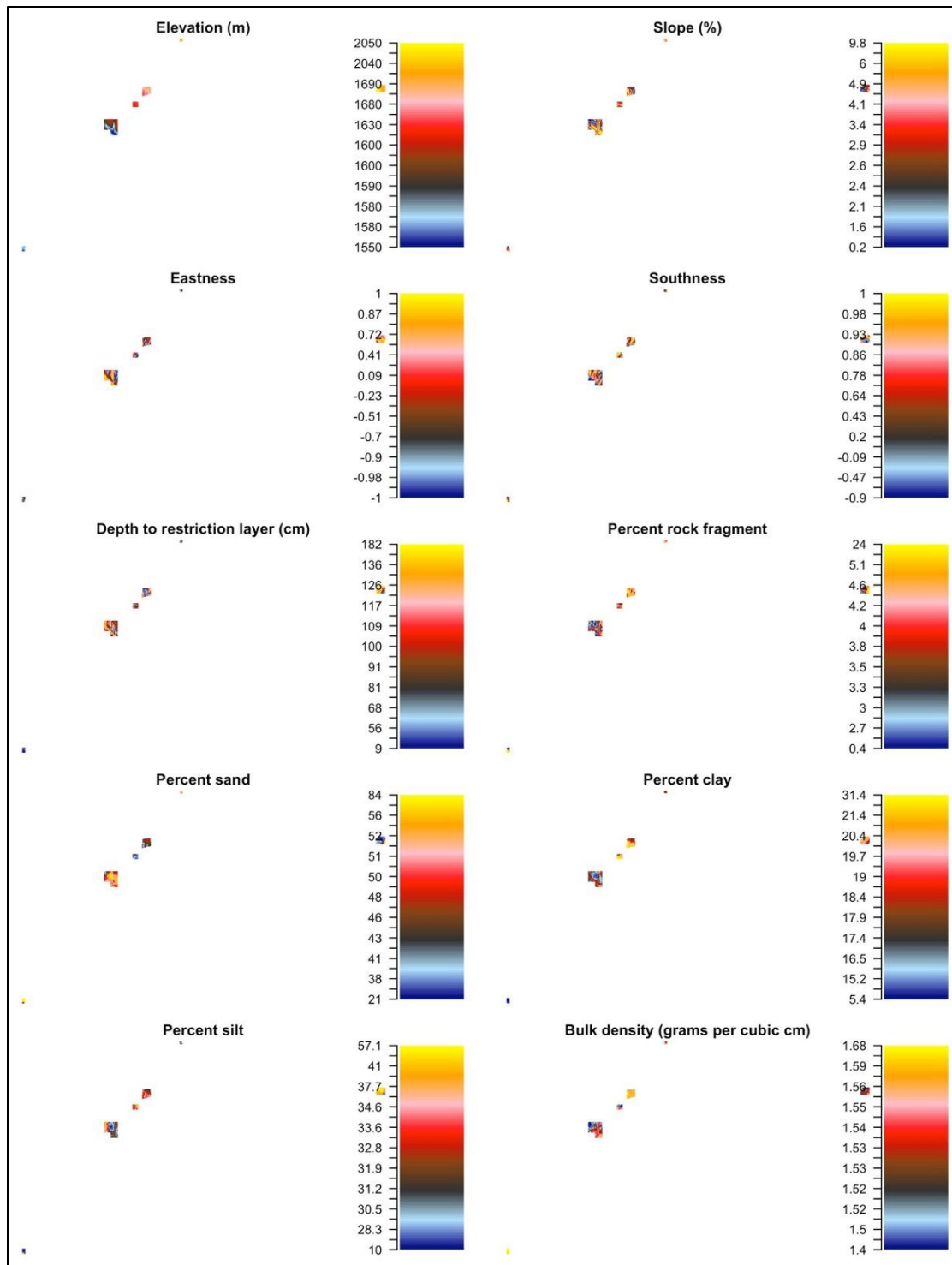


Figure A.2.3. Hovenweep National Monument elevation and soil characteristics. From top left, elevation, slope, eastness, southness, depth to restriction layer, percent rock fragment, percent sand, percent clay, percent silt and bulk density. Detailed data for visualizing climate and drought exposure results at HOVE (and the entire study area) are available from the USGS digital repository, ScienceBase, at <https://www.sciencebase.gov/catalog/item/61a6952fd34eb622f6978d9f>.

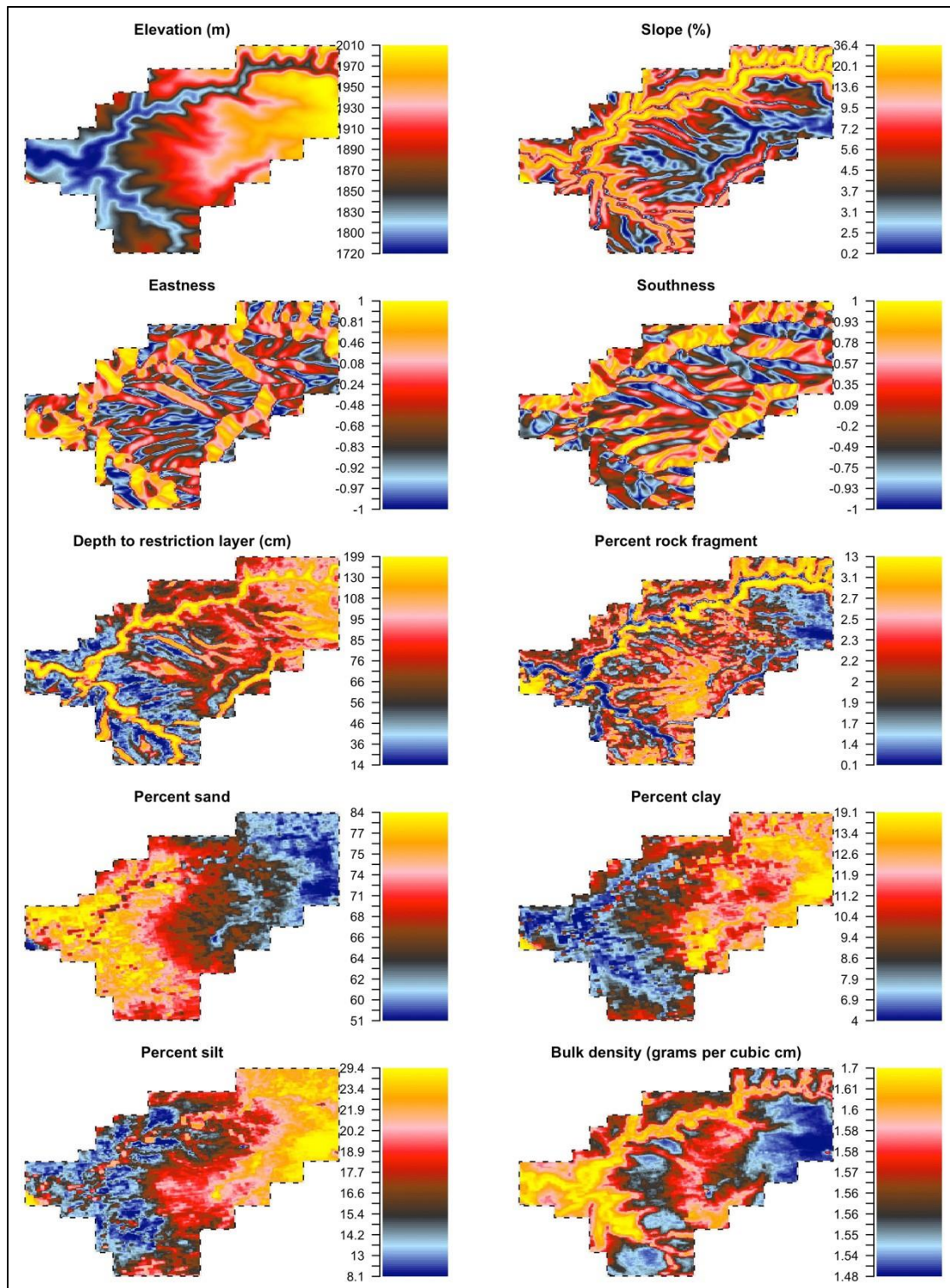


Figure A.2.4. Natural Bridges National Monument elevation and soil characteristics. From top left, elevation, slope, eastness, southness, depth to restriction layer, percent rock fragment, percent sand, percent clay, percent silt and bulk density.

ARCH

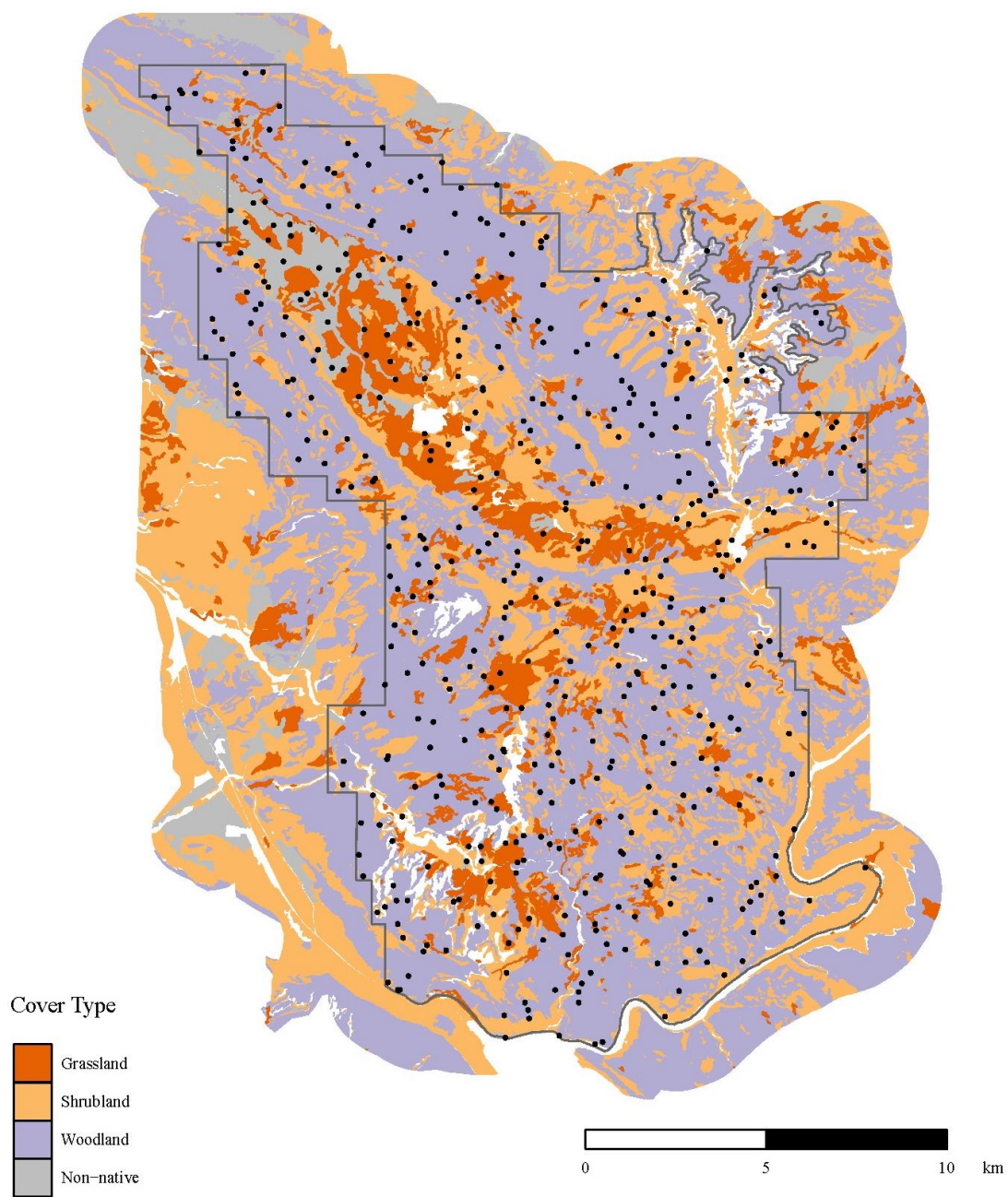


Figure A.2.5. Stratified random point selection locations for Arches National Park

CANY

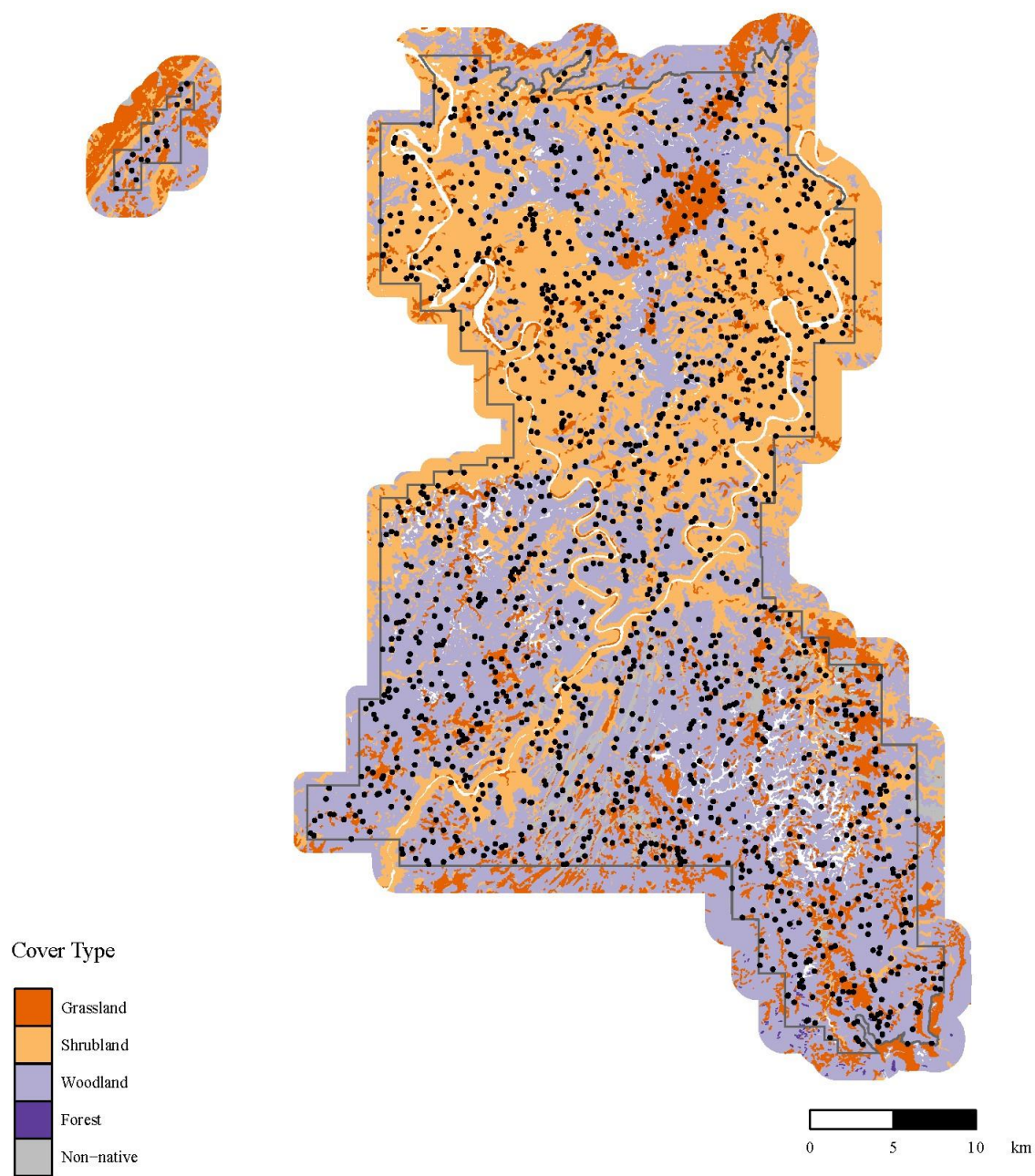


Figure A.2.6. Stratified random point selection locations for Canyonlands National Park.

NABR

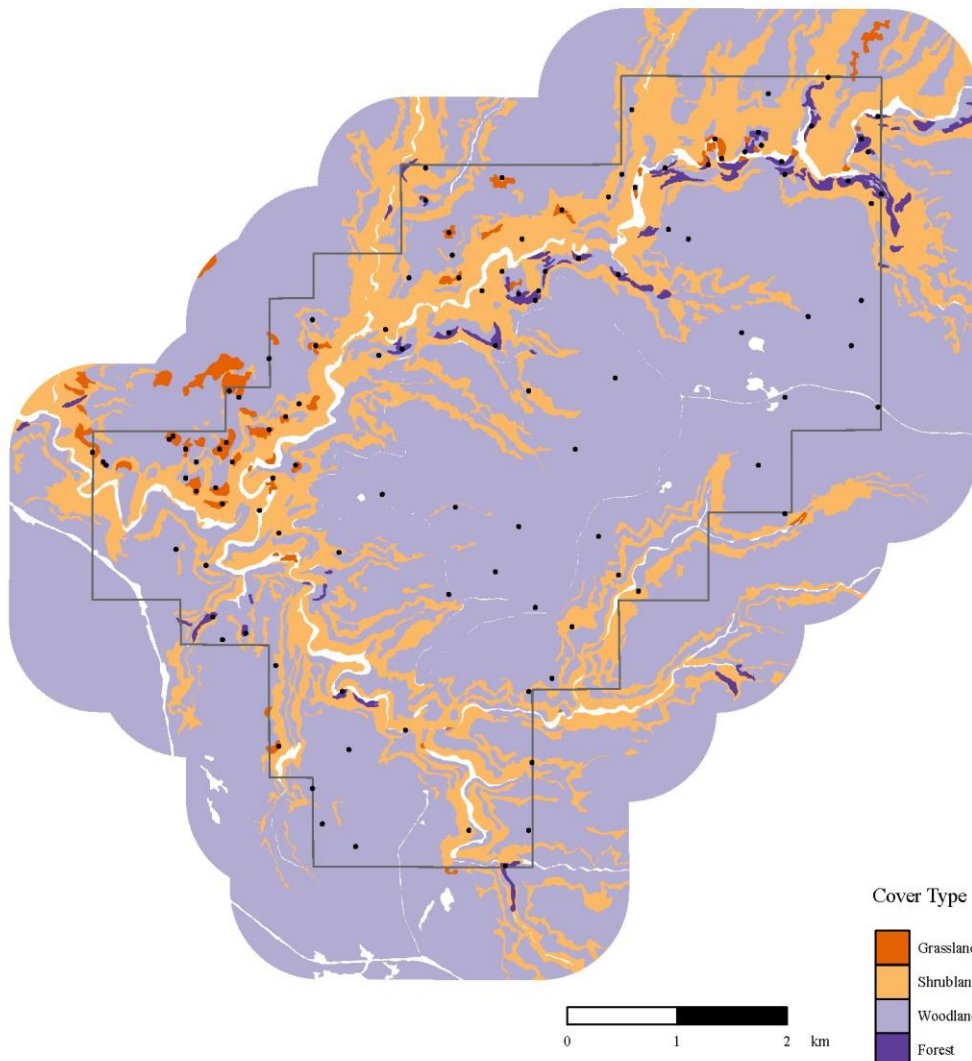


Figure A.2.7. Stratified random point selection locations for Natural Bridges National Monument.

Appendix 3: Perennial Grass Climate Sensitivity

This appendix provides additional figures and tables related to analysis to quantify the sensitivity of perennial grasslands in Southeast Utah Group (SEUG) national parks to expected 21st century shifts in climate and drought conditions. These figures and tables include:

- Maps of data used to generate niche models for each of the 11 perennial grass species
 - (Figures A.3.1–A.3.11).
- Map of historical (1970–2000) environmental conditions
 - (Figure A.3.12)
- Maps of change in environmental conditions under representative concentration pathway 4.5 and 8.5 for a range of climate models
 - (Figures A.3.13–A.3.18)
- Maps of historical and future climate suitability for each species across the western U.S.
 - (Figures A.3.19–A.3.26)
- Maps of historical and future climate suitability for each species within the Colorado Plateau
 - (Figures A.3.27–A.3.34)
- Table of environmental variables examined
 - (Table A.3.1)
- Table of variables utilized and model performance of species distribution modeling results by species
 - (Table A.3.2)
- Table of change in environmental conditions for the western U.S.
 - (Table A.3.3)
- Table of change in climate suitability for each grass species in the western U.S.
 - (Table A.3.4)
- Table of change in environmental conditions for the Colorado Plateau
 - (Table A.3.5)
- Table of change in climate suitability for each grass species in the Colorado Plateau
 - (Table A.3.6)
- Tables of change in environmental conditions for each of the SEUG parks
 - (Tables A.3.7, A.3.9, A.3.11, A.3.13)
- Tables of change in climate suitability for each grass species in each of the SEUG parks
 - (Tables A.3.8, A.3.10, A.3.12, A.3.14)

***A. hymenoides* species occurrence data**

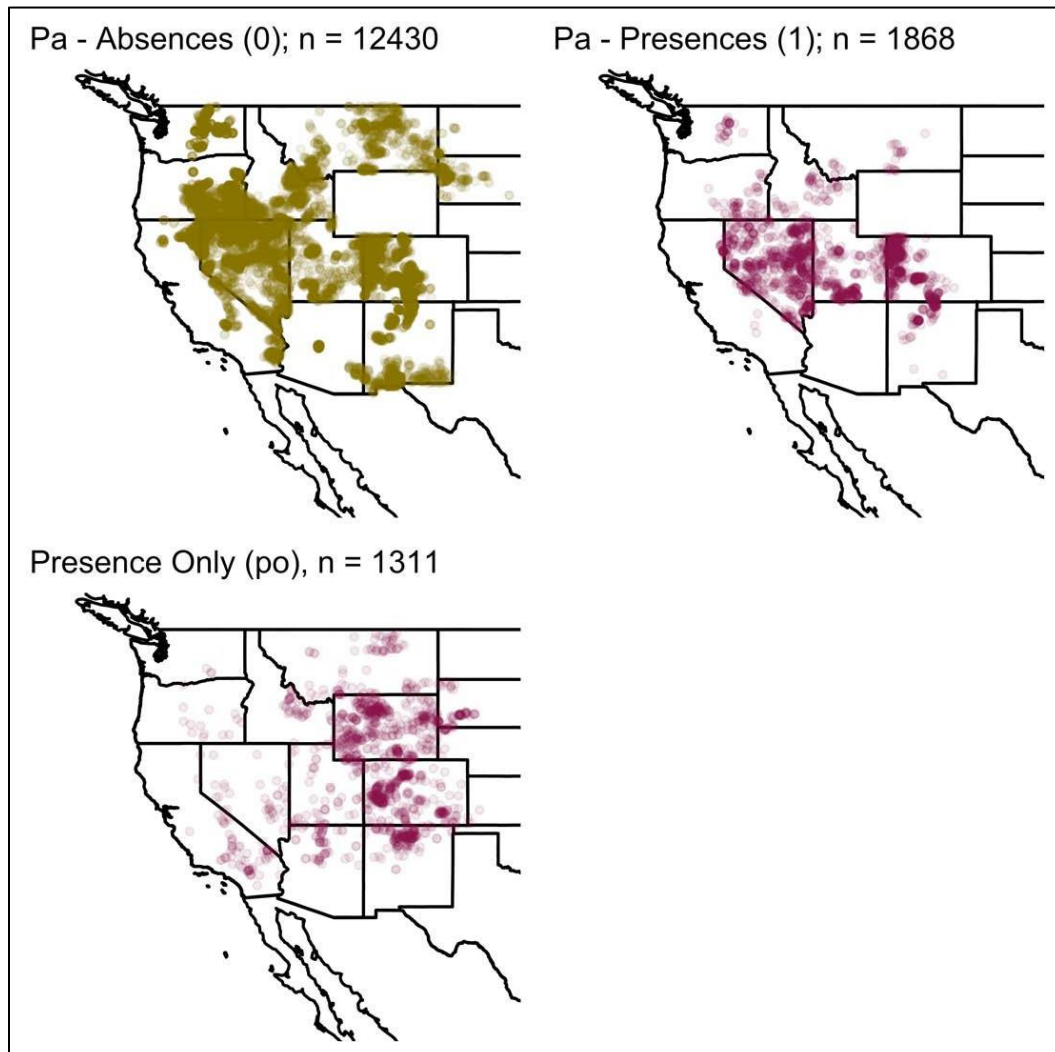


Figure A.3.1. *Achnatherum hymenoides* presence and absence records used for species distribution model (SDM) training. Presence/absence (Pa) data represent species presence and absence records acquired from the Bureau of Land Management Assessment, Inventory, and Monitoring (AIM) TerraDat species inventory dataset. Pa data within the state of Wyoming were excluded for this species because the dataset reported zero occurrences of these species even though they are a common species in this region. Presence only (Po) records were acquired from the SEINet database and those pictured and utilized in the SDM represent those records collected since 1980 with reliable associated georeferencing data (i.e., those records with a GPS georeferencing source, coordinate uncertainty <2000 m, or verbatim UTM coordinates).

E. elymoides species occurrence data

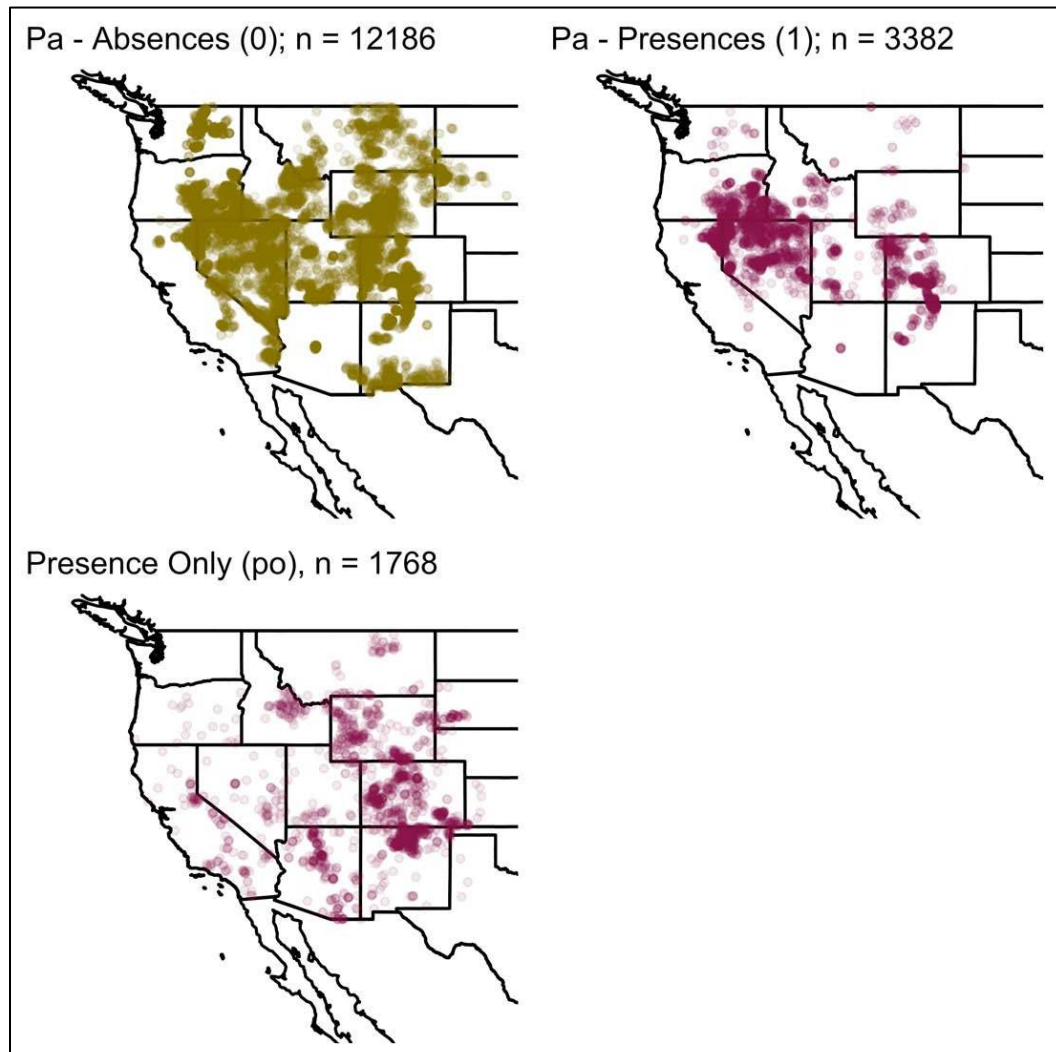


Figure A.3.2. *Elymus elymoides* presence and absence records used for species distribution model (SDM) training. Presence/absence (Pa) data represent species presence and absence records acquired from the Bureau of Land Management Assessment, Inventory, and Monitoring (AIM) TerraDat species inventory dataset. Presence only (Po) records were acquired from the SEINet database and those pictured and utilized in the SDM represent those records collected since 1980 with reliable associated georeferencing data (i.e., those records with a GPS georeferencing source, coordinate uncertainty <2000 m, or verbatim UTM coordinates).

H. comata species occurrence data

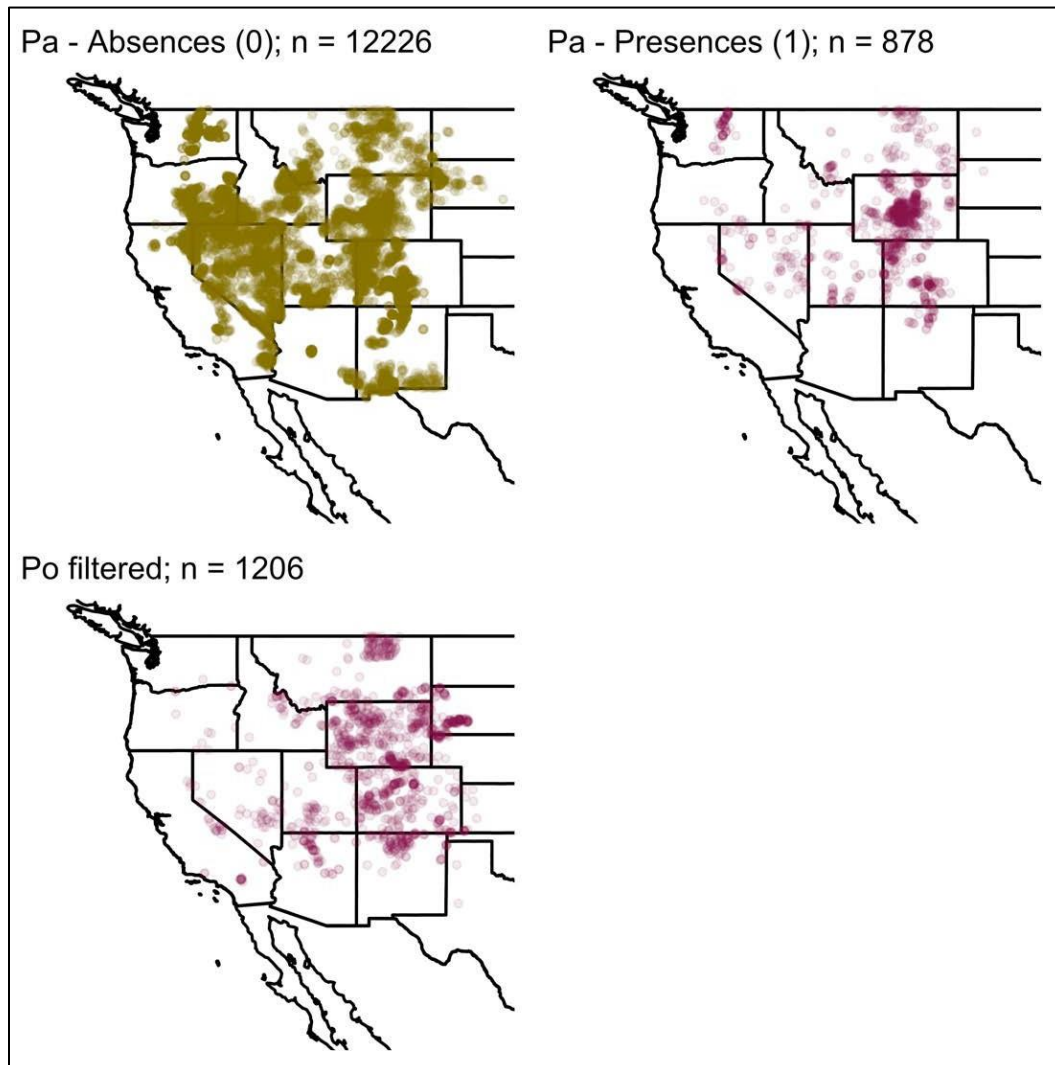


Figure A.3.3. *Hesperostipa comata* presence and absence records used for species distribution model (SDM) training. Presence/absence (Pa) data represent species presence and absence records acquired from the Bureau of Land Management Assessment, Inventory, and Monitoring (AIM) TerraDat species inventory dataset. Presence only (Po) records were acquired from the SEINet database and those pictured and utilized in the SDM represent those records collected since 1980 with reliable associated georeferencing data (i.e., those records with a GPS georeferencing source, coordinate uncertainty <2000 m, or verbatim UTM coordinates).

P. smithii species occurrence data

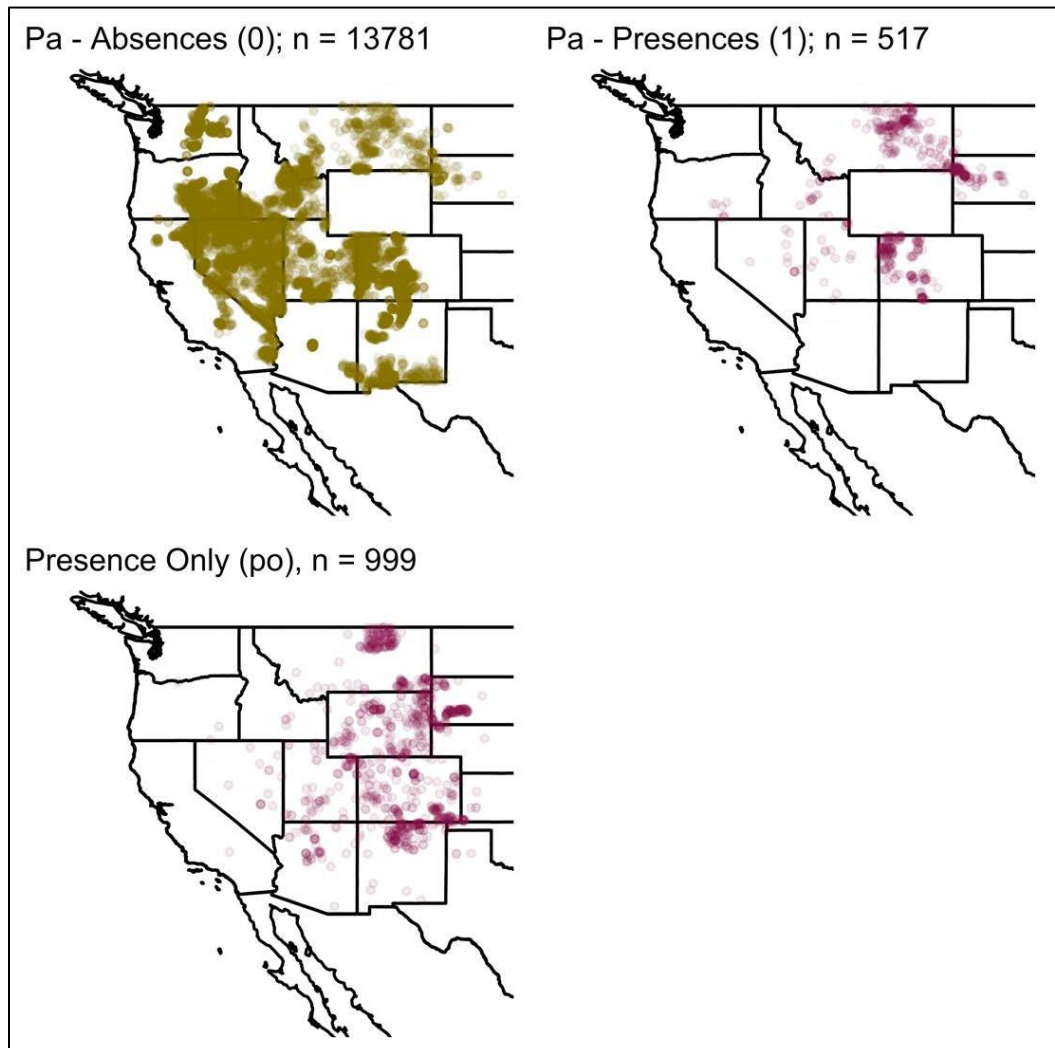


Figure A.3.4. *Pascopyrum smithii* presence and absence records used for species distribution model (SDM) training. Presence/absence (Pa) data represent species presence and absence records acquired from the Bureau of Land Management Assessment, Inventory, and Monitoring (AIM) TerraDat species inventory dataset. Pa data within the state of Wyoming were excluded for this species because the dataset reported zero occurrences of these species even though they are a common species in this region. Presence only (Po) records were acquired from the SEINet database and those pictured and utilized in the SDM represent those records collected since 1980 with reliable associated georeferencing data (i.e., those records with a GPS georeferencing source, coordinate uncertainty <2000 m, or verbatim UTM coordinates).

***P. secunda* species occurrence data**

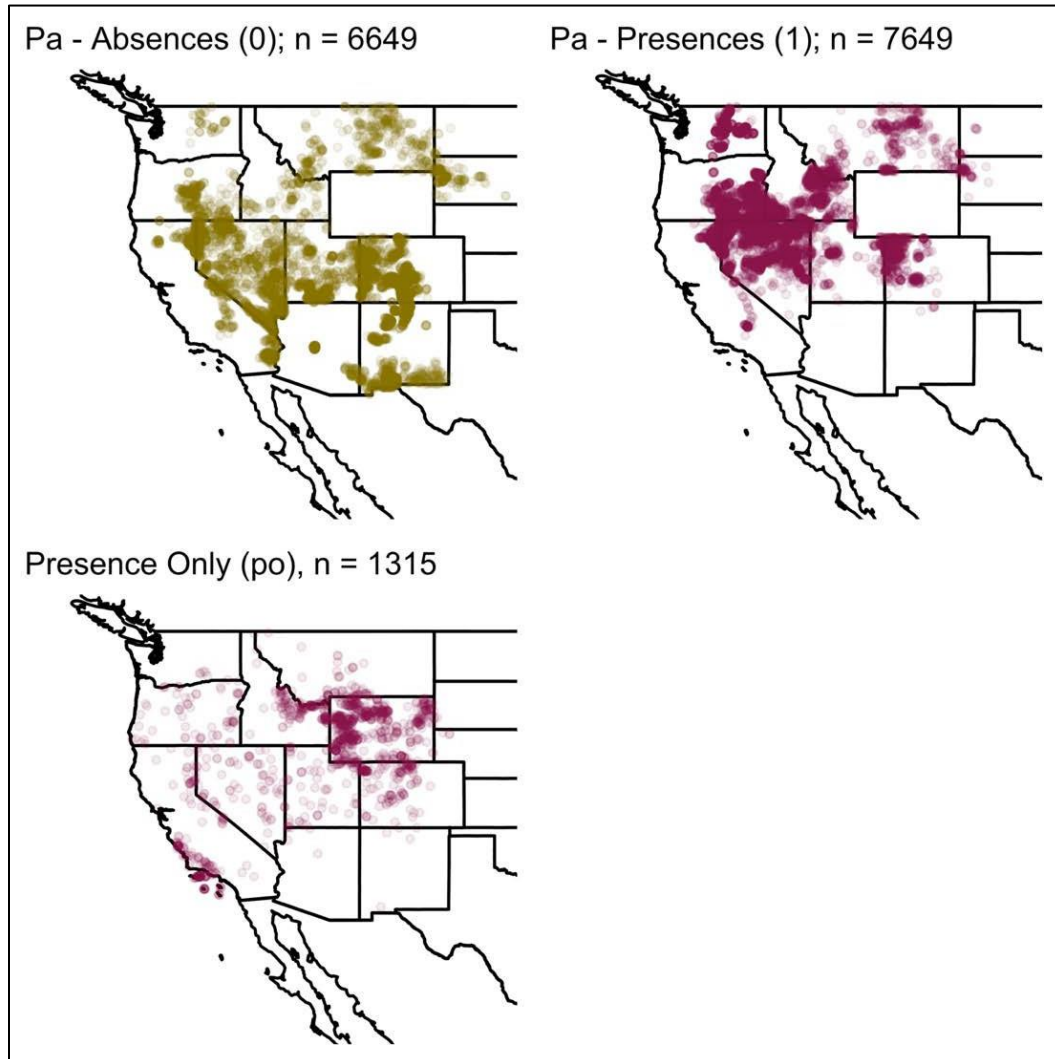


Figure A.3.5. *Poa secunda* presence and absence records used for species distribution model (SDM) training. Presence/absence (Pa) data represent species presence and absence records acquired from the Bureau of Land Management Assessment, Inventory, and Monitoring (AIM) TerraDat species inventory dataset. Pa data within the state of Wyoming were excluded for this species because the dataset reported zero occurrences of these species even though they are a common species in this region. Presence only (Po) records were acquired from the SEINet database and those pictured and utilized in the SDM represent those records collected since 1980 with reliable associated georeferencing data (i.e., those records with a GPS georeferencing source, coordinate uncertainty <2000 m, or verbatim UTM coordinates).

***A. purpurea* species occurrence data**

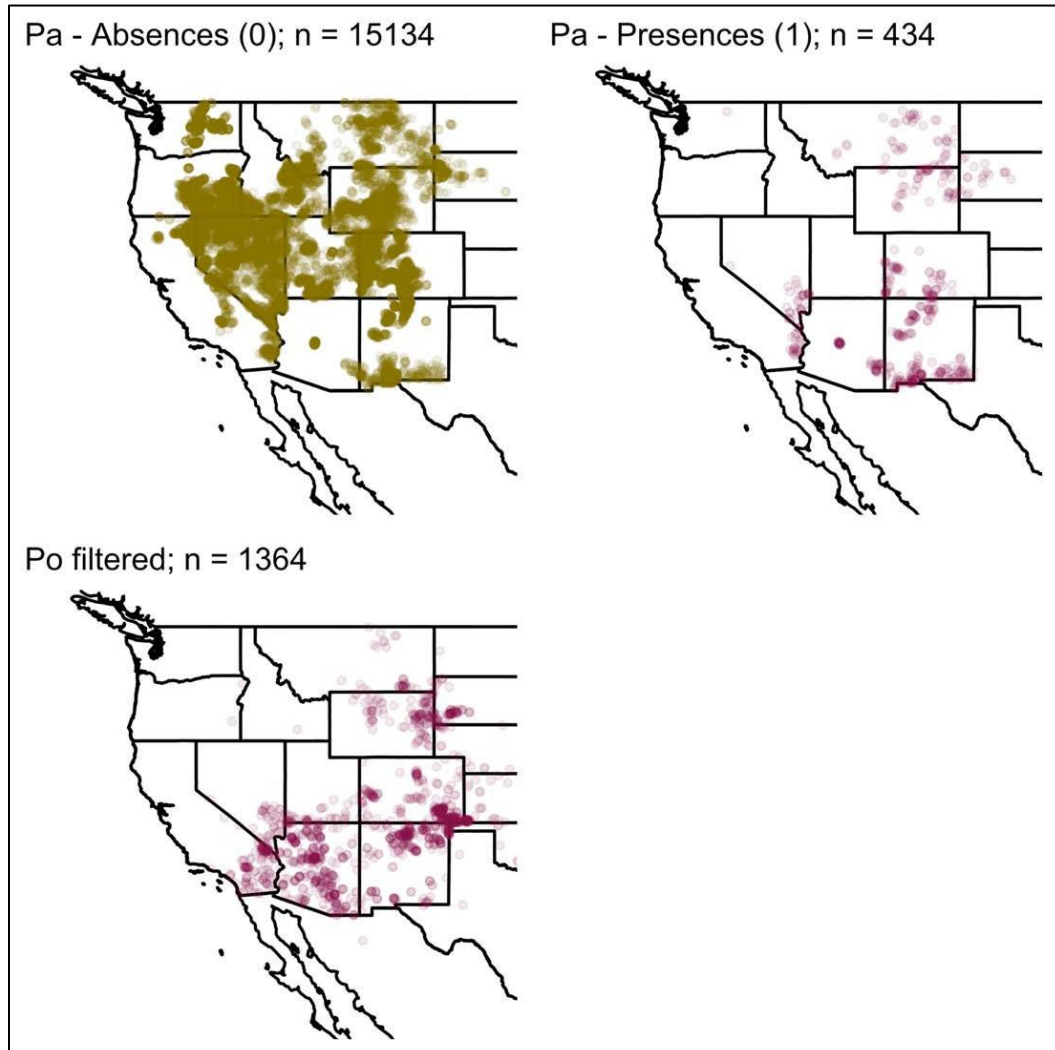


Figure A.3.6. *Aristida purpurea* presence and absence records used for species distribution model (SDM) training. Presence/absence (Pa) data represent species presence and absence records acquired from the Bureau of Land Management Assessment, Inventory, and Monitoring (AIM) TerraDat species inventory dataset. Presence only (Po) records were acquired from the SEINet database and those pictured and utilized in the SDM represent those records collected since 1980 with reliable associated georeferencing data (i.e., those records with a GPS georeferencing source, coordinate uncertainty <2000 m, or verbatim UTM coordinates).

***B. gracilis* species occurrence data**

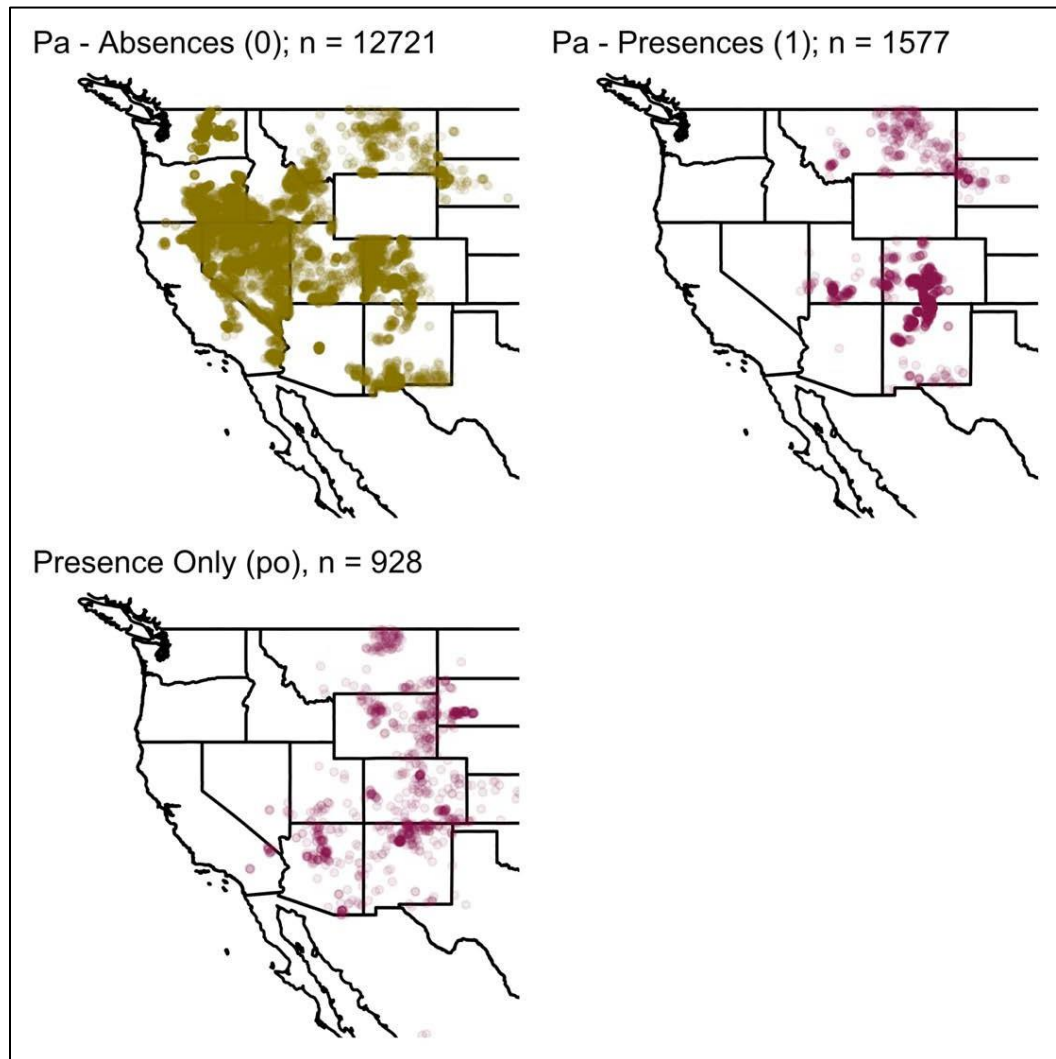


Figure A.3.7. *Bouteloua gracilis* presence and absence records used for species distribution model (SDM) training. Presence/absence (Pa) data represent species presence and absence records acquired from the Bureau of Land Management Assessment, Inventory, and Monitoring (AIM) TerraDat species inventory dataset. Pa data within the state of Wyoming were excluded for this species because the dataset reported zero occurrences of these species even though they are a common species in this region. Presence only (Po) records were acquired from the SEINet database and those pictured and utilized in the SDM represent those records collected since 1980 with reliable associated georeferencing data (i.e., those records with a GPS georeferencing source, coordinate uncertainty <2000 m, or verbatim UTM coordinates).

***B. eriopoda* species occurrence data**

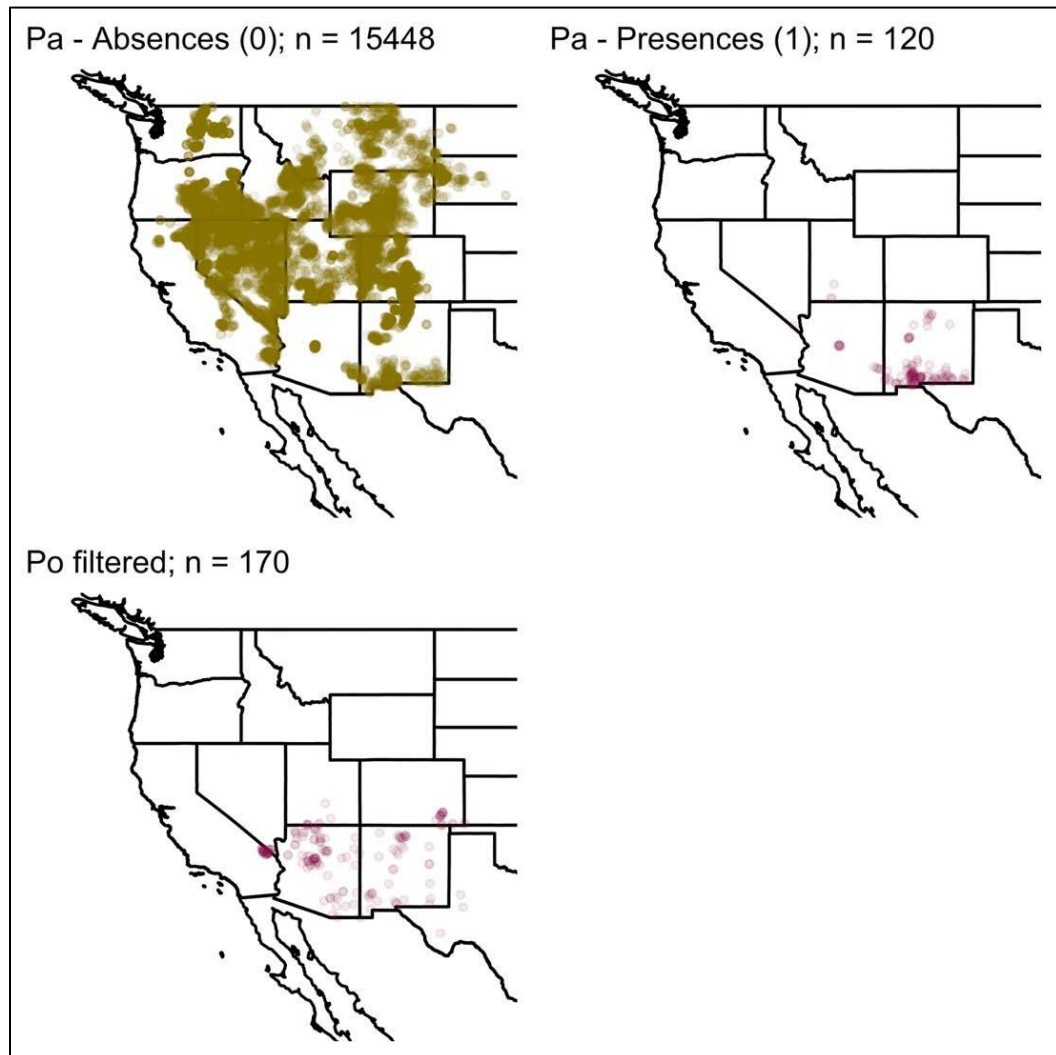


Figure A.3.8. *Bouteloua eriopoda* presence and absence records used for species distribution model (SDM) training. Presence/absence (Pa) data represent species presence and absence records acquired from the Bureau of Land Management Assessment, Inventory, and Monitoring (AIM) TerraDat species inventory dataset. Presence only (Po) records were acquired from the SEINet database and those pictured and utilized in the SDM represent those records collected since 1980 with reliable associated georeferencing data (i.e., those records with a GPS georeferencing source, coordinate uncertainty <2000 m, or verbatim UTM coordinates).

***P. jamesii* species occurrence data**

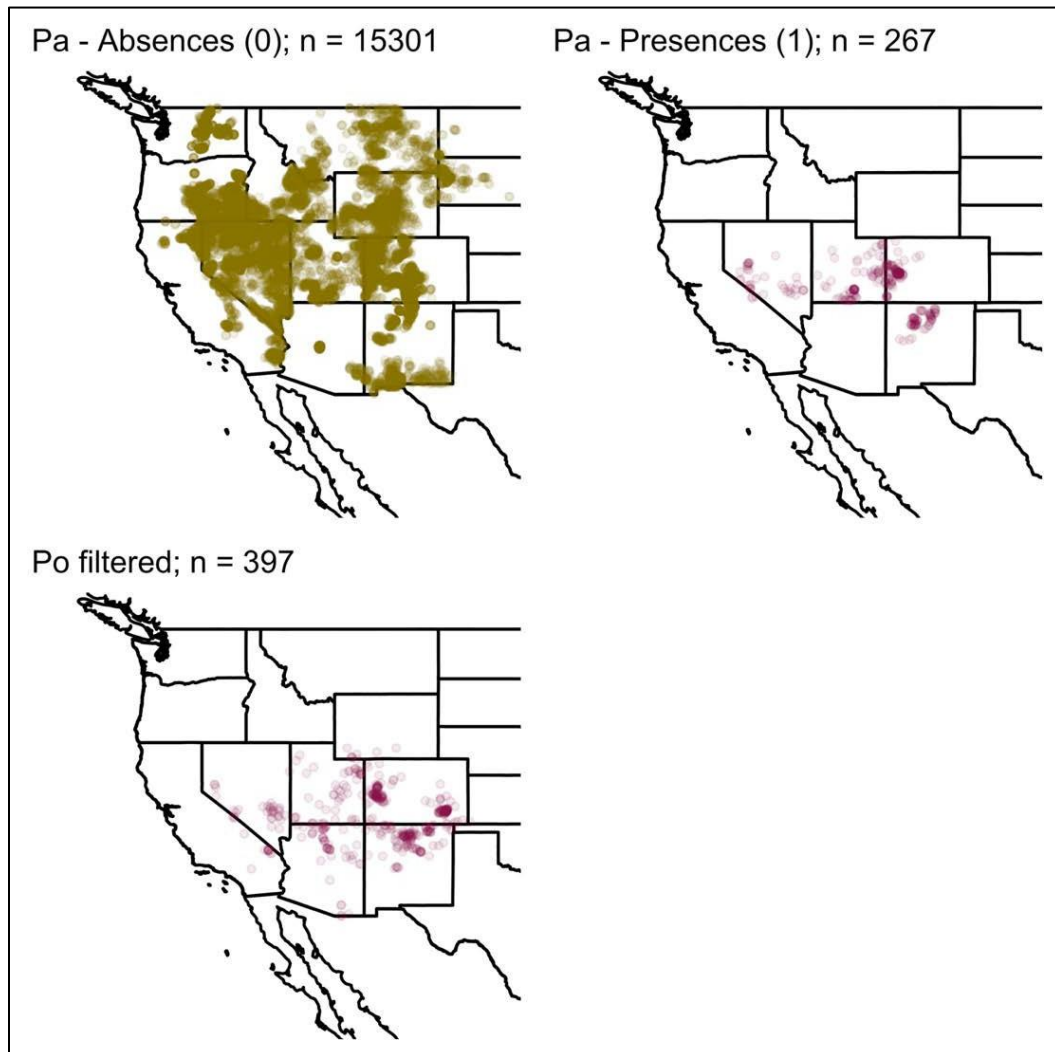


Figure A.3.9. *Pleuraphis jamesii* presence and absence records used for species distribution model (SDM) training. Presence/absence (Pa) data represent species presence and absence records acquired from the Bureau of Land Management Assessment, Inventory, and Monitoring (AIM) TerraDat species inventory dataset. Presence only (Po) records were acquired from the SEINet database and those pictured and utilized in the SDM represent those records collected since 1980 with reliable associated georeferencing data (i.e., those records with a GPS georeferencing source, coordinate uncertainty <2000 m, or verbatim UTM coordinates).

***S. airoides* species occurrence data**

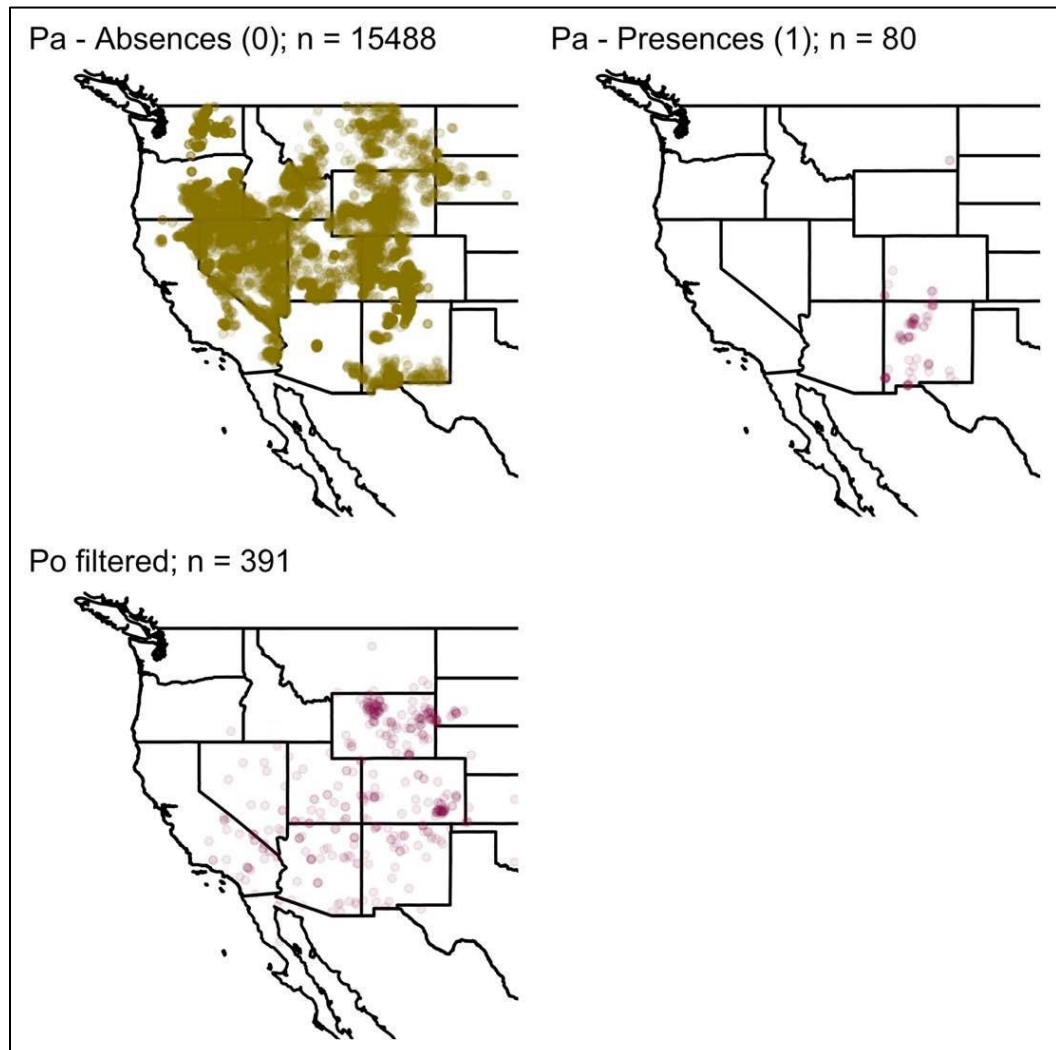


Figure A.3.10. *Sporobolus airoides* presence and absence records used for species distribution model (SDM) training. Presence/absence (Pa) data represent species presence and absence records acquired from the Bureau of Land Management Assessment, Inventory, and Monitoring (AIM) TerraDat species inventory dataset. Presence only (Po) records were acquired from the SEINet database and those pictured and utilized in the SDM represent those records collected since 1980 with reliable associated georeferencing data (i.e., those records with a GPS georeferencing source, coordinate uncertainty <2000 m, or verbatim UTM coordinates).

***S. cryptandrus* species occurrence data**

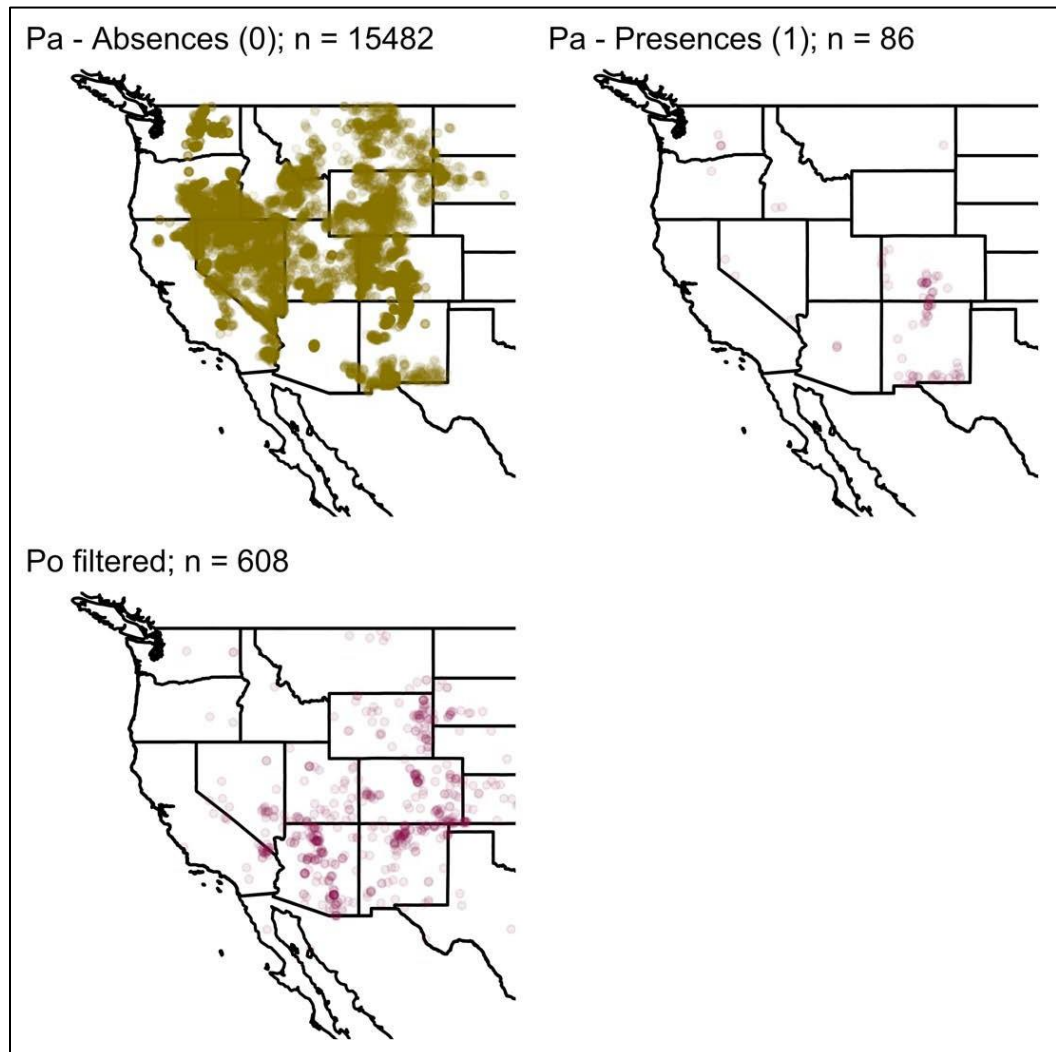


Figure A.3.11. *Sporobolus cryptandrus* presence and absence records used for species distribution model (SDM) training. Presence/absence (Pa) data represent species presence and absence records acquired from the Bureau of Land Management Assessment, Inventory, and Monitoring (AIM) TerraDat species inventory dataset. Presence only (Po) records were acquired from the SEINet database and those pictured and utilized in the SDM represent those records collected since 1980 with reliable associated georeferencing data (i.e., those records with a GPS georeferencing source, coordinate uncertainty <2000 m, or verbatim UTM coordinates).

Historical (1970–2000) environmental conditions

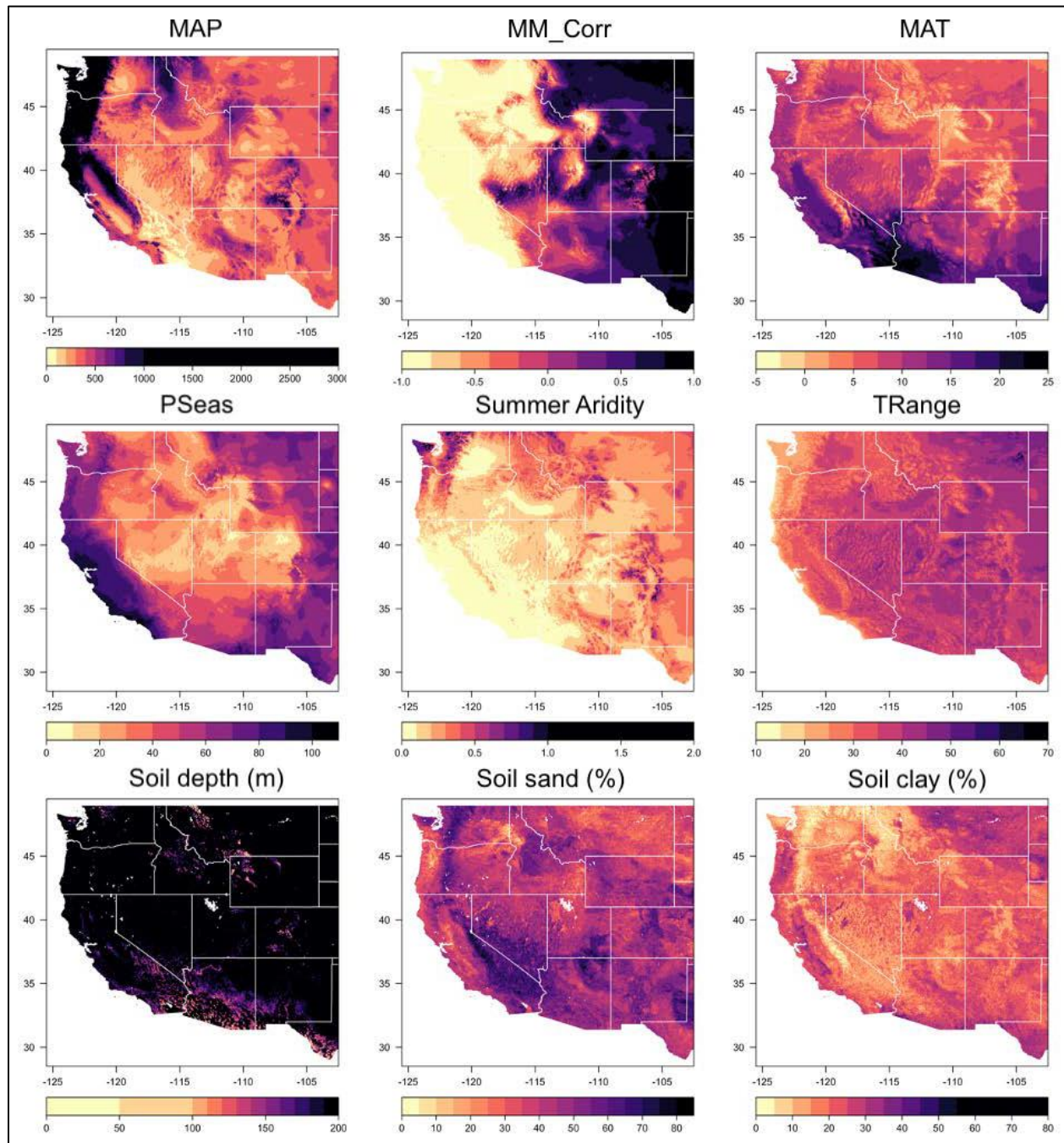


Figure A.3.12. Historical (1970–2000) environmental conditions for the western United States. Climate variables (mean annual precipitation (MAP), correlation between monthly precipitation and temperature (MM_corr), mean annual temperature (MAT), precipitation seasonality (PSeas), Summer_Aridity, and annual temperature range (TRange)) represent climatic variables derived from WordClim2 data (Fick and Hijmans 2017). Soils data (Soil depth (cm), Soil sand (%), and Soil clay (%)) were downloaded from the SoilGrids data platform (<https://www.isric.org/explore/soilgrids>).

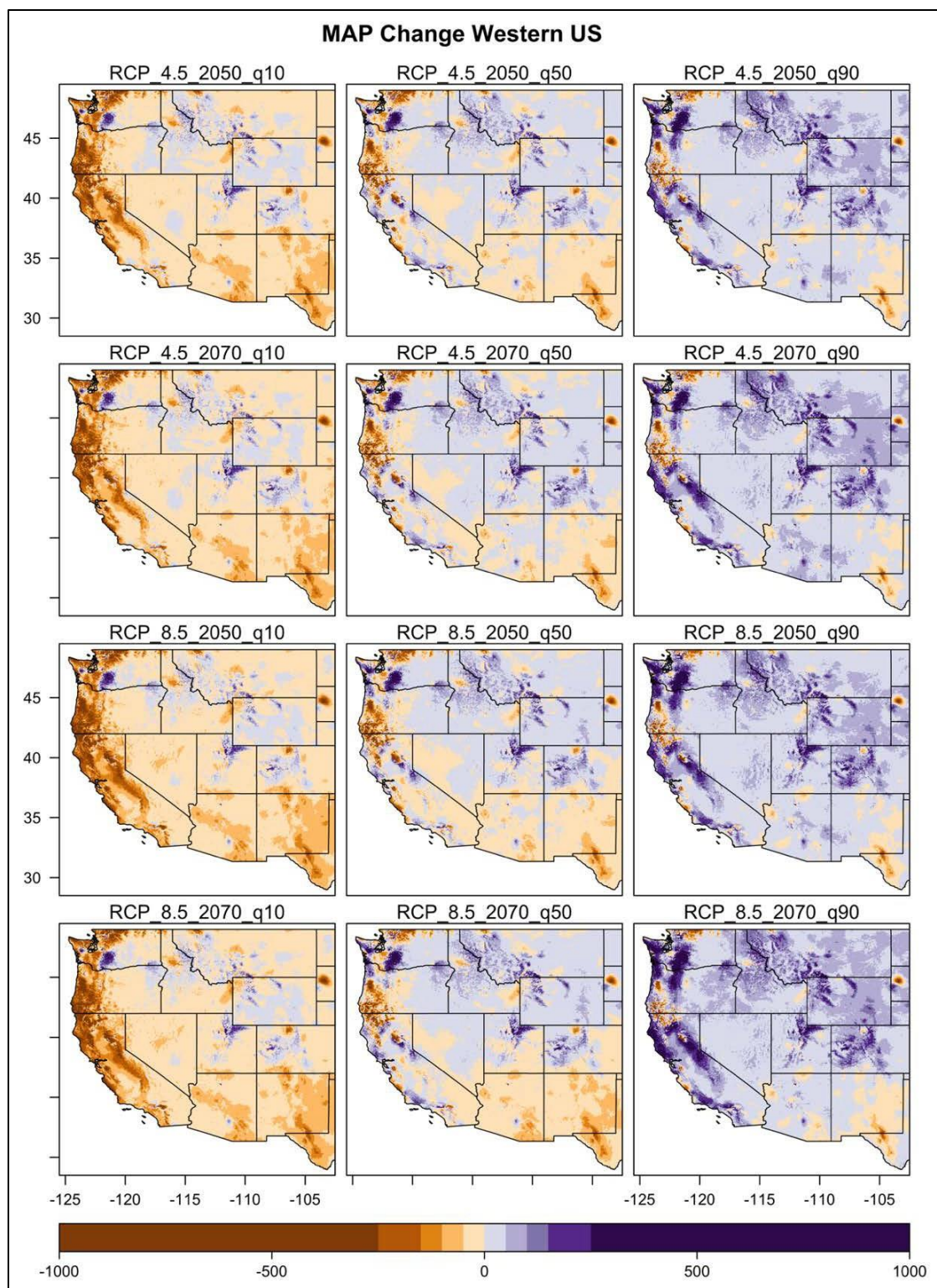


Figure A.3.13. Change in mean annual precipitation (MAP; mm) for the western United States calculated for the 10th, 50th, and 90th quantiles of ensemble future climate scenarios (17 GCMs) for two representative concentration pathways (RCPs) (4.5, 8.5) and two future time periods (2050, 2070). Change in MAP was calculated by subtracting values in the future climate scenario from historical conditions (1970–2000 average) at the pixel-level at 30 second (~900 m at the Equator) resolution.

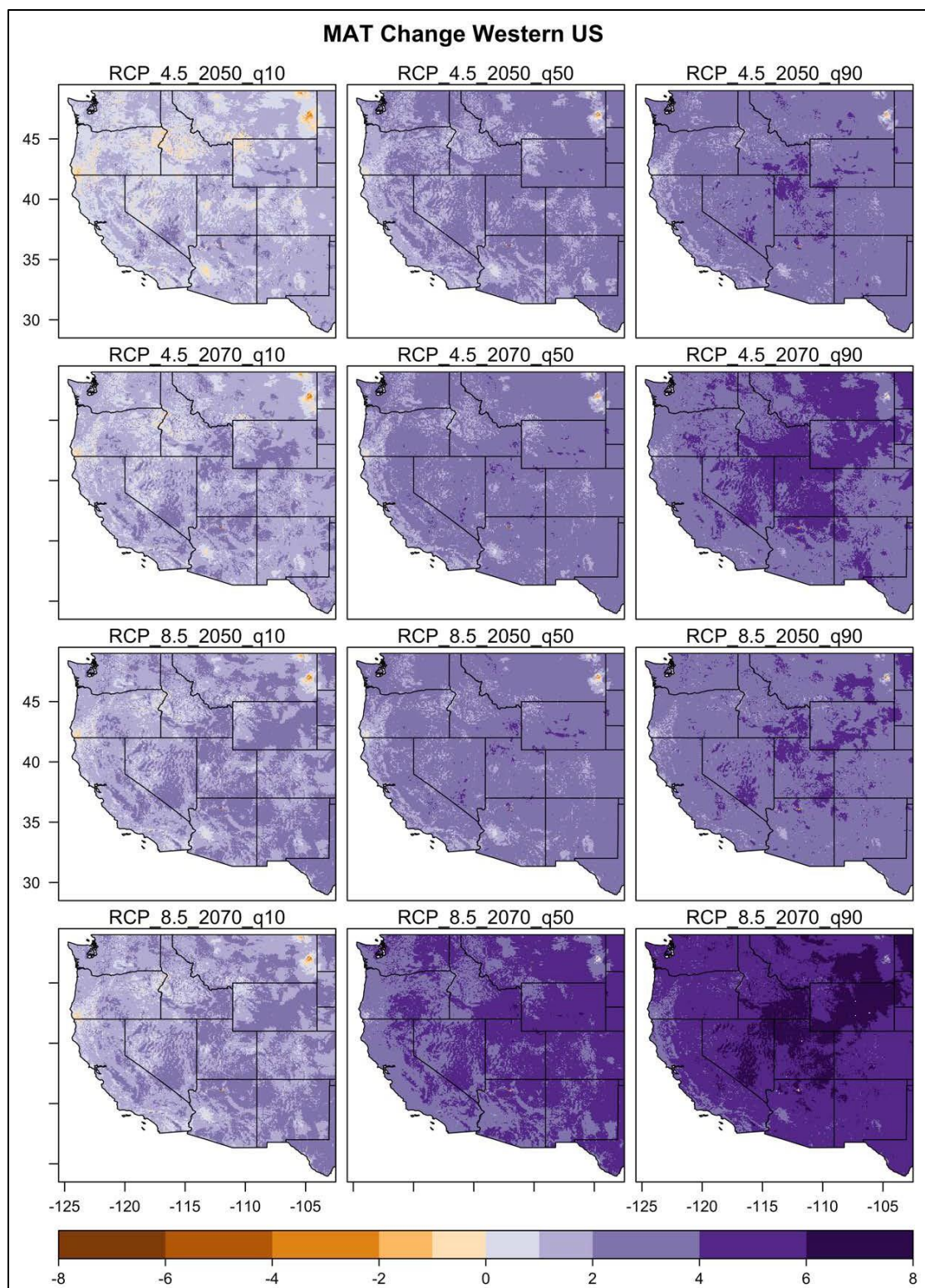


Figure A.3.14. Change in mean annual temperature (MAT; °C) for the western United States calculated for the 10th, 50th, and 90th quantiles of ensembled future climate scenarios (17 GCMs) for two representative concentration pathways (RCPs) (4.5, 8.5) and two future time periods (2050, 2070). Change in MAT was calculated by subtracting values in the future climate scenario from historical conditions (1970–2000) at the pixel-level at 30 second (~900 m at the Equator) resolution.

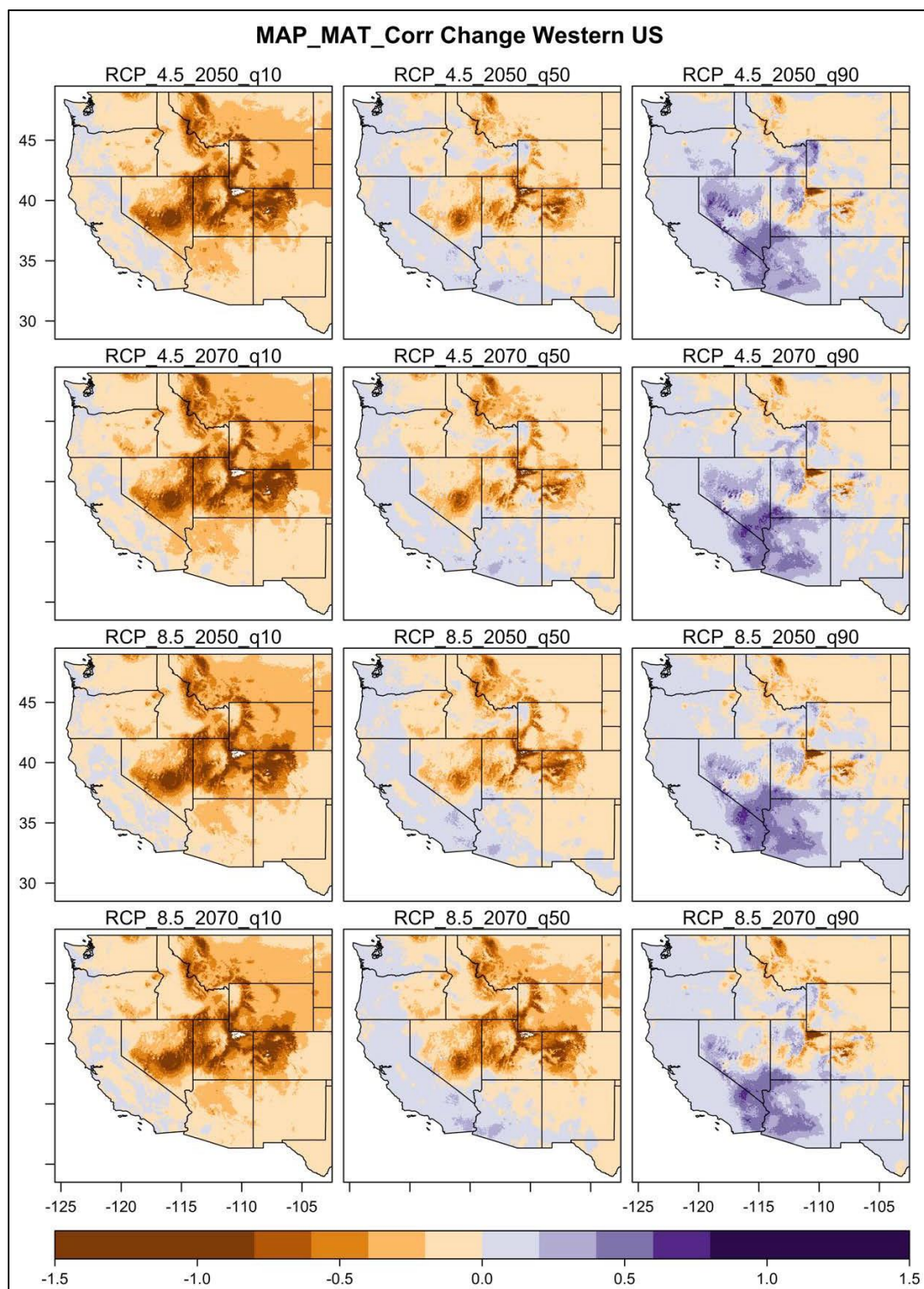


Figure A.3.15. Change in the correlation between monthly precipitation and monthly temperature (MAP_MAT_Corr) for the western United States calculated for the 10th, 50th, and 90th quantiles of ensembled future climate scenarios (17 GCMs) for two representative concentration pathways (RCPs) (4.5, 8.5) and two future time periods (2050, 2070). Change in MAP_MAT_Corr was calculated by subtracting values in the future climate scenario from historical conditions (1970–2000) at the pixel-level at 30 second (~900 m at the Equator) resolution

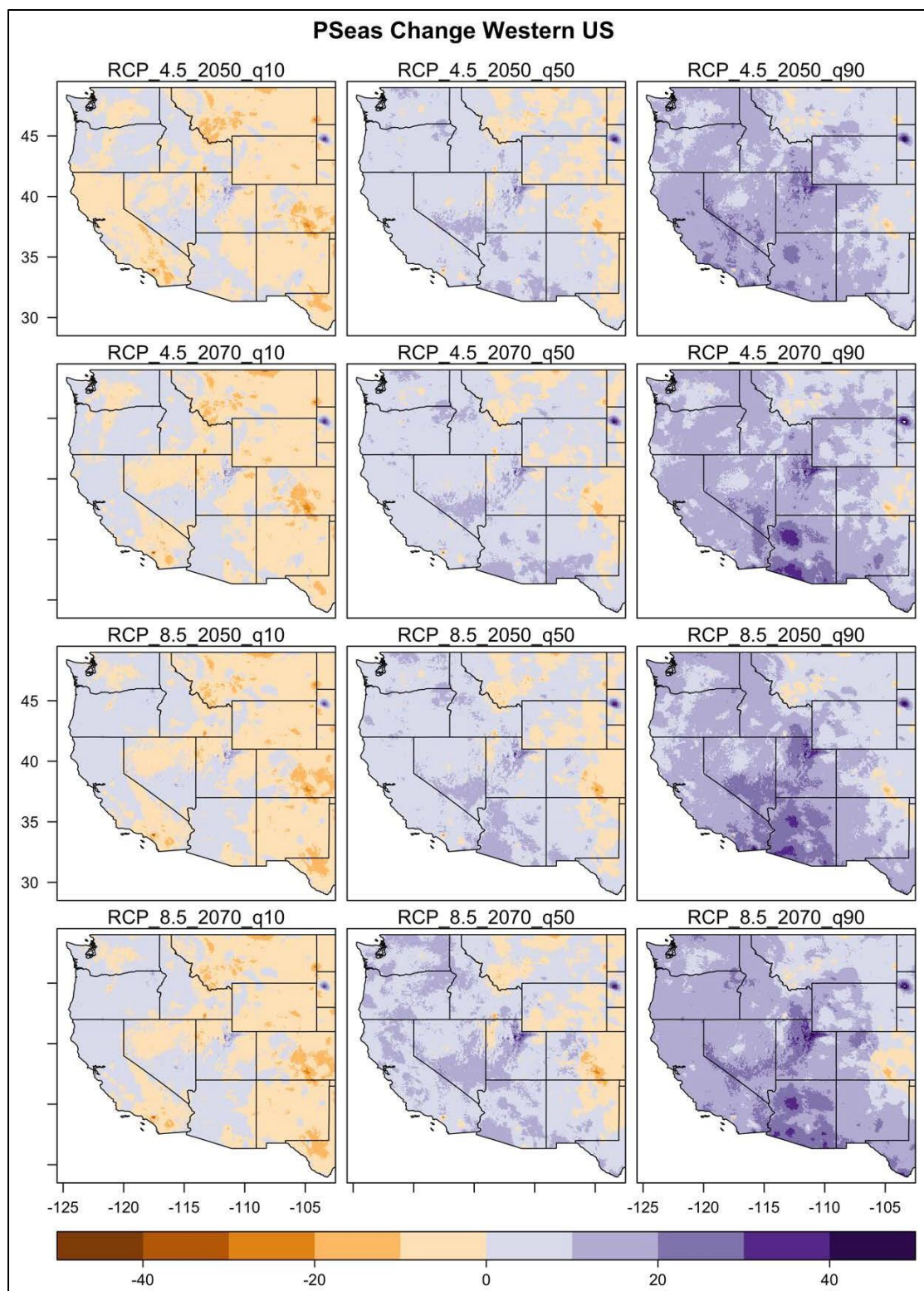


Figure A.3.16. Change in precipitation seasonality (PSeas) for the western United States calculated for the 10th, 50th, and 90th quantiles of ensembled future climate scenarios (17 GCMs) for two representative concentration pathways (RCPs) (4.5, 8.5) and two future time periods (2050, 2070). Change in PSeas was calculated by subtracting values in the future climate scenario from historical conditions (1970–2000) at the pixel-level at 30 second (~900 m at the Equator) resolution.

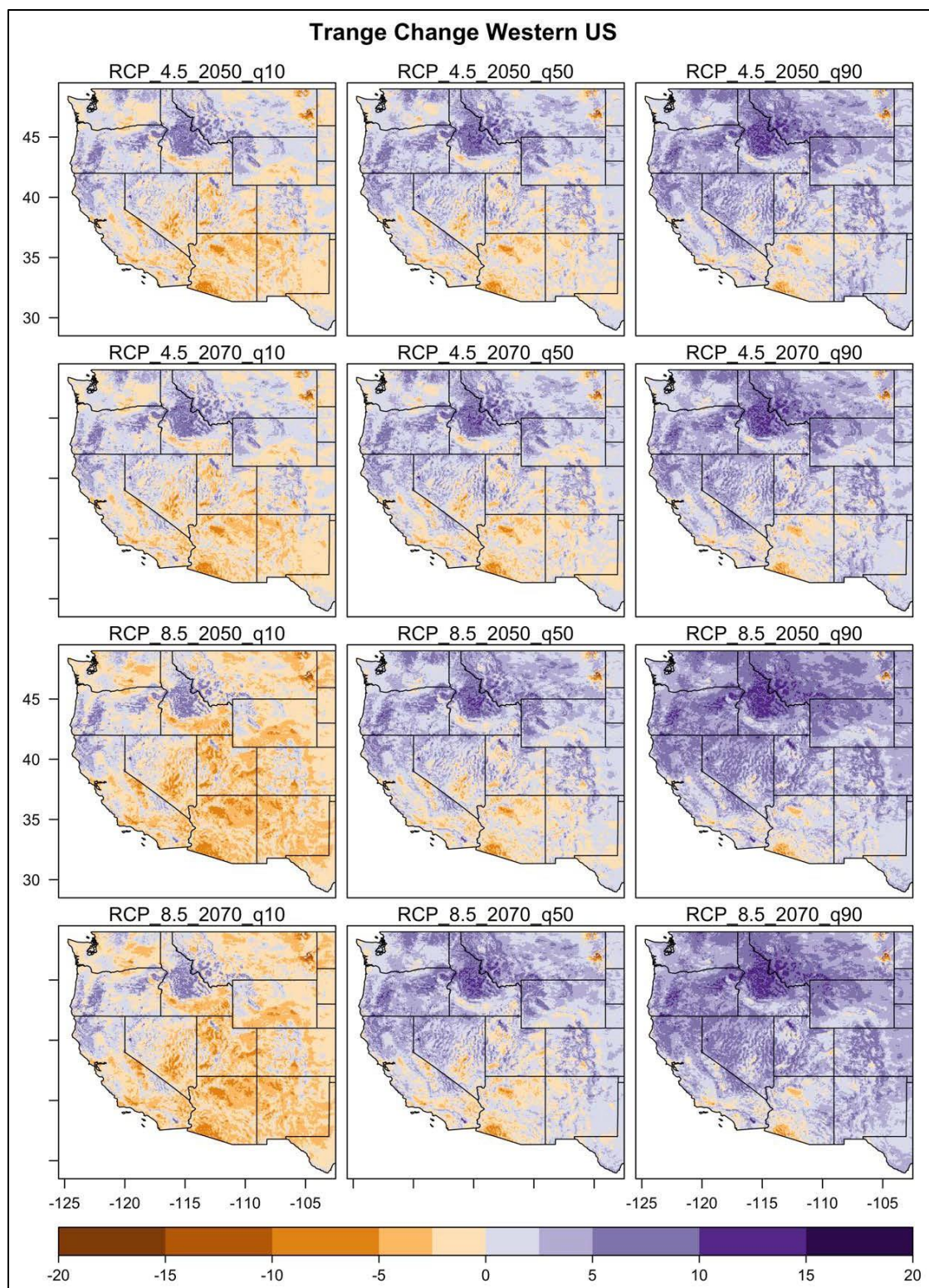


Figure A.3.17. Change in temperature range (TRange; °C) for the western United States calculated for the 10th, 50th, and 90th quantiles of ensemble future climate scenarios (17 GCMs) for two representative concentration pathways (RCPs) (4.5, 8.5) and two future time periods (2050, 2070). Change in TRange was calculated by subtracting values in the future climate scenario from historical conditions (1970–2000) at the pixel-level at 30 second (~900 m at the Equator) resolution.

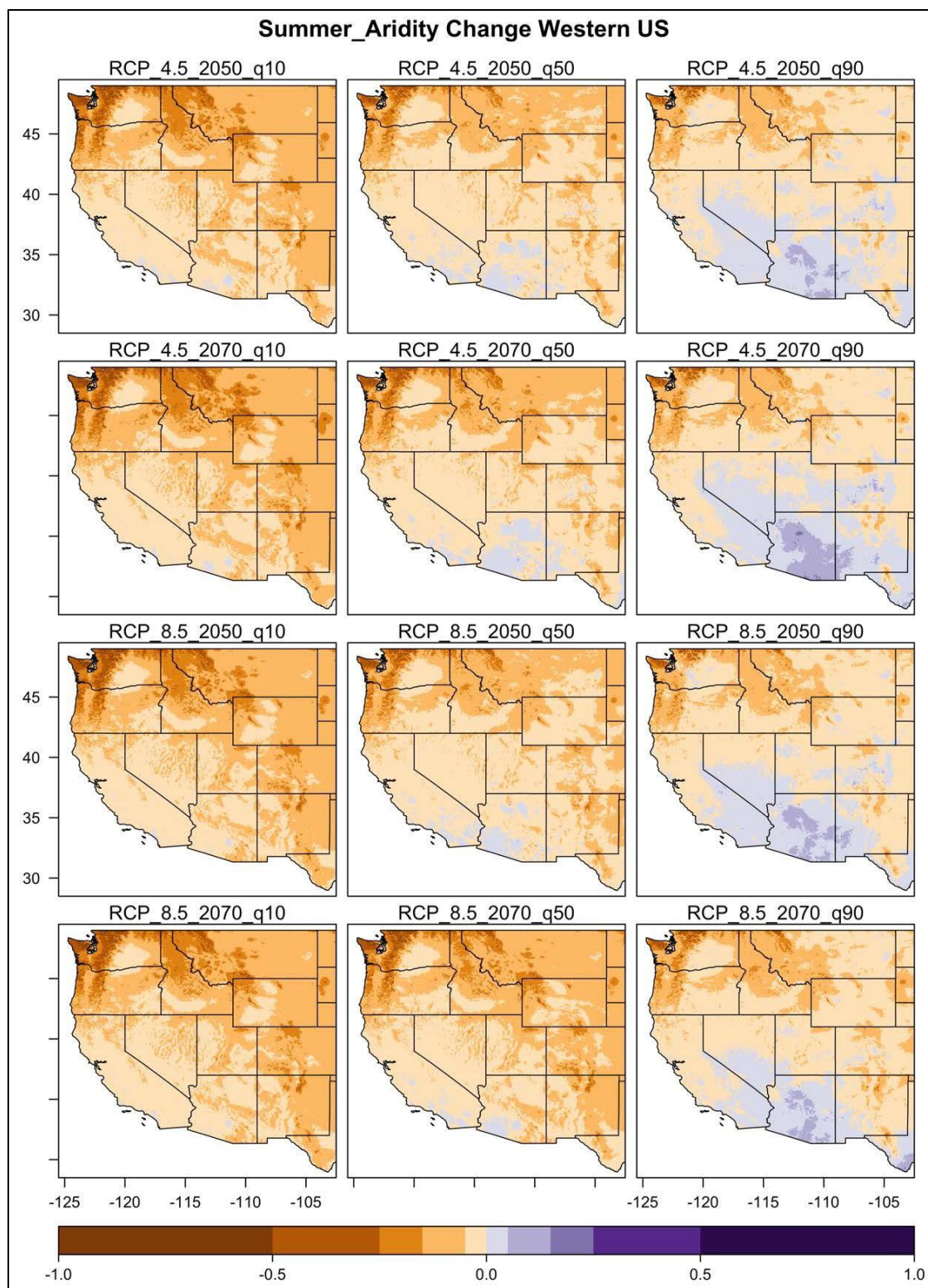


Figure A.3.18. Change in summer aridity index for the western United States calculated for the 10th, 50th, and 90th quantiles of ensembled future climate scenarios (17 GCMs) for two representative concentration pathways (RCPs) (4.5, 8.5) and two future time periods (2050, 2070). Change in summer aridity was calculated by subtracting values in the future climate scenario from historical conditions (1970–2000) at the pixel-level at 30 second (~900 m at the Equator) resolution.

Figures A.3.19 through A.3.34 provide future projections of grass habitat suitability for the western United States and for the Colorado Plateau. The figures show historical habitat suitability, future habitat suitability, and areas of robust change in habitat suitability for all 11 species of perennial grass. Change in habitat suitability was calculated as

$$\frac{\lambda_{future} - \lambda_{historic}}{\max(\lambda_{historic})}$$

for the 50th quantile of ensembled global circulation models (GCMs) for the representative concentration pathway (RCP) 8.5, 2070 climate scenario adjusted by the maximum historical lambda for that species.

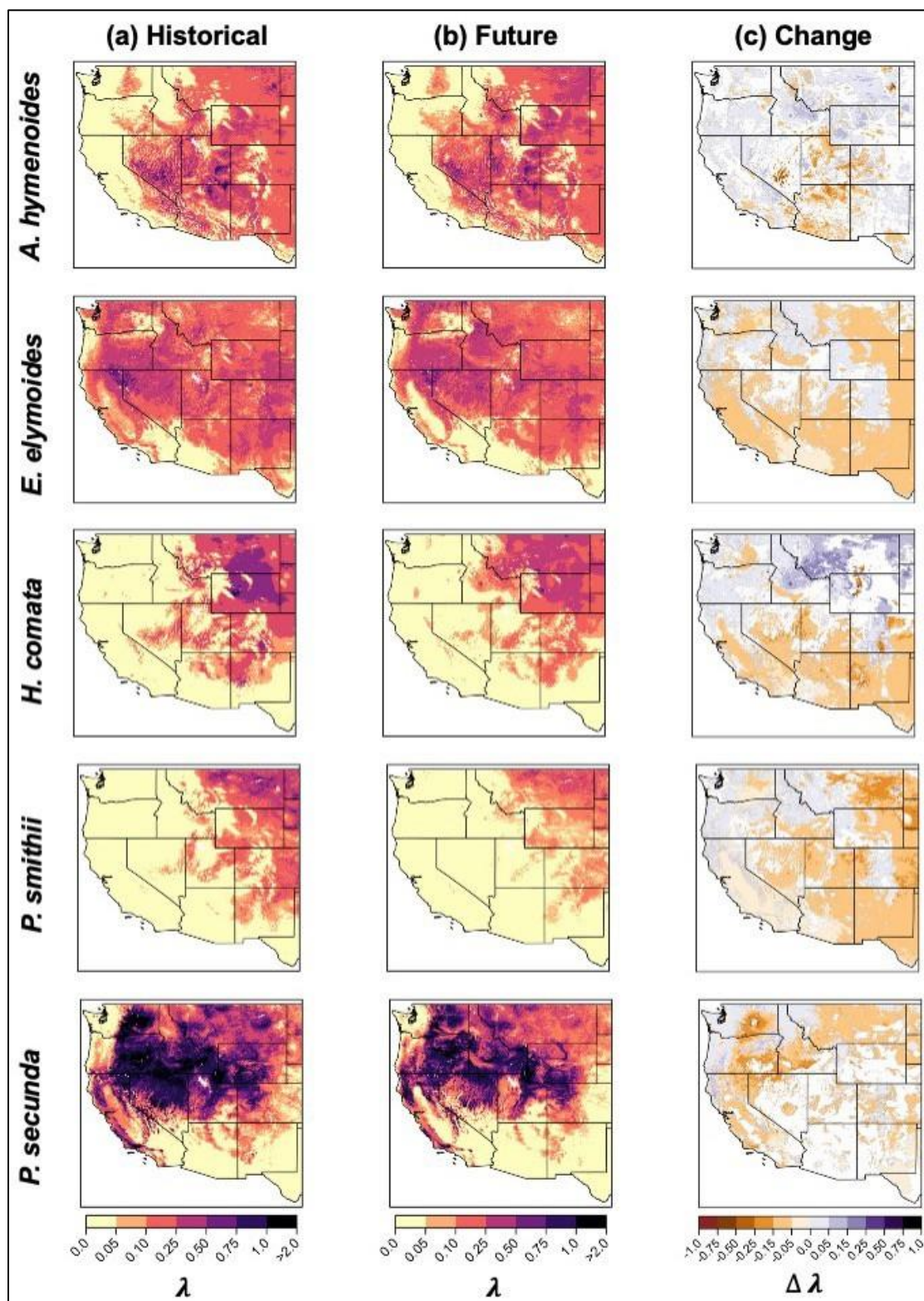


Figure A.3.19. Future projections of C₃ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 4.5 for the 2050 climate scenario in the western United States. (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 4.5, 2050 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 4.5, 2050. All areas in panel “c” are robust except for white shaded areas.

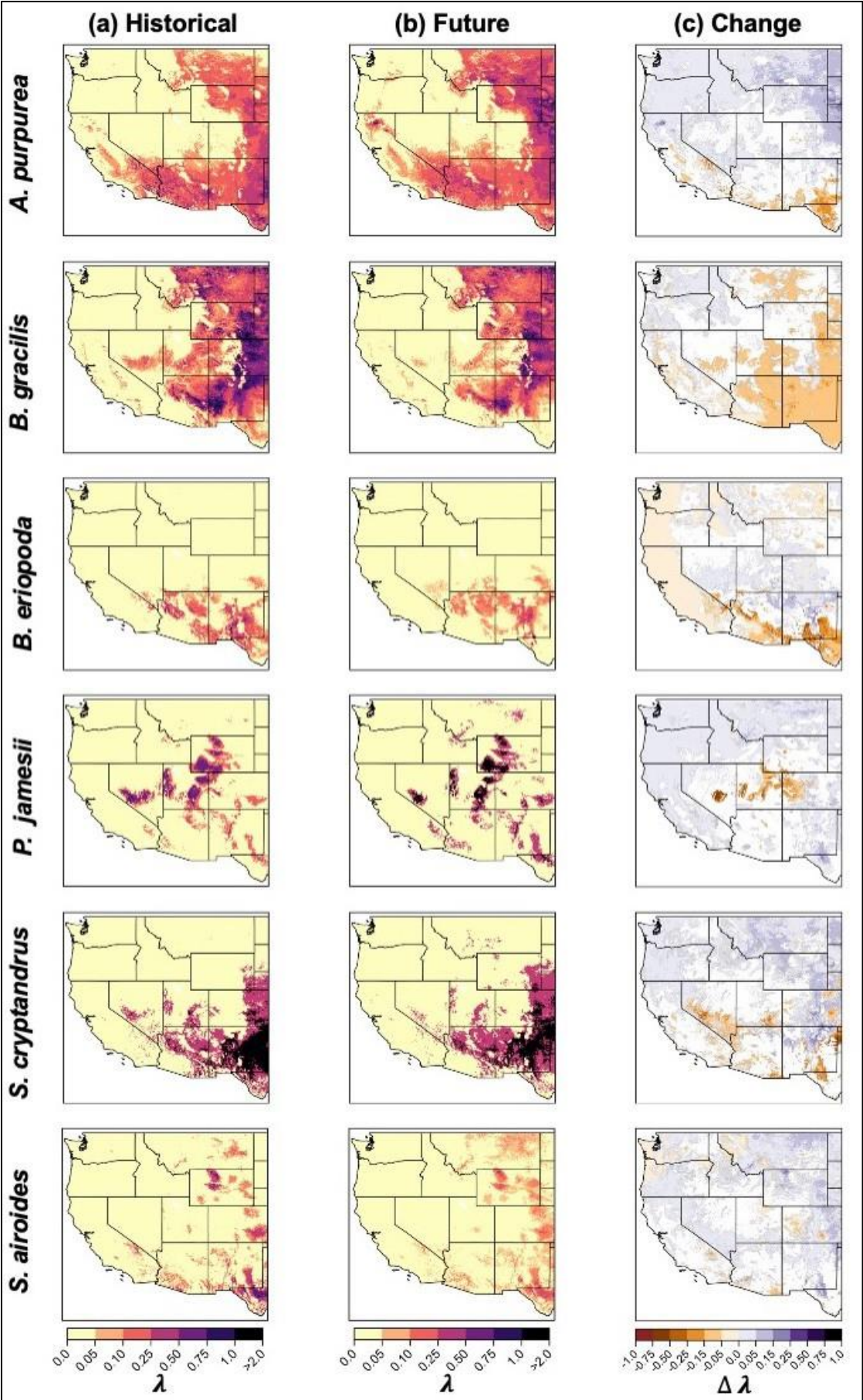


Figure A.3.20. Future projections of C₄ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 4.5 for the 2050 climate scenario in the western United States. (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 4.5, 2050 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 4.5, 2050. All areas in panel “c” are robust except for white shaded areas.

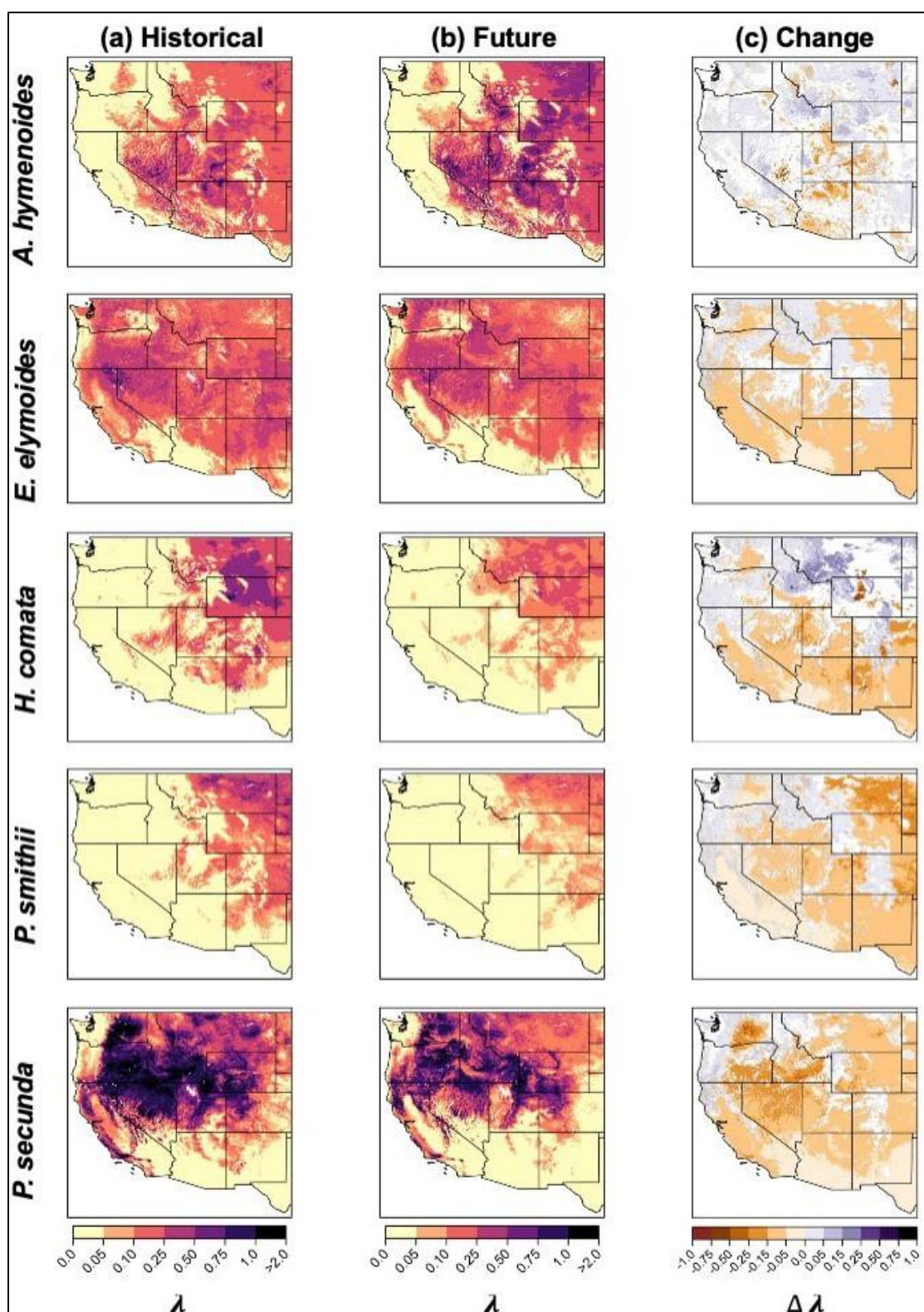


Figure A.3.21. Future projections of C₃ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 4.5 for the 2070 climate scenario in the western United States. (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 4.5, 2070 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 4.5, 2070. All areas in panel “c” are robust except for white shaded areas.

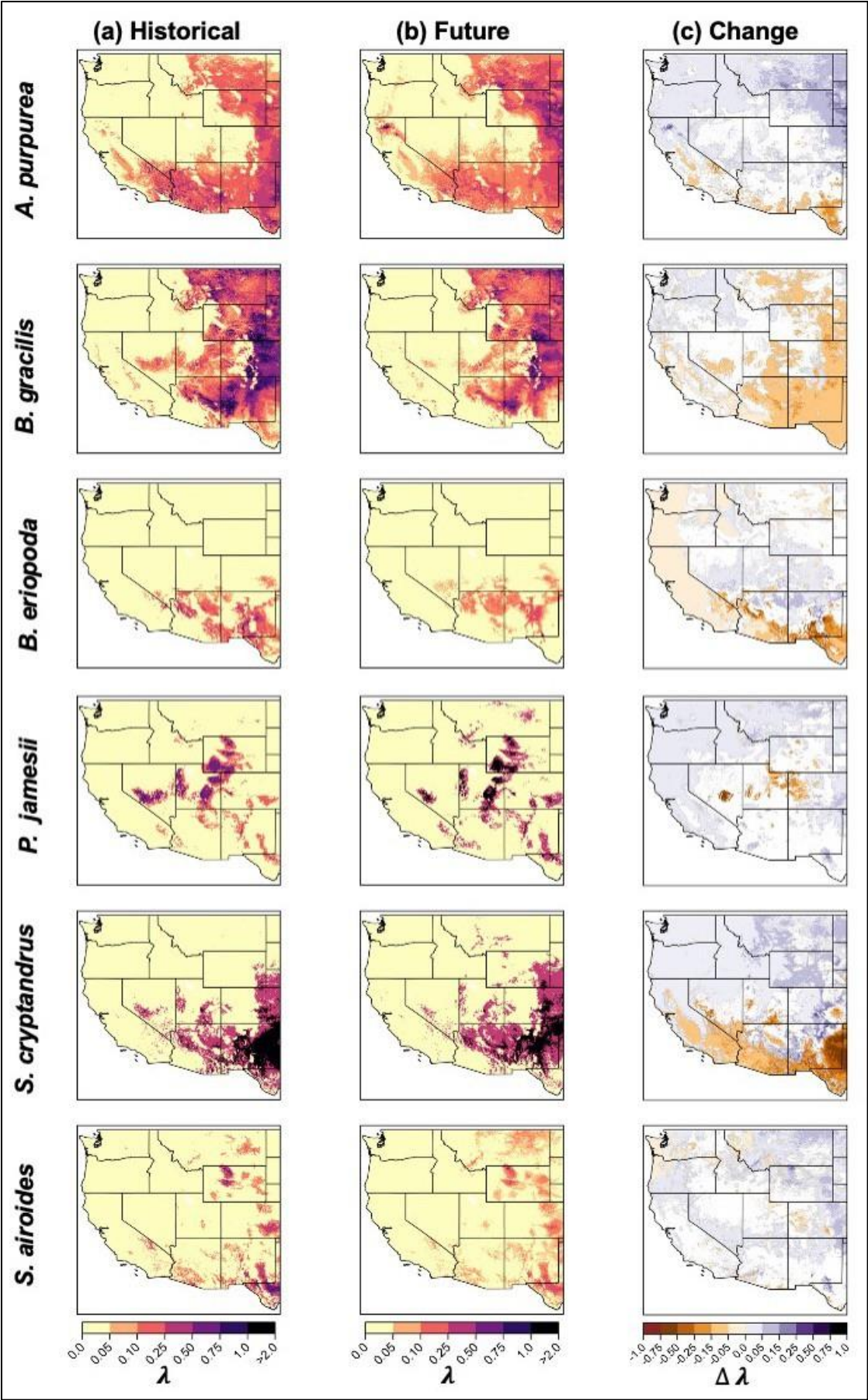


Figure A.3.22. Future projections of C₄ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 4.5 for the 2070 climate scenario in the western United States. (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 4.5, 2070 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 4.5, 2070. All areas in panel “c” are robust except for white shaded areas.

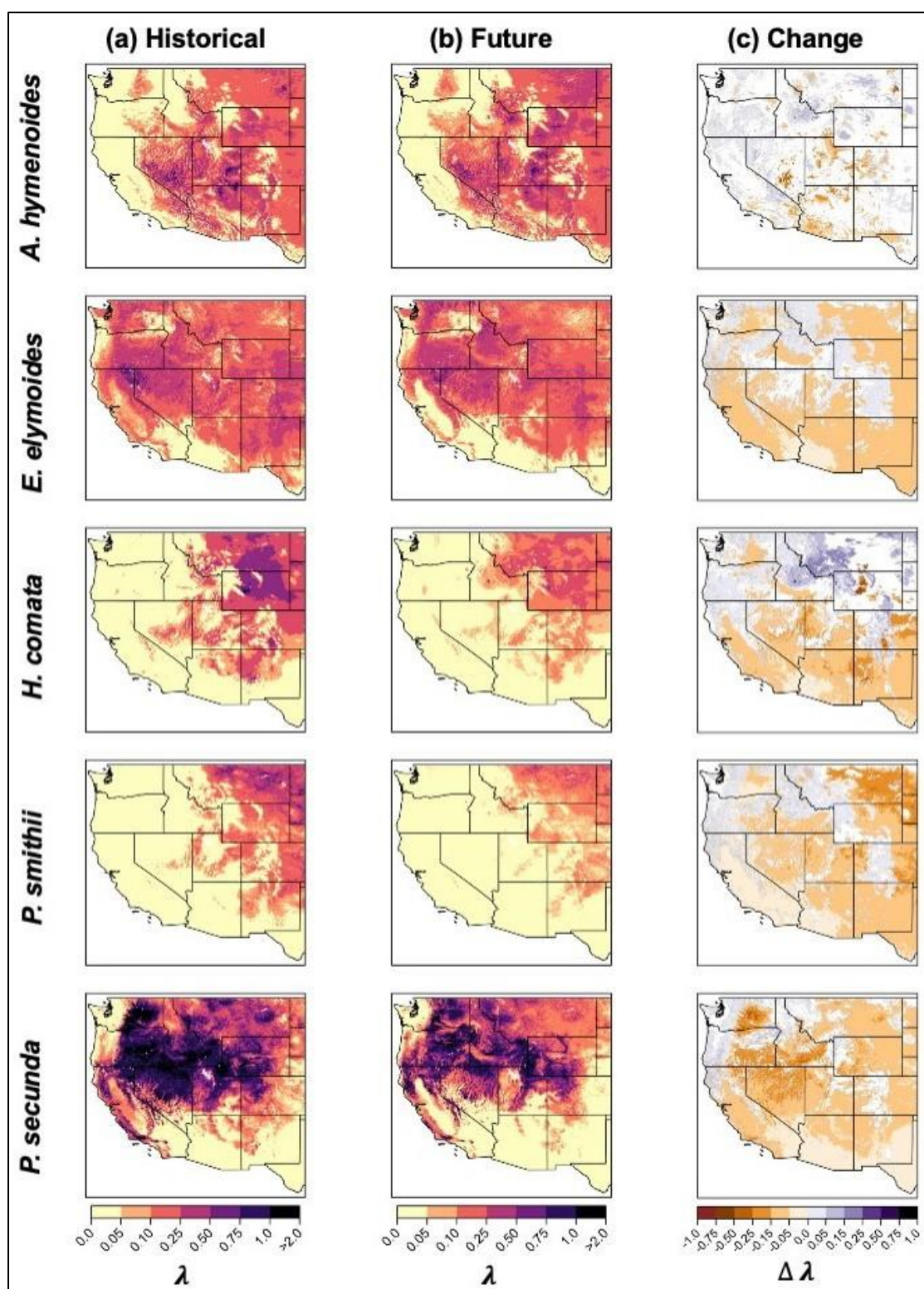


Figure A.3.23. Future projections of C₃ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 8.5 for the 2050 climate scenario in the western United States. (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 8.5, 2050 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 8.5, 2050. All areas in panel “c” are robust except for white shaded areas.

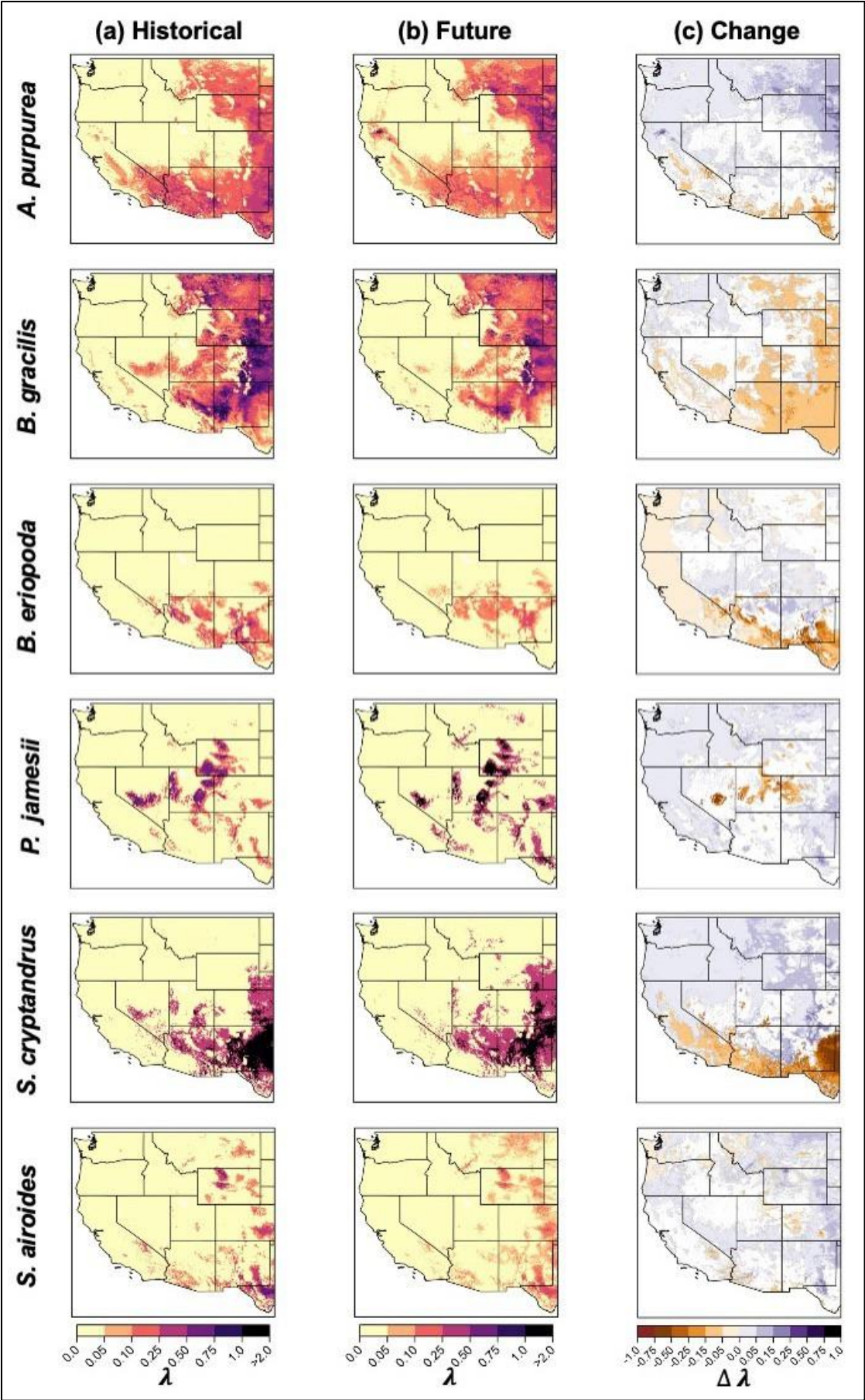


Figure A.3.24. Future projections of C₄ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 8.5 for the 2050 climate scenario in the western United States. (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 8.5, 2050 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 8.5, 2050. All areas in panel “c” are robust except for white shaded areas.

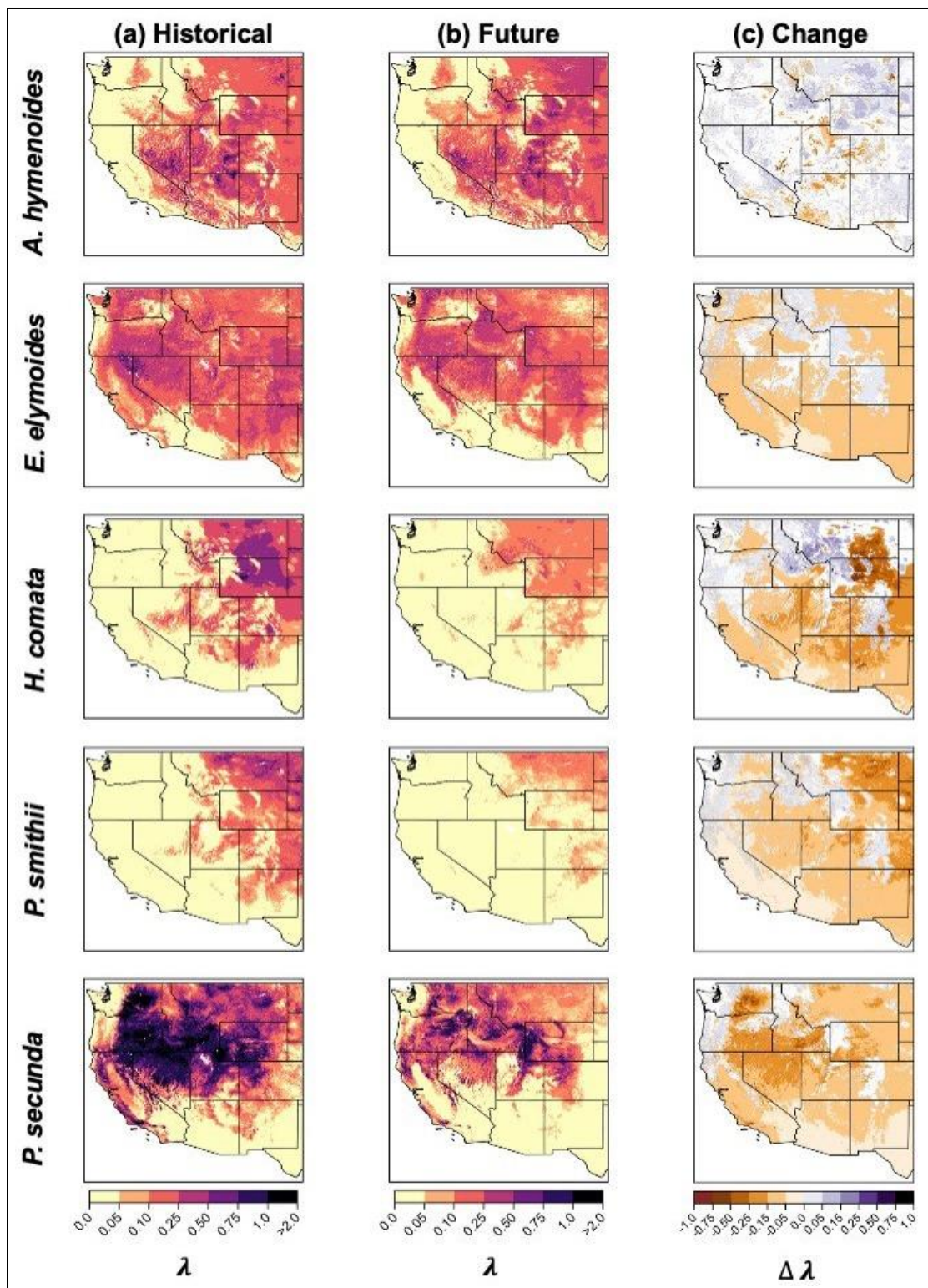


Figure A.3.25. Future projections of C₃ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 8.5 for the 2070 climate scenario in the western United States. (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 8.5, 2070 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 8.5, 2070. All areas in panel “c” are robust except for white shaded areas.

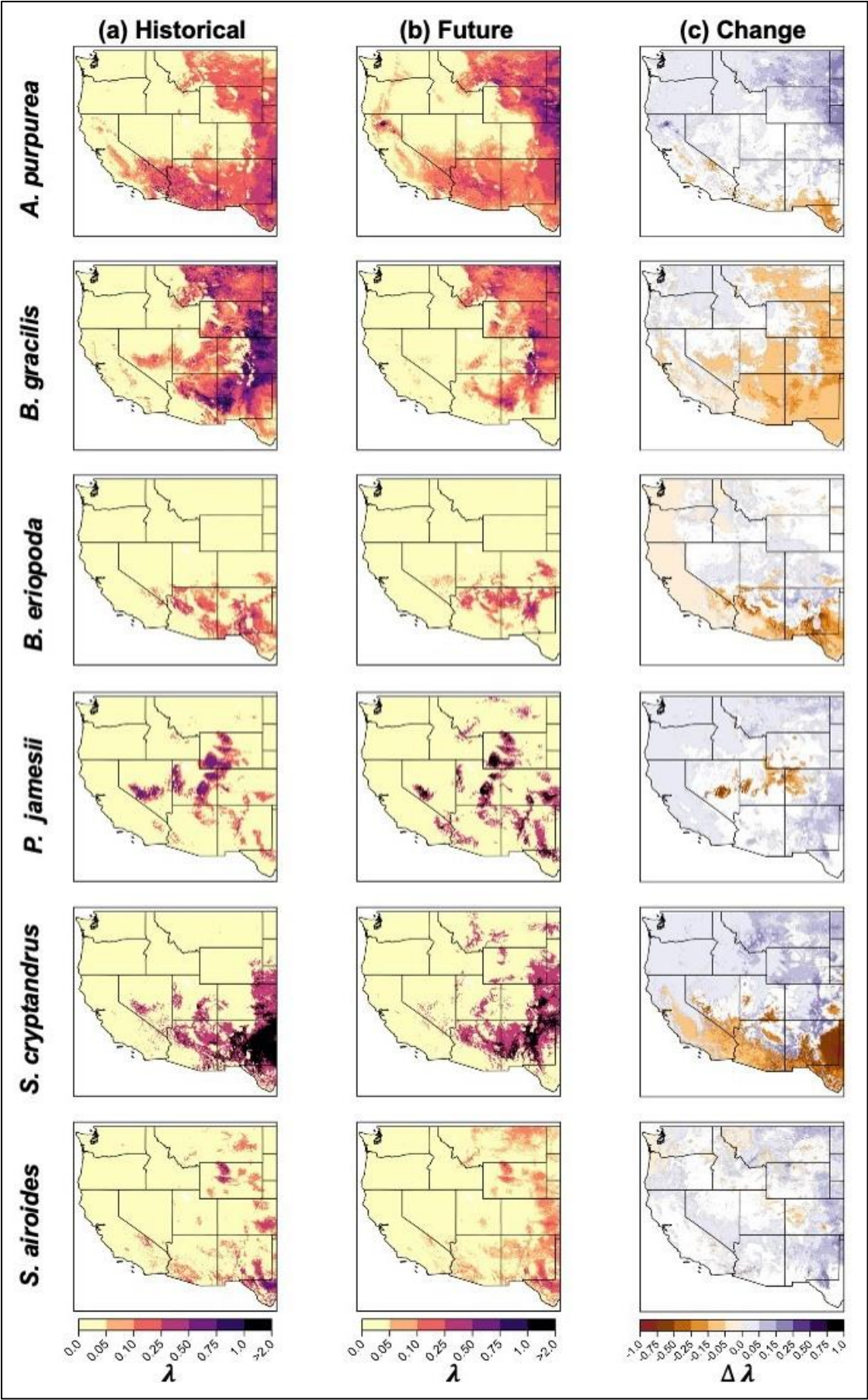


Figure A.3.26. Future projections of C₄ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 8.5 for the 2070 climate scenario in the western United States. (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 8.5, 2070 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 8.5, 2070. All areas in panel “c” are robust except for white shaded areas.

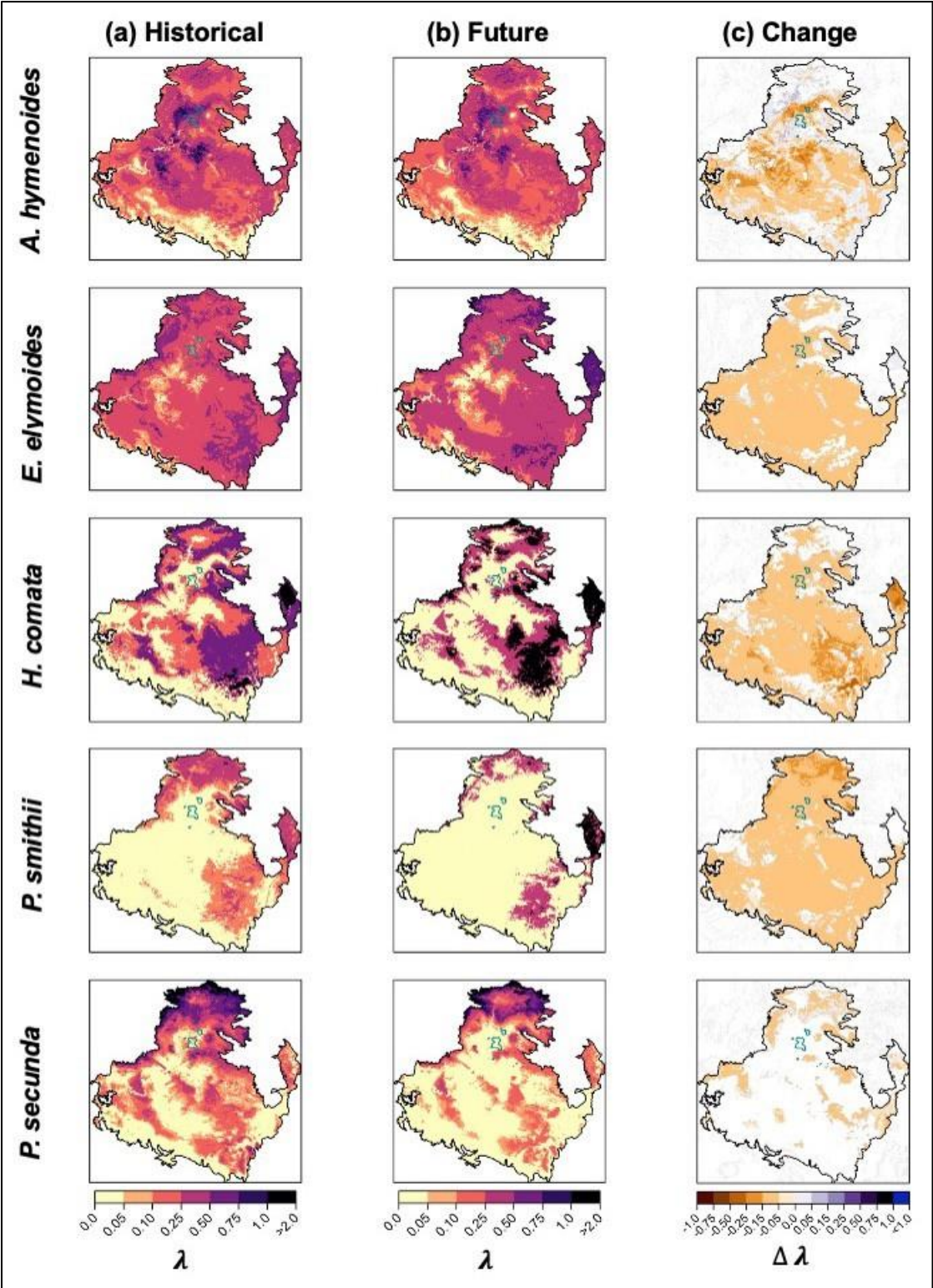


Figure A.3.27. Future projections of C₃ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 4.5 for the 2050 climate scenario in the Colorado Plateau (and Southeast Utah Group national parks). (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 4.5, 2050 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 4.5, 2050. All areas in panel “c” are robust except for white shaded areas.

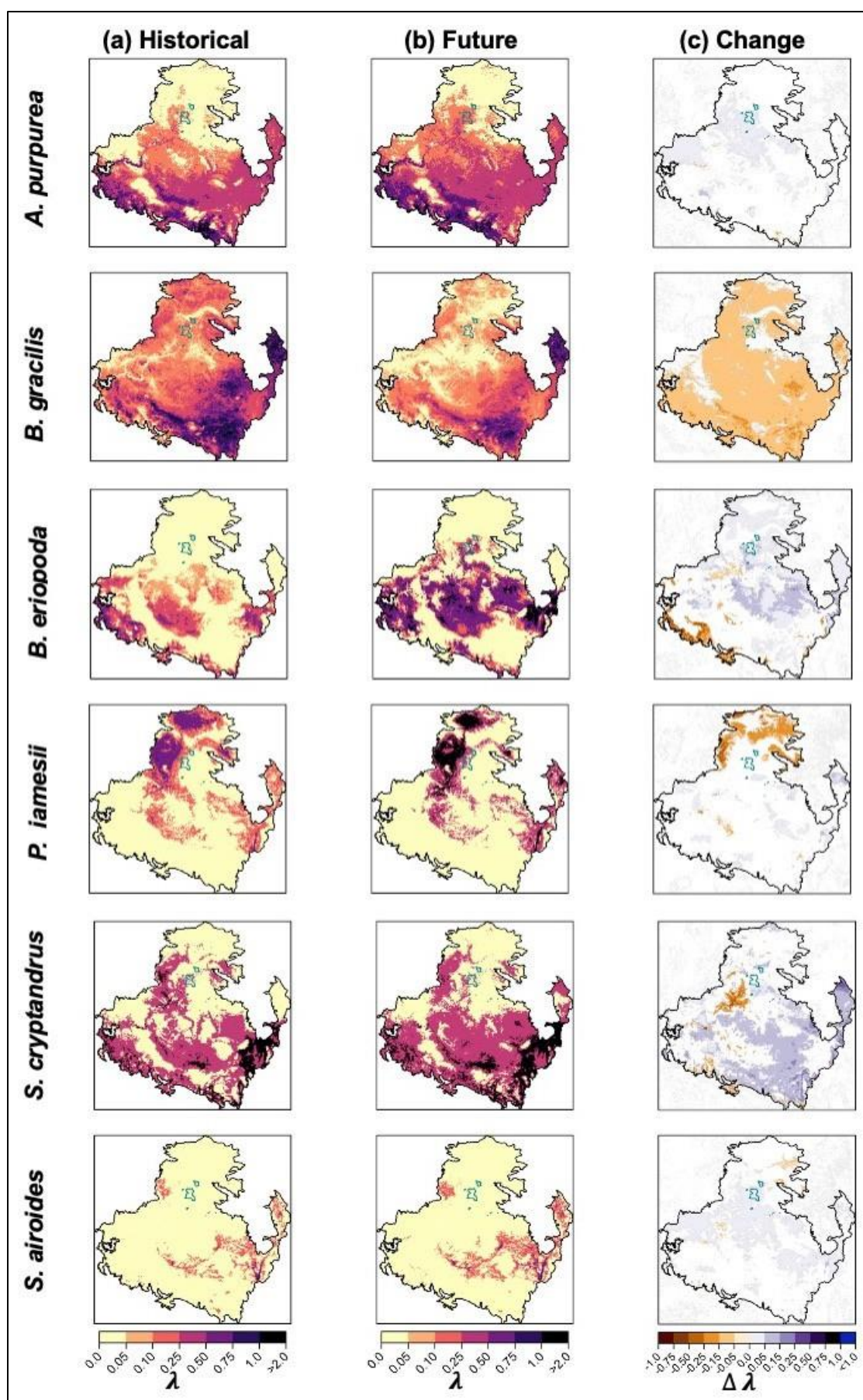


Figure A.3.28. Future projections of C₄ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 4.5 for the 2050 climate scenario in the Colorado Plateau (and Southeast Utah Group national parks). (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 4.5, 2050 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 4.5, 2050. All areas in panel “c” are robust except for white shaded areas.

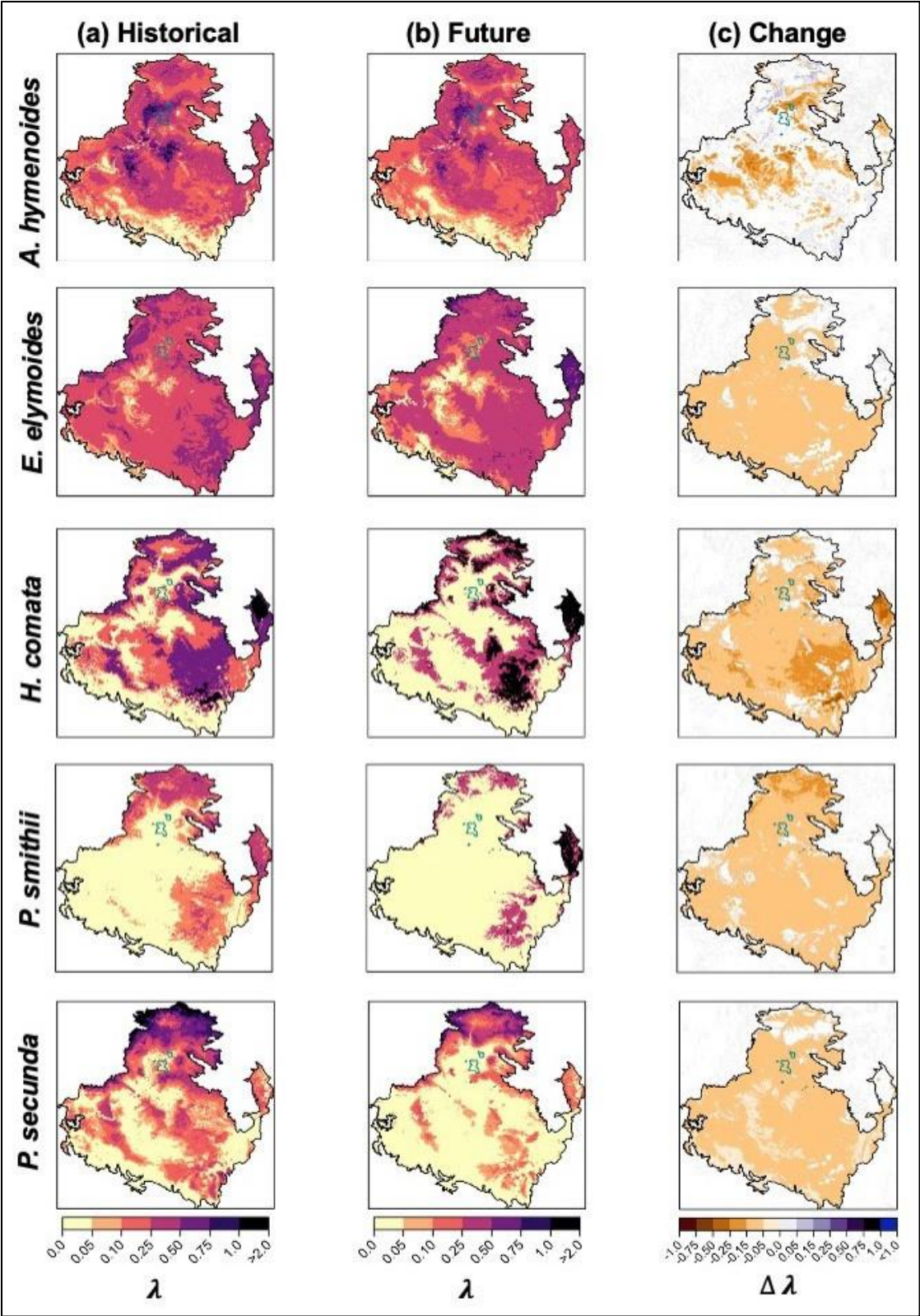


Figure A.3.29. Future projections of C₃ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 4.5 for the 2070 climate scenario in the Colorado Plateau (and Southeast Utah Group national parks). (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 4.5, 2070 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 4.5, 2070. All areas in panel “c” are robust except for white shaded areas.

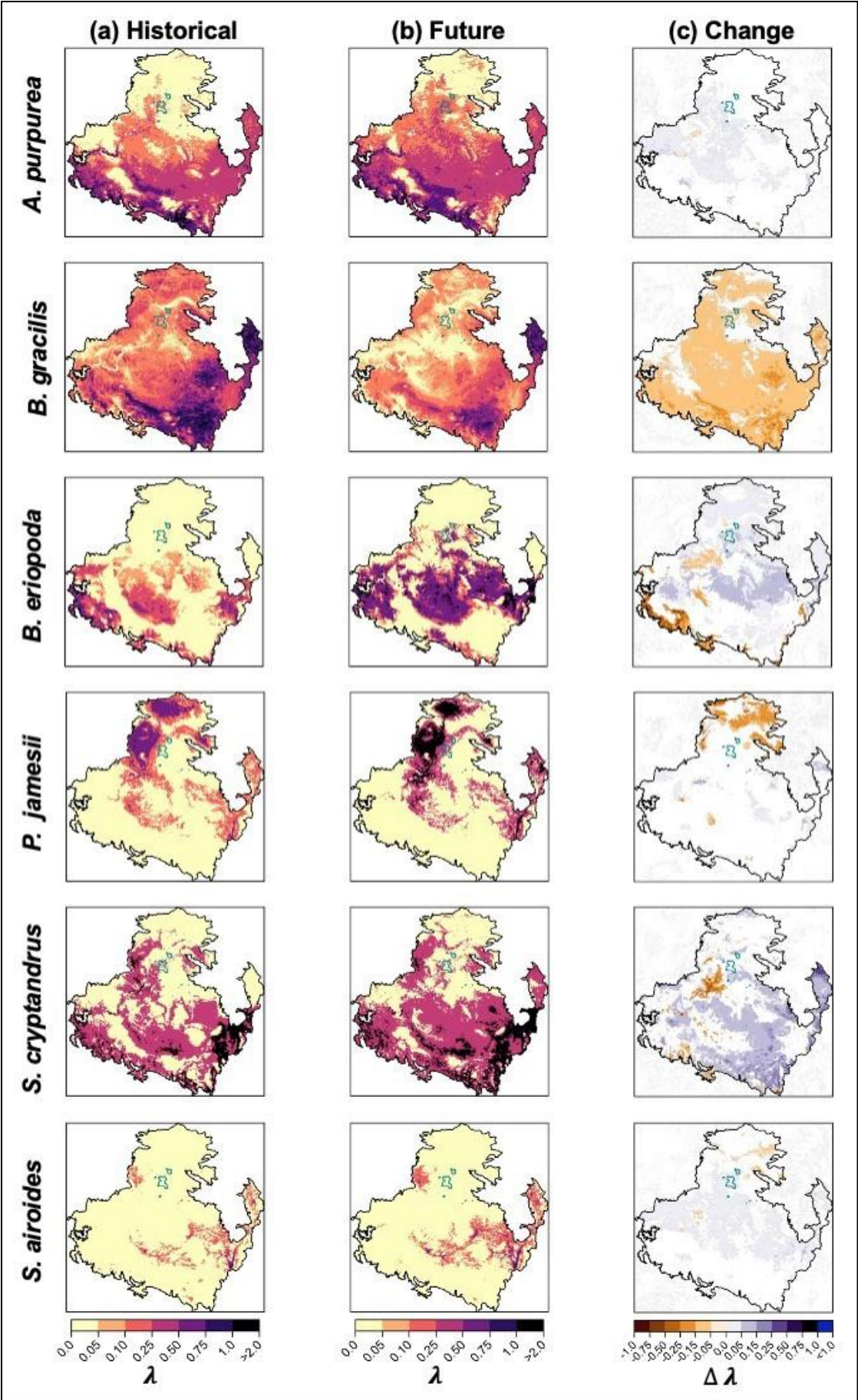


Figure A.3.30. Future projections of C₄ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 4.5 for the 2070 climate scenario in the Colorado Plateau (and Southeast Utah Group national parks). (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 4.5, 2070 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 4.5, 2070. All areas in panel “c” are robust except for white shaded areas.

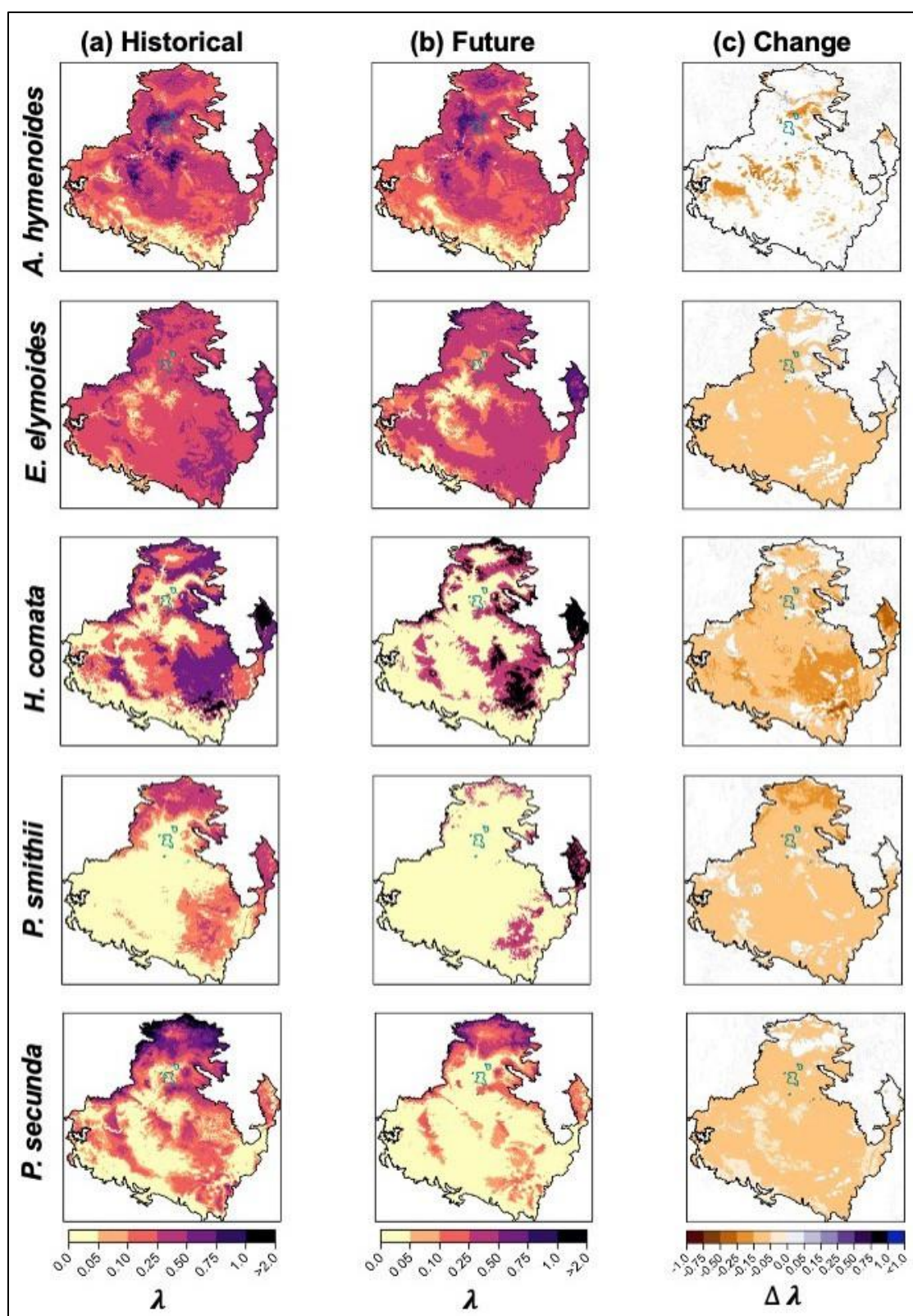


Figure A.3.31. Future projections of C_3 grassland species habitat suitability (λ) at representative concentration pathway (RCP) 8.5 for the 2050 climate scenario in the Colorado Plateau (and Southeast Utah Group national parks). (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 8.5, 2050 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 8.5, 2050. All areas in panel “c” are robust except for white shaded areas.

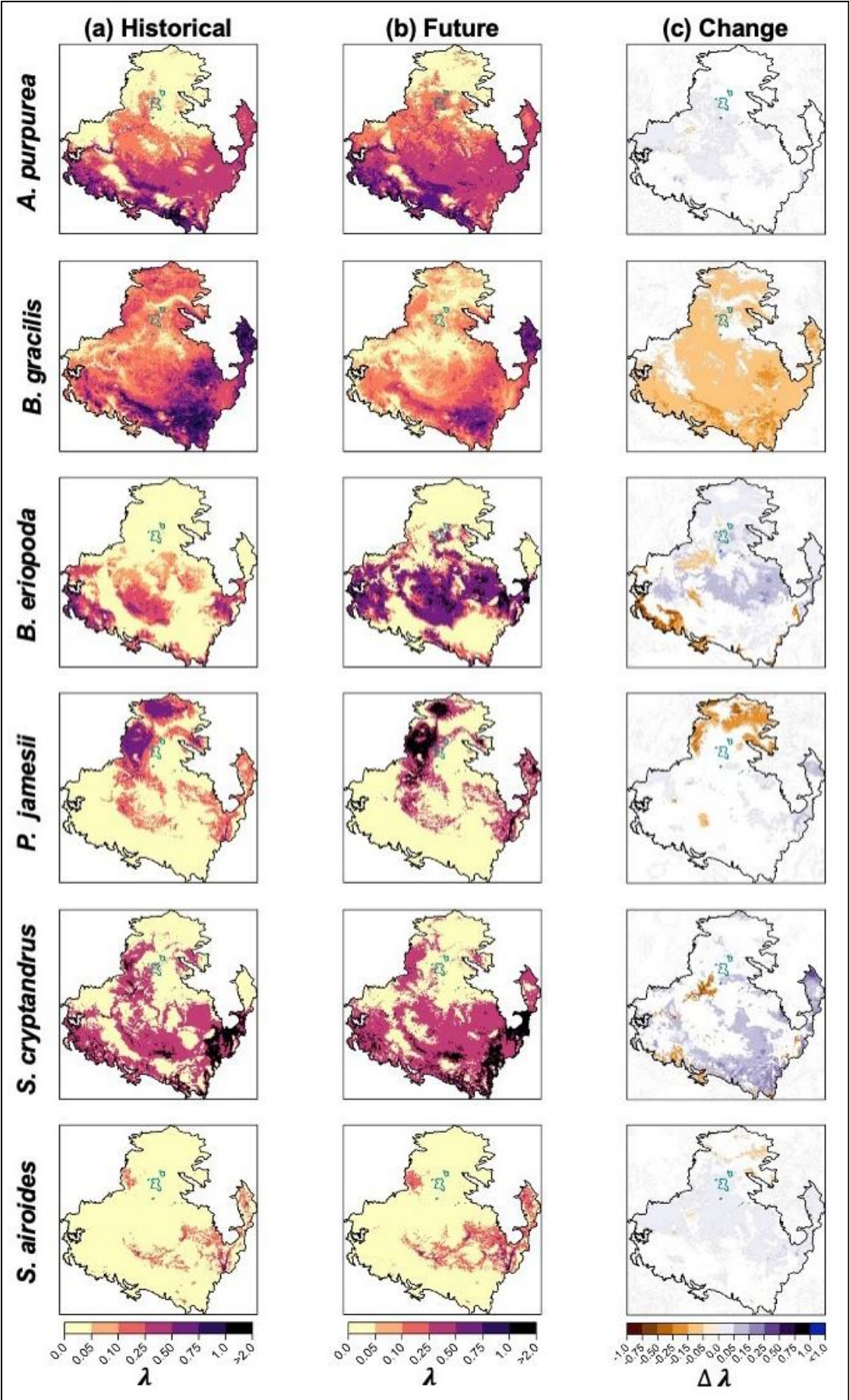


Figure A.3.32. Future projections of C₄ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 8.5 for the 2050 climate scenario in the Colorado Plateau (and Southeast Utah Group national parks). (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 8.5, 2050 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 8.5, 2050. All areas in panel “c” are robust except for white shaded areas.

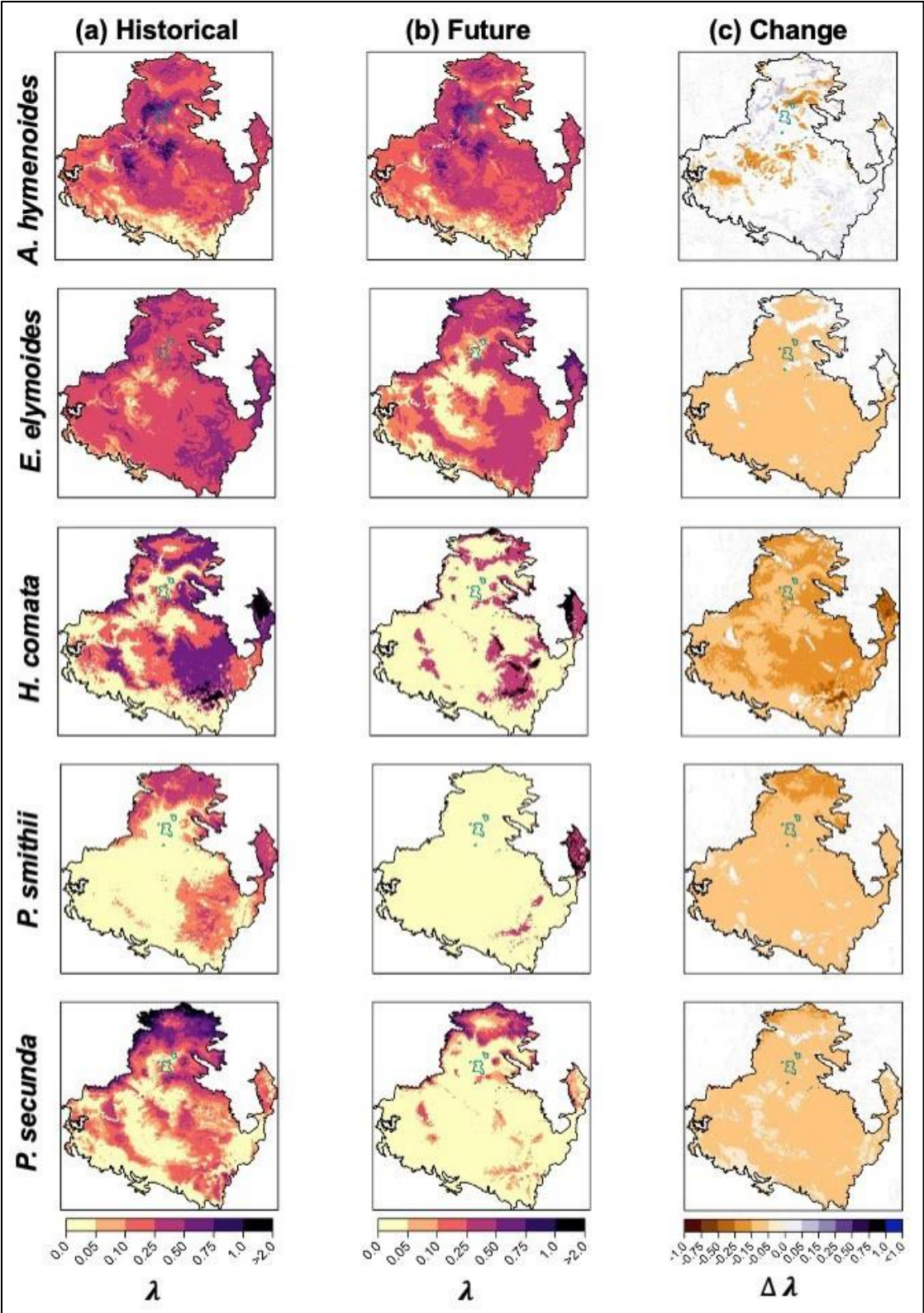


Figure A.3.33. Future projections of C₃ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 8.5 for the 2070 climate scenario in the Colorado Plateau (and Southeast Utah Group national parks). (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 8.5, 2070 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 8.5, 2070. All areas in panel “c” are robust except for white shaded areas.

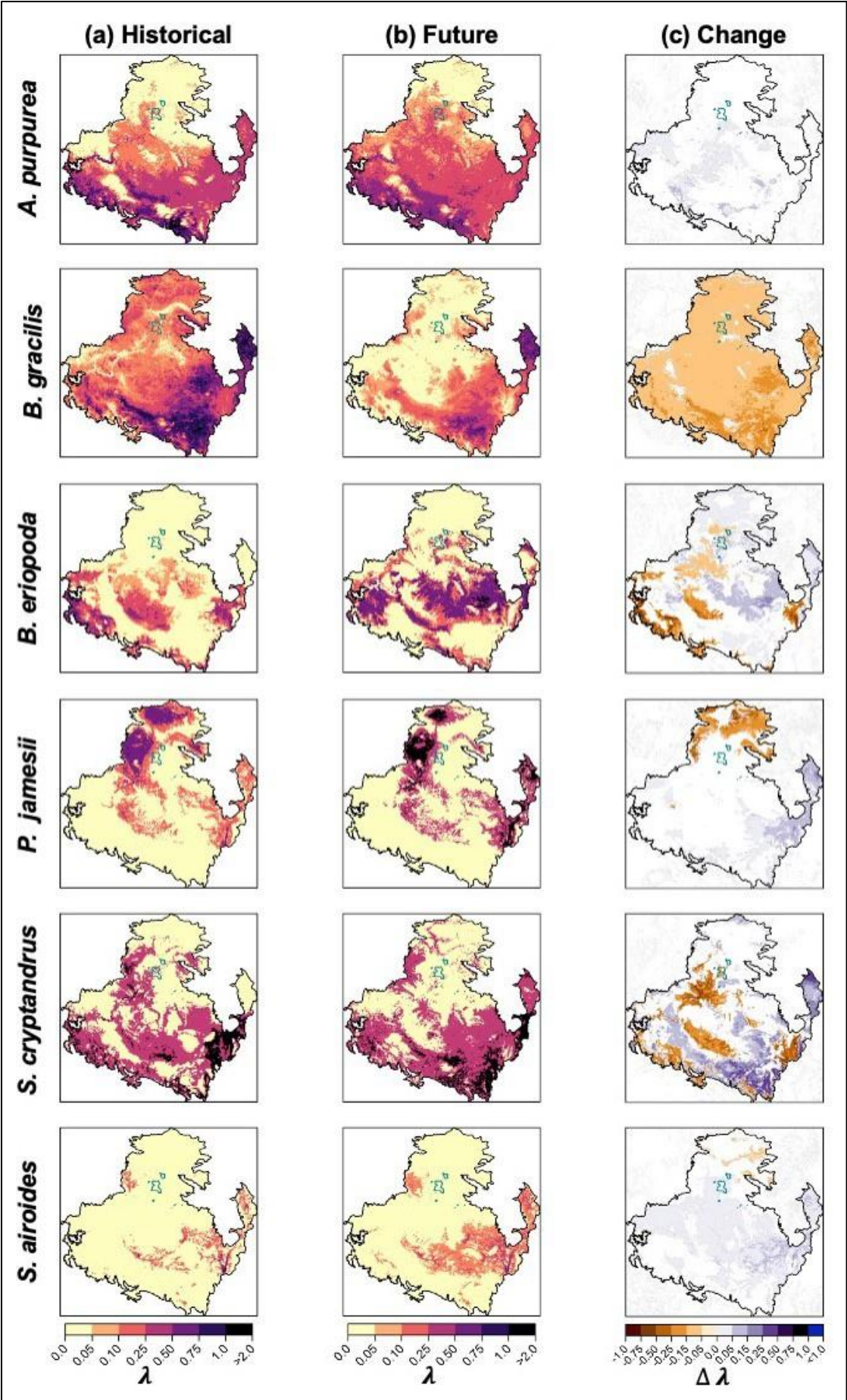


Figure A.3.34. Future projections of C₄ grassland species habitat suitability (λ) at representative concentration pathway (RCP) 8.5 for the 2070 climate scenario in the Colorado Plateau (and Southeast Utah Group national parks). (a) historical habitat suitability (λ) based on historical (1970–2000) WorldClim2 data, (b) future habitat suitability (λ) based on an ensemble of 17 global circulation models (GCMs) for RCP 8.5, 2070 climate scenario, and (c) areas of robust change in habitat suitability ($\Delta\lambda$) between historical and future suitability projections. Robust change indicates areas where 90% of GCMs agreed in the direction of change in habitat suitability for RCP 8.5, 2070. All areas in panel “c” are robust except for white shaded areas.

Tables A.3.1–A.3.14 list candidate environmental covariates for species distribution modeling, modeling results, changes in climate, and changes in habitat suitability for the 11 perennial grass species at different spatial scales across the western United States.

Table A.3.1. Candidate environmental covariates considered for inclusion in our species distribution model selection pipeline.

Covariate type	Covariate	Description and units	Retained for niche model candidacy?
Climatic	Mean annual temperature (MAT) (bio1)	°C	yes
	Mean diurnal temperature range (bio2)	Mean of monthly (max temp-min temp) °C	–
	Isothermality (bio3)	(bio2 / bio7) *100	–
	Temperature seasonality (TSeas) (bio4)	(standard deviation *100)	–
	Maximum temperature of warmest month (bio5)	°C	–
	Minimum temperature of coldest month (bio6)	°C	–
	Temperature annual range (Trange) (bio7)	(bio5 - bio6)	yes
	Mean temperature of wettest quarter (bio8)	°C	–
	Mean temperature of driest quarter (bio9)	°C	–
	Mean temperature of warmest quarter (bio10)	°C	–
	Mean temperature of coldest quarter (bio11)	°C	–
	Mean annual precipitation (MAP) (bio12)	mm	yes
	Precipitation of wettest month (bio13)	mm	–
	Precipitation of driest month (bio14)	mm	–
	Precipitation seasonality (PSeas) (bio15)	Coefficient of variation (CV); represents the tendency for a location to have more rainfall during certain months than others	yes
	Precipitation of wettest quarter (bio16)	mm	–
	Precipitation of driest quarter (bio17)	mm	–
	Precipitation of warmest quarter (bio18)	mm	–
	Precipitation of coldest quarter (bio19)	mm	–
	Spring aridity	Aridity index (AI), March-May	–
	Summer aridity	Aridity index (AI), June-August	yes
	Fall aridity	Aridity index (AI), September-November	–

Table A.3.1 (continued). Candidate environmental covariates considered for inclusion in our species distribution model selection pipeline.

Covariate type	Covariate	Description and units	Retained for niche model candidacy?
Climatic (continued)	Winter aridity	Aridity index (AI), December-February	–
	MAP:MAT correlation	Pearson correlation between MAP and MAT	yes
Other	Soil depth	Total soil depth (cm) to bedrock (R horizon)	yes
	Soil sand (%)	Mean % soil sand over top 1 m of soil profile	yes
	Soil clay (%)	Mean % soil clay over top 1 m of soil profile	yes
	Soil silt (%)	Mean % soil silt over top 1 m of soil profile	–
	SEINet grass species sampling effort	Density (# / 900 m ² grid cell) of sampling records for family Poaceae within the SEINet database	yes

Table A.3.2. Species distribution model (SDM) results for the 11 grass species in the western United States showing parameters retained in final models, parameter type (i.e., intercept, main effect, quadratic effect, or interaction), parameter estimate and standard error (SE).

Species	Carbon fixation pathway	Parameter	Type	Value	SE
<i>A. hymenoides</i> AUC_{in} = 0.855 AUC_{out} = 0.752	C3	Intercept _{FULL_MODEL}	Intercept	-2.43	0.06
	C3	Intercept _{SEINET_SAMPLING_INTENSITY}	Intercept	-2.32	0.09
	C3	Slope _{SEINET_SAMPLING_INTENSITY}	Slope	2.08	0.09
	C3	MAP	Main	-1.42	0.13
	C3	TRange	Main	0.80	0.07
	C3	q_MAP	Quadratic	-1.22	0.11
	C3	q_MAP_MAT_Corr	Quadratic	-0.34	0.03
	C3	q_Soil_depth	Quadratic	-0.28	0.06
	C3	I_MAP:Soil_clay	Interaction	0.51	0.04
	C3	I_MAP:Soil_depth	Interaction	-0.85	0.14
	C3	I_MAP_MAT_Corr:Soil_depth	Interaction	0.92	0.07
	C3	I_MAP_MAT_Corr:TRange	Interaction	-0.19	0.05
	C3	I_Soil_depth:TRange	Interaction	-0.26	0.13

Table A.3.2 (continued). Species distribution model (SDM) results for the 11 grass species in the western United States showing parameters retained in final models, parameter type (i.e., intercept, main effect, quadratic effect, or interaction), parameter estimate and standard error (SE).

Species	Carbon fixation pathway	Parameter	Type	Value	SE
<i>E. elymoides</i> AUC _{in} = 0.819 AUC _{out} = 0.732	C3	Intercept _{FULL_MODEL}	Intercept	-1.56	0.05
	C3	Intercept _{SEINET_SAMPLING_INTENSITY}	Intercept	-2.85	0.08
	C3	Slope _{SEINET_SAMPLING_INTENSITY}	Slope	2.20	0.08
	C3	MAT	Main	-0.34	0.03
	C3	Soil_sand	Main	0.23	0.02
	C3	TRange	Main	0.25	0.03
	C3	q_MAP_MAT_Corr	Quadratic	0.34	0.02
	C3	q_MAT	Quadratic	-0.53	0.03
	C3	q_Soil_sand	Quadratic	-0.39	0.03
	C3	q_TRange	Quadratic	-0.23	0.03
	C3	I_MAP_MAT_Corr:PSeas	Interaction	0.23	0.02
	C3	I_MAP_MAT_Corr:Soil_clay	Interaction	-0.18	0.02
	C3	I_PSeas:Soil_sand	Interaction	0.07	0.02
	C3	I_PSeas:TRange	Interaction	-0.25	0.03
	C3	I_Soil_clay:Soil_sand	Interaction	-0.35	0.03
	C3	I_Soil_sand:TRange	Interaction	0.11	0.03
<i>H. comata</i> AUC _{in} = 0.869 AUC _{out} = 0.810	C3	Intercept _{FULL_MODEL}	Intercept	-2.04	0.10
	C3	Intercept _{SEINET_SAMPLING_INTENSITY}	Intercept	-2.06	0.12
	C3	Slope _{SEINET_SAMPLING_INTENSITY}	Slope	2.36	0.13
	C3	MAP	Main	1.33	0.18
	C3	MAP_MAT_Corr	Main	0.91	0.12
	C3	MAT	Main	-1.11	0.13
	C3	PSeas	Main	0.59	0.09
	C3	Soil_depth	Main	0.62	0.16
	C3	Summer_aridity	Main	-1.75	0.17
	C3	q_MAP	Quadratic	-0.29	0.20
	C3	q_MAP_MAT_Corr	Quadratic	-0.28	0.10
	C3	q_MAT	Quadratic	-0.54	0.10
	C3	q_PSeas	Quadratic	0.03	0.06
	C3	q_Summer_aridity	Quadratic	-0.01	0.21
	C3	I_MAP:MAP_MAT_Corr	Interaction	0.60	0.29
	C3	I_MAP:MAT	Interaction	-0.13	0.16
	C3	I_MAP:Summer_aridity	Interaction	0.15	0.39

Table A.3.2 (continued). Species distribution model (SDM) results for the 11 grass species in the western United States showing parameters retained in final models, parameter type (i.e., intercept, main effect, quadratic effect, or interaction), parameter estimate and standard error (SE).

Species	Carbon fixation pathway	Parameter	Type	Value	SE
<i>H. comata</i> (continued) AUC _{in} = 0.869 AUC _{out} = 0.810	C3	I_MAP:TRange	Interaction	0.13	0.12
	C3	I_MAP_MAT_Corr:Soil_depth	Interaction	0.90	0.14
	C3	I_MAP_MAT_Corr:Summer_aridity	Interaction	-0.56	0.29
	C3	I_MAP_MAT_Corr:TRange	Interaction	-0.50	0.08
	C3	I_MAT:PSeas	Interaction	-0.32	0.11
	C3	I_MAT:Soil_depth	Interaction	0.17	0.11
	C3	I_MAT:TRange	Interaction	-0.62	0.11
	C3	I_PSeas:TRange	Interaction	0.36	0.07
<i>P. smithii</i> AUC _{in} = 0.894 AUC _{out} = 0.901	C3	Intercept _{FULL_MODEL}	Intercept	-3.80	0.10
	C3	Intercept _{SEINET_SAMPLING_INTENSITY}	Intercept	-1.78	0.13
	C3	Slope _{SEINET_SAMPLING_INTENSITY}	Slope	2.03	0.13
	C3	MAP_MAT_Corr	Main	1.18	0.11
	C3	MAT	Main	-0.64	0.16
	C3	Soil_sand	Main	-0.14	0.10
	C3	TRange	Main	0.72	0.17
	C3	q_MAT	Quadratic	-0.85	0.10
	C3	q_TRange	Quadratic	0.54	0.14
	C3	I_MAP_MAT_Corr:MAT	Interaction	0.32	0.18
	C3	I_MAP_MAT_Corr:Soil_depth	Interaction	0.12	0.12
	C3	I_MAT_Soil_depth	Interaction	-0.03	0.08
	C3	I_MAT_TRange	Interaction	-0.52	0.14
	C3	I_Soil_depth:Soil_sand	Interaction	-0.41	0.16
	C3	I_Soil_depth:TRange	Interaction	0.05	0.20
	C3	I_Soil_sand:TRange	Interaction	-0.13	0.07
<i>P. secunda</i> AUC _{in} = 0.832 AUC _{out} = 0.867	C3	Intercept _{FULL_MODEL}	Intercept	-1.27	0.07
	C3	Intercept _{SEINET_SAMPLING_INTENSITY}	Intercept	-3.30	0.06
	C3	Slope _{SEINET_SAMPLING_INTENSITY}	Slope	1.14	0.04
	C3	MAT	Main	-2.60	0.12
	C3	PSeas	Main	0.34	0.06
	C3	Soil_clay	Main	-0.19	0.04
	C3	Soil_depth	Main	-0.35	0.09
	C3	Soil_sand	Main	-0.56	0.05

Table A.3.2 (continued). Species distribution model (SDM) results for the 11 grass species in the western United States showing parameters retained in final models, parameter type (i.e., intercept, main effect, quadratic effect, or interaction), parameter estimate and standard error (SE).

Species	Carbon fixation pathway	Parameter	Type	Value	SE
<i>P. secunda</i> (continued) AUC_{in} = 0.832 AUC_{out} = 0.867	C3	Summer_aridity	Main	-1.81	0.08
	C3	TRange	Main	-0.65	0.04
	C3	q_MAP	Quadratic	0.08	0.02
	C3	q_MAT	Quadratic	-1.09	0.11
	C3	q_PSeas	Quadratic	0.21	0.04
	C3	q_Soil_depth	Quadratic	-0.12	0.04
	C3	q_Soil_sand	Quadratic	-0.16	0.02
	C3	q_Summer_aridity	Quadratic	-0.01	0.05
	C3	q_TRange	Quadratic	-0.22	0.03
	C3	I_MAP:Soil_clay	Interaction	0.15	0.04
	C3	I_MAP:Soil_sand	Interaction	0.07	0.05
	C3	I_MAP:TRange	Interaction	0.35	0.06
	C3	I_MAT:PSeas	Interaction	0.23	0.09
	C3	I_MAT:Soil_depth	Interaction	-0.06	0.08
	C3	I_MAT:Soil_sand	Interaction	0.17	0.06
	C3	I_MAT:Summer_aridity	Interaction	-0.61	0.14
	C3	I_PSeas:Soil_sand	Interaction	-0.29	0.03
	C3	I_PSeas:Summer_aridity	Interaction	0.40	0.07
	C3	I_PSeas:TRange	Interaction	-0.15	0.04
	C3	I_Soil_clay:Soil_sand	Interaction	-0.01	0.03
	C3	I_Soil_depth:Soil_sand	Interaction	-0.24	0.05
	C3	I_Soil_depth:Summer_aridity	Interaction	0.01	0.07
	C3	I_Soil_depth:TRange	Interaction	0.26	0.06
	C3	I_Soil_sand:Summer_aridity	Interaction	-0.04	0.05
	C3	I_Soil_sand:TRange	Interaction	-0.27	0.04
	C3	I_Summer_aridity:TRange	Interaction	-0.39	0.06
	C3	Intercept _{FULL_MODEL}	Intercept	-1.27	0.07
	C3	Intercept _{SEINET_SAMPLING_INTENSITY}	Intercept	-3.30	0.06
	C3	Slope _{SEINET_SAMPLING_INTENSITY}	Slope	1.14	0.04
	C3	MAT	Main	-2.60	0.12
	C3	PSeas	Main	0.34	0.06
	C3	Soil_clay	Main	-0.19	0.04

Table A.3.2 (continued). Species distribution model (SDM) results for the 11 grass species in the western United States showing parameters retained in final models, parameter type (i.e., intercept, main effect, quadratic effect, or interaction), parameter estimate and standard error (SE).

Species	Carbon fixation pathway	Parameter	Type	Value	SE
<i>P. secunda</i> (continued) AUC_{in} = 0.832 AUC_{out} = 0.867	C3	Soil_depth	Main	-0.35	0.09
	C3	Soil_sand	Main	-0.56	0.05
	C3	Summer_aridity	Main	-1.81	0.08
	C3	TRange	Main	-0.65	0.04
	C3	q_MAP	Quadratic	0.08	0.02
	C3	q_MAT	Quadratic	-1.09	0.11
	C3	q_PSeas	Quadratic	0.21	0.04
	C3	q_Soil_depth	Quadratic	-0.12	0.04
	C3	q_Soil_sand	Quadratic	-0.16	0.02
	C3	q_Summer_aridity	Quadratic	-0.01	0.05
	C3	q_TRange	Quadratic	-0.22	0.03
<i>A. purpurea</i> AUC_{in} = 0.862 AUC_{out} = 0.882	C4	Intercept _{FULL_MODEL}	Intercept	-1.94	0.09
	C4	Intercept _{SEINET_SAMPLING_INTENSITY}	Intercept	-1.58	0.10
	C4	Slope _{SEINET_SAMPLING_INTENSITY}	Slope	2.16	0.13
	C4	MAP	Main	2.15	0.18
	C4	MAP_MAT_Corr	Main	2.61	0.16
	C4	PSeas	Main	1.13	0.06
	C4	Soil_depth	Main	-0.83	0.08
	C4	Summer_aridity	Main	-3.25	0.20
	C4	q_MAP_MAT_Corr	Quadratic	-1.36	0.17
	C4	q_PSeas	Quadratic	-0.75	0.07
	C4	q_Soil_clay	Quadratic	-0.26	0.03
	C4	q_Soil_depth	Quadratic	-0.21	0.03
	C4	q_Summer_aridity	Quadratic	-2.10	0.18
	C4	q_TRange	Quadratic	-0.36	0.08
	C4	I_MAP:Summer_aridity	Interaction	1.21	0.18
	C4	I_MAP:TRange	Interaction	1.59	0.19
	C4	I_MAP_MAT_Corr:Summer_aridity	Interaction	3.14	0.25
	C4	I_MAP_MAT_Corr:TRange	Interaction	1.19	0.18
	C4	I_PSeas:Soil_clay	Interaction	0.40	0.07
	C4	I_PSeas:Soil_depth	Interaction	0.57	0.07
	C4	I_Soil_clay:Soil_depth	Interaction	-0.23	0.04

Table A.3.2 (continued). Species distribution model (SDM) results for the 11 grass species in the western United States showing parameters retained in final models, parameter type (i.e., intercept, main effect, quadratic effect, or interaction), parameter estimate and standard error (SE).

Species	Carbon fixation pathway	Parameter	Type	Value	SE
<i>A. purpurea</i> (continued) AUC_{in} = 0.862 AUC_{out} = 0.882	C4	I_Soil_clay:Summer_aridity	Interaction	0.56	0.06
	C4	I_Soil_depth:Summer_aridity	Interaction	0.29	0.07
	C4	I_Soil_depth:TRange	Interaction	0.39	0.07
	C4	I_Summer_aridity:TRange	Interaction	-2.00	0.22
<i>B. gracilis</i> AUC_{in} = 0.882 AUC_{out} = 0.935	C4	Intercept _{FULL_MODEL}	Intercept	-1.61	0.09
	C4	Intercept _{SEINET_SAMPLING_INTENSITY}	Intercept	-3.49	0.10
	C4	Slope _{SEINET_SAMPLING_INTENSITY}	Slope	1.48	0.06
	C4	MAP	Main	1.24	0.10
	C4	MAP_MAT_Corr	Main	1.70	0.10
	C4	Soil_clay	Main	1.89	0.14
	C4	Soil_sand	Main	1.85	0.13
	C4	q_MAP	Quadratic	-1.08	0.12
	C4	q_MAP_MAT_Corr	Quadratic	-0.51	0.08
	C4	q_MAT	Quadratic	-0.69	0.06
	C4	I_MAP:MAP_MAT_Corr	Interaction	-1.46	0.15
	C4	I_MAP:Soil_sand	Interaction	-0.45	0.07
	C4	I_MAP_MAT_Corr:Soil_clay	Interaction	-0.93	0.15
	C4	I_MAP_MAT_Corr:Soil_sand	Interaction	-1.18	0.13
	C4	I_MAT:Soil_clay	Interaction	-1.28	0.07
	C4	I_MAT:Soil_sand	Interaction	-1.12	0.07
	C4	I_Soil_clay:Soil_sand	Interaction	0.18	0.02
	C4	I_Soil_depth:Soil_sand	Interaction	0.00	0.08
<i>B. eriopoda</i> AUC_{in} = 0.955 AUC_{out} = 0.975	C4	Intercept _{FULL_MODEL}	Intercept	-9.74	1.29
	C4	Intercept _{SEINET_SAMPLING_INTENSITY}	Intercept	-2.10	0.23
	C4	Slope _{SEINET_SAMPLING_INTENSITY}	Slope	1.66	0.22
	C4	MAP	Main	-27.74	4.77
	C4	MAT	Main	15.86	2.10
	C4	PSeas	Main	-12.39	2.24
	C4	Soil_clay	Main	1.24	1.23
	C4	Soil_sand	Main	1.30	1.08
	C4	Summer_aridity	Main	28.30	4.74
	C4	TRange	Main	0.51	0.67
	C4	q_MAP	Quadratic	-31.38	5.35

Table A.3.2 (continued). Species distribution model (SDM) results for the 11 grass species in the western United States showing parameters retained in final models, parameter type (i.e., intercept, main effect, quadratic effect, or interaction), parameter estimate and standard error (SE).

Species	Carbon fixation pathway	Parameter	Type	Value	SE
<i>B. eriopoda</i> (continued) AUC_{in} = 0.955 AUC_{out} = 0.975	C4	q_MAT	Quadratic	-7.76	1.06
	C4	q_PSeas	Quadratic	-8.89	1.36
	C4	q_Soil_clay	Quadratic	-0.24	0.28
	C4	q_Soil_sand	Quadratic	-0.47	0.23
	C4	q_Summer_aridity	Quadratic	-39.11	5.69
	C4	I_MAP:MAT	Interaction	25.08	4.14
	C4	I_MAP:PSeas	Interaction	-34.97	5.20
	C4	I_MAP:Soil_clay	Interaction	2.46	2.25
	C4	I_MAP:Soil_sand	Interaction	0.57	1.93
	C4	I_MAP:Summer_aridity	Interaction	68.68	10.79
	C4	I_MAP:TRange	Interaction	2.42	1.19
	C4	I_MAT:PSeas	Interaction	11.79	2.02
	C4	I_MAT:Soil_clay	Interaction	-0.27	0.95
	C4	I_MAT:Soil_sand	Interaction	0.22	0.89
	C4	I_MAT:Summer_aridity	Interaction	-26.44	4.32
	C4	I_MAT:TRange	Interaction	-0.51	0.59
	C4	I_PSeas:Soil_clay	Interaction	0.39	1.13
	C4	I_PSeas:Soil_sand	Interaction	-0.78	0.97
	C4	I_PSeas:Summer_aridity	Interaction	36.37	5.38
	C4	I_Soil_clay:Soil_sand	Interaction	-0.41	0.43
	C4	I_Soil_clay:Summer_aridity	Interaction	-2.21	2.28
	C4	I_Soil_clay:TRange	Interaction	0.21	0.47
	C4	I_Soil_sand:Summer_aridity	Interaction	-0.38	2.01
	C4	I_Soil_sand:TRange	Interaction	0.05	0.44
	C4	I_Summer_aridity:TRange	Interaction	-2.14	0.91
<i>P. jamesii</i> AUC_{in} = 0.866 AUC_{out} = 0.847	C4	Intercept _{FULL_MODEL}	Intercept	-4.75	0.10
	C4	Intercept _{SEINET_SAMPLING_INTENSITY}	Intercept	-0.96	0.19
	C4	Slope _{SEINET_SAMPLING_INTENSITY}	Slope	2.74	0.44
	C4	MAP_MAT_Corr	Main	1.54	0.07
	C4	Summer_aridity	Main	-1.90	0.11
	C4	q_Soil_clay	Quadratic	-1.48	0.21
	C4	q_Soil_sand	Quadratic	-0.70	0.13
	C4	I_Soil_clay:Soil_sand	Interaction	-2.06	0.31

Table A.3.2 (continued). Species distribution model (SDM) results for the 11 grass species in the western United States showing parameters retained in final models, parameter type (i.e., intercept, main effect, quadratic effect, or interaction), parameter estimate and standard error (SE).

Species	Carbon fixation pathway	Parameter	Type	Value	SE
<i>S. airoides</i> AUC_{in} = 0.876 AUC_{out} = 0.905	C4	Intercept _{FULL_MODEL}	Intercept	-5.50	0.28
	C4	Intercept _{SEINET_SAMPLING_INTENSITY}	Intercept	-0.75	0.22
	C4	Slope _{SEINET_SAMPLING_INTENSITY}	Slope	2.40	0.37
	C4	MAP_MAT_Corr	Main	2.70	0.35
	C4	PSeas	Main	0.71	0.25
	C4	Soil_clay	Main	0.99	0.25
	C4	Soil_sand	Main	1.81	0.24
	C4	Summer_aridity	Main	-2.76	0.36
	C4	q_MAP_MAT_Corr	Quadratic	-0.01	0.19
	C4	q_PSeas	Quadratic	-0.33	0.14
	C4	q_Soil_clay	Quadratic	0.11	0.11
	C4	q_Soil_depth	Quadratic	-0.02	0.05
	C4	q_Soil_sand	Quadratic	-0.34	0.11
	C4	q_Summer_aridity	Quadratic	-0.20	0.24
	C4	I_MAP:MAP_MAT_Corr	Interaction	1.81	0.38
	C4	I_MAP:Soil_clay	Interaction	2.49	0.47
	C4	I_MAP_MAT_Corr:PSeas	Interaction	0.49	0.19
	C4	I_MAP_MAT_Corr:Soil_depth	Interaction	0.43	0.18
	C4	I_MAP_MAT_Corr:Soil_sand	Interaction	-0.41	0.15
	C4	I_MAP_MAT_Corr:Summer_aridity	Interaction	-0.39	0.51
	C4	I_PSeas:Soil_clay	Interaction	-0.30	0.22
	C4	I_PSeas:Soil_depth	Interaction	0.26	0.19
	C4	I_PSeas:Soil_sand	Interaction	-0.63	0.19
	C4	I_PSeas:Summer_aridity	Interaction	-0.46	0.26
	C4	I_Soil_clay:Soil_depth	Interaction	-0.15	0.18
	C4	I_Soil_clay:Soil_sand	Interaction	0.03	0.19
	C4	I_Soil_clay:Summer_aridity	Interaction	-0.65	0.37
	C4	I_Soil_depth:Soil_sand	Interaction	-0.47	0.18
	C4	I_Soil_depth:Summer_aridity	Interaction	-0.45	0.16
	C4	I_Soil_sand_Summer_aridity	Interaction	-0.91	0.42

Table A.3.2 (continued). Species distribution model (SDM) results for the 11 grass species in the western United States showing parameters retained in final models, parameter type (i.e., intercept, main effect, quadratic effect, or interaction), parameter estimate and standard error (SE).

Species	Carbon fixation pathway	Parameter	Type	Value	SE
<i>S. cryptandrus</i> AUC _{in} = 0.845 AUC _{out} = 0.823	C4	Intercept _{FULL_MODEL}	Intercept	-3.77	0.10
	C4	Intercept _{SEINET_SAMPLING_INTENSITY}	Intercept	-1.12	0.17
	C4	Slope _{SEINET_SAMPLING_INTENSITY}	Slope	2.55	0.32
	C4	MAP_MAT_Corr	Main	0.72	0.08
	C4	MAT	Main	1.99	0.15
	C4	Soil_clay	Main	0.75	0.19
	C4	Soil_sand	Main	0.85	0.17
	C4	TRange	Main	0.78	0.18
	C4	q_MAT	Quadratic	-0.85	0.09
	C4	q_Soil_clay	Quadratic	-0.10	0.06
	C4	q_Soil_depth	Quadratic	-0.22	0.06
	C4	q_Soil_sand	Quadratic	-0.03	0.05
	C4	q_TRange	Quadratic	-0.44	0.11
	C4	I_MAP_MAT_Corr:Soil_clay	Interaction	-0.06	0.09
	C4	I_MAP_MAT_Corr:Soil_depth	Interaction	0.29	0.12
	C4	I_MAT:Soil_clay	Interaction	-0.64	0.13
	C4	I_MAT:Soil_depth	Interaction	-0.38	0.12
	C4	I_MAT:Soil_sand	Interaction	-0.58	0.12
	C4	I_MAT:TRange	Interaction	-0.34	0.17
	C4	I_Soil_clay:Soil_depth	Interaction	-0.20	0.09
	C4	I_Soil_clay:TRange	Interaction	-0.41	0.21
	C4	I_Soil_depth:TRange	Interaction	-0.30	0.15
	C4	I_Soil_sand:TRange	Interaction	-0.53	0.17

Table A.3.3. Changes in climate for the western United States. Mean values for the six climatic covariates: mean annual precipitation (MAP; mm/yr), mean annual temperature (MAT; °C), the correlation between MAP and MAT (MM_Corr), precipitation seasonality (PSeas; coefficient of variation), annual temperature range (TRange; °C), and summer aridity index for the western United States. Table shows historical (1970–2000) and future values (50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations), overall mean robust change in each covariate, the percent area (pixel-wise) where the covariate is robustly increasing and decreasing, and the mean values for regions of robust increase and decrease. Orange- and magenta-labeled rows indicate robust decreases and increases in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Environmental covariate	Historical (1970–2000)	Future: (Ensem 50 th quant.)	Percent area: increasing	Pos: mean	Percent area: decreasing	Neg: mean	Robust change: mean	Direction of change
RCP 4.5	2050	MAP	461.24	464.00	58.47	57.83	41.53	-68.53	5.35	Increasing
	2050	MAT	9.32	11.51	99.93	2.25	0.07	-1.68	2.25	Increasing
	2050	MM_Corr	0.04	-0.05	56.51	0.62	43.49	-0.69	0.05	Increasing
	2050	PSeas	48.98	52.83	80.77	5.77	19.23	-2.79	4.13	Increasing
	2050	Trange	37.24	38.68	82.94	3.24	17.06	-2.53	2.26	Increasing
	2050	Summer_Aridity	0.23	0.18	1.07	0.01	98.93	-0.06	-0.06	Decreasing
	2070	MAP	461.24	468.55	64.48	67.81	35.52	-82.90	14.27	Increasing
	2070	MAT	9.32	11.95	99.97	2.66	0.03	-2.26	2.66	Increasing
	2070	MM_Corr	0.04	-0.06	14.74	0.05	85.26	-0.20	-0.17	Decreasing
	2070	PSeas	48.98	53.59	94.42	8.34	5.58	-6.86	7.49	Increasing
	2070	Trange	37.24	38.68	82.94	3.24	17.06	-2.53	2.26	Increasing
	2070	Summer_Aridity	0.23	0.17	0.73	0.02	99.27	-0.07	-0.07	Decreasing
RCP 8.5	2050	MAP	461.24	467.14	61.34	72.43	38.66	-82.14	12.68	Increasing
	2050	MAT	9.32	11.99	99.96	2.69	0.04	-2.00	2.68	Increasing
	2050	MM_Corr	0.04	-0.07	26.29	0.05	73.71	-0.16	-0.16	Decreasing
	2050	PSeas	48.98	53.35	93.89	8.41	6.11	-7.83	7.42	Increasing
	2050	Trange	37.24	39.10	81.06	4.80	18.94	-2.83	3.33	Increasing
	2050	Summer_Aridity	0.23	0.17	0.41	0.02	99.59	-0.04	-0.04	Decreasing
	2070	MAP	461.24	465.45	57.43	71.90	42.57	-79.15	7.60	Increasing
	2070	MAT	9.32	13.43	100.00	4.13	0.00	-3.65	4.13	Increasing

Table A.3.3 (continued). Changes in climate for the western United States. Mean values for the six climatic covariates: mean annual precipitation (MAP; mm/yr), mean annual temperature (MAT; °C), the correlation between MAP and MAT (MM_Corr), precipitation seasonality (PSeas; coefficient of variation), annual temperature range (TRange; °C), and summer aridity index for the western United States. Table shows historical (1970–2000) and future values (50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations), overall mean robust change in each covariate, the percent area (pixel-wise) where the covariate is robustly increasing and decreasing, and the mean values for regions of robust increase and decrease. Orange- and magenta-labeled rows indicate robust decreases and increases in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Environmental covariate	Historical (1970–2000)	Future: (Ensem 50 th quant.)	Percent area: increasing	Pos: mean	Percent area: decreasing	Neg: mean	Robust change: mean	Direction of change
RCP 8.5 (cont.)	2070	MM_Corr	0.04	-0.11	15.39	0.07	84.61	-0.30	-0.24	Decreasing
	2070	PSeas	48.98	54.43	92.04	10.28	7.96	-8.35	8.80	Increasing
	2070	Trange	37.24	39.40	84.86	5.21	15.14	-2.97	3.97	Increasing
	2070	Summer_Aridity	0.23	0.15	0.38	0.01	99.62	-0.08	-0.08	Decreasing

Table A.3.4. Changes in habitat suitability for the western United States. Habitat suitability (lambda) values for the 11 grass species for the western United States showing historical (1970–2000) lambda, future lambda for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations, overall mean robust change in lambda, the percent area (pixel-wise) where lambda is robustly increasing and decreasing, and the mean lambda values for regions of robust increase and decrease. Historical and future lambda values should not be compared among species. However, since robust change in habitat suitability was adjusted by the maximum historical habitat suitability for each species, mean changes in lambda values can be compared across species and can be used to infer relative changes in habitat suitability among species. Orange-, magenta-, and beige-labeled rows indicate robust decreases, increases, and neutral shifts in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% +λ)	Pos (+ λ)	Percent area decreasing (% -λ)	Neg (- λ)	Mean robust change λ	Direction of change
RCP 4.5	2050	C3	<i>A. hymenoides</i>	0.140	0.144	68.68	0.027	31.31	-0.038	0.007	Increasing
	2050	C3	<i>E. elymoides</i>	0.187	0.172	23.06	0.006	76.94	-0.004	-0.001	Decreasing
	2050	C3	<i>H. comata</i>	0.076	0.084	43.30	0.063	56.70	-0.021	0.015	Increasing
	2050	C3	<i>P. smithii</i>	0.068	0.049	22.63	0.007	77.37	-0.018	-0.012	Decreasing
	2050	C3	<i>P. secunda</i>	0.566	0.407	10.15	0.027	89.85	-0.019	-0.014	Decreasing
	2050	C4	<i>A. purpurea</i>	0.087	0.120	96.64	0.029	9.36	-0.048	0.021	Increasing

Table A.3.4 (continued). Changes in habitat suitability for the western United States. Habitat suitability (lambda) values for the 11 grass species for the western United States showing historical (1970–2000) lambda, future lambda for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations, overall mean robust change in lambda, the percent area (pixel-wise) where lambda is robustly increasing and decreasing, and the mean lambda values for regions of robust increase and decrease. Historical and future lambda values should not be compared among species. However, since robust change in habitat suitability was adjusted by the maximum historical habitat suitability for each species, mean changes in lambda values can be compared across species and can be used to infer relative changes in habitat suitability among species. Orange-, magenta-, and beige-labeled rows indicate robust decreases, increases, and neutral shifts in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% + λ)	Pos (+ λ)	Percent area decreasing (% - λ)	Neg (- λ)	Mean robust change λ	Direction of change
RCP 4.5 (cont.)	2050	C4	<i>B. eriopoda</i>	0.019	0.017	37.22	0.016	62.78	-0.015	-0.003	Decreasing
	2050	C4	<i>B. gracilis</i>	0.198	0.139	26.15	0.001	75.19	-0.017	-0.011	Decreasing
	2050	C4	<i>P. jamesii</i>	0.020	0.020	93.36	0.013	6.64	-0.086	0.007	Increasing
	2050	C4	<i>S. airoides</i>	0.019	0.027	83.21	0.023	16.79	-0.004	0.018	Increasing
	2050	C4	<i>S. cryptandrus</i>	0.027	0.029	83.03	0.033	16.97	-0.091	0.012	Increasing
	2070	C3	<i>A. hymenoides</i>	0.140	0.146	72.61	0.028	42.78	-0.039	0.010	Increasing
	2070	C3	<i>E. elymoides</i>	0.187	0.165	21.44	0.007	78.56	-0.004	-0.002	Decreasing
	2070	C3	<i>H. comata</i>	0.076	0.075	33.61	0.068	66.39	-0.026	0.006	Increasing
	2070	C3	<i>P. smithii</i>	0.068	0.044	18.61	0.008	81.39	-0.021	-0.015	Decreasing
	2070	C3	<i>P. secunda</i>	0.566	0.349	7.27	0.027	92.73	-0.023	-0.019	Decreasing
	2070	C4	<i>A. purpurea</i>	0.087	0.127	90.69	0.035	9.32	-0.050	0.027	Increasing
	2070	C4	<i>B. eriopoda</i>	0.019	0.015	37.84	0.017	62.16	-0.019	-0.005	Decreasing
	2070	C4	<i>B. gracilis</i>	0.198	0.129	24.81	0.001	75.19	-0.017	-0.013	Decreasing
	2070	C4	<i>P. jamesii</i>	0.020	0.020	93.54	0.014	6.46	-0.082	0.007	Increasing
	2070	C4	<i>S. airoides</i>	0.019	0.027	81.21	0.026	18.79	-0.004	0.020	Increasing
	2070	C4	<i>S. cryptandrus</i>	0.027	0.030	79.83	0.036	20.17	-0.111	0.013	Increasing
RCP 8.5	2050	C3	<i>A. hymenoides</i>	0.140	0.147	57.22	0.030	42.78	-0.042	0.000	Neutral
	2050	C3	<i>E. elymoides</i>	0.187	0.164	21.44	0.007	78.56	-0.005	-0.002	Decreasing
	2050	C3	<i>H. comata</i>	0.076	0.071	33.61	0.061	66.39	-0.028	0.002	Increasing
	2050	C3	<i>P. smithii</i>	0.068	0.042	18.61	0.008	81.39	-0.021	-0.015	Decreasing

Table A.3.4 (continued). Changes in habitat suitability for the western United States. Habitat suitability (lambda) values for the 11 grass species for the western United States showing historical (1970–2000) lambda, future lambda for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations, overall mean robust change in lambda, the percent area (pixel-wise) where lambda is robustly increasing and decreasing, and the mean lambda values for regions of robust increase and decrease. Historical and future lambda values should not be compared among species. However, since robust change in habitat suitability was adjusted by the maximum historical habitat suitability for each species, mean changes in lambda values can be compared across species and can be used to infer relative changes in habitat suitability among species. Orange-, magenta-, and beige-labeled rows indicate robust decreases, increases, and neutral shifts in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% +λ)	Pos (+ λ)	Percent area decreasing (% -λ)	Neg (- λ)	Mean robust change λ	Direction of change
RCP 8.5 (cont.)	2050	C3	<i>P. secunda</i>	0.566	0.324	7.27	0.025	92.73	-0.024	-0.021	Decreasing
	2050	C4	<i>A. purpurea</i>	0.087	0.127	90.69	0.035	9.31	-0.047	0.028	Increasing
	2050	C4	<i>B. eriopoda</i>	0.019	0.016	37.83	0.019	62.17	-0.019	-0.004	Decreasing
	2050	C4	<i>B. gracilis</i>	0.198	0.128	24.81	0.001	75.19	-0.017	-0.013	Decreasing
	2050	C4	<i>P. jamesii</i>	0.020	0.021	92.89	0.015	7.11	-0.081	0.009	Increasing
	2050	C4	<i>S. airoides</i>	0.019	0.028	82.15	0.028	17.85	-0.004	0.022	Increasing
	2050	C4	<i>S. cryptandrus</i>	0.027	0.029	79.83	0.036	20.17	-0.111	0.006	Increasing
	2070	C3	<i>A. hymenoides</i>	0.140	0.150	77.16	0.037	22.84	-0.042	0.019	Increasing
	2070	C3	<i>E. elymoides</i>	0.187	0.144	15.36	0.010	84.64	-0.006	-0.004	Decreasing
	2070	C3	<i>H. comata</i>	0.076	0.054	19.71	0.067	80.29	-0.052	-0.029	Decreasing
	2070	C3	<i>P. smithii</i>	0.068	0.029	12.54	0.008	87.46	-0.027	-0.023	Decreasing
	2070	C3	<i>P. secunda</i>	0.566	0.211	3.22	0.021	96.78	-0.032	-0.030	Decreasing
	2070	C4	<i>A. purpurea</i>	0.087	0.141	91.77	0.044	8.23	-0.055	0.036	Increasing
	2070	C4	<i>B. eriopoda</i>	0.019	0.012	34.50	0.017	65.50	-0.024	-0.010	Decreasing
	2070	C4	<i>B. gracilis</i>	0.198	0.094	21.76	0.001	78.24	-0.022	-0.017	Decreasing
	2070	C4	<i>P. jamesii</i>	0.020	0.021	93.29	0.021	6.71	-0.109	0.012	Increasing
	2070	C4	<i>S. airoides</i>	0.019	0.032	81.13	0.040	18.87	-0.002	0.032	Increasing
	2070	C4	<i>S. cryptandrus</i>	0.027	0.028	75.71	0.052	24.29	-0.146	0.004	Increasing
RCP 4.5	2050	C3	<i>A. hymenoides</i>	0.140	0.144	68.68	0.027	31.31	-0.038	0.007	Increasing
	2050	C3	<i>E. elymoides</i>	0.187	0.172	23.06	0.006	76.94	-0.004	-0.001	Decreasing

Table A.3.4 (continued). Changes in habitat suitability for the western United States. Habitat suitability (lambda) values for the 11 grass species for the western United States showing historical (1970–2000) lambda, future lambda for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations, overall mean robust change in lambda, the percent area (pixel-wise) where lambda is robustly increasing and decreasing, and the mean lambda values for regions of robust increase and decrease. Historical and future lambda values should not be compared among species. However, since robust change in habitat suitability was adjusted by the maximum historical habitat suitability for each species, mean changes in lambda values can be compared across species and can be used to infer relative changes in habitat suitability among species. Orange-, magenta-, and beige-labeled rows indicate robust decreases, increases, and neutral shifts in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% +λ)	Pos (+ λ)	Percent area decreasing (% -λ)	Neg (- λ)	Mean robust change λ	Direction of change
RCP 4.5 (cont.)	2050	C3	<i>H. comata</i>	0.076	0.084	43.30	0.063	56.70	-0.021	0.015	Increasing
	2050	C3	<i>P. smithii</i>	0.068	0.049	22.63	0.007	77.37	-0.018	-0.012	Decreasing
	2050	C3	<i>P. secunda</i>	0.566	0.407	10.15	0.027	89.85	-0.019	-0.014	Decreasing
	2050	C4	<i>A. purpurea</i>	0.087	0.120	96.64	0.029	9.36	-0.048	0.021	Increasing
	2050	C4	<i>B. eriopoda</i>	0.019	0.017	37.22	0.016	62.78	-0.015	-0.003	Decreasing
	2050	C4	<i>B. gracilis</i>	0.198	0.139	26.15	0.001	75.19	-0.017	-0.011	Decreasing
	2050	C4	<i>P. jamesii</i>	0.020	0.020	93.36	0.013	6.64	-0.086	0.007	Increasing
	2050	C4	<i>S. airoides</i>	0.019	0.027	83.21	0.023	16.79	-0.004	0.018	Increasing
	2050	C4	<i>S. cryptandrus</i>	0.027	0.029	83.03	0.033	16.97	-0.091	0.012	Increasing
	2070	C3	<i>A. hymenoides</i>	0.140	0.146	72.61	0.028	42.78	-0.039	0.010	Increasing
	2070	C3	<i>E. elymoides</i>	0.187	0.165	21.44	0.007	78.56	-0.004	-0.002	Decreasing
	2070	C3	<i>H. comata</i>	0.076	0.075	33.61	0.068	66.39	-0.026	0.006	Increasing
	2070	C3	<i>P. smithii</i>	0.068	0.044	18.61	0.008	81.39	-0.021	-0.015	Decreasing
	2070	C3	<i>P. secunda</i>	0.566	0.349	7.27	0.027	92.73	-0.023	-0.019	Decreasing
	2070	C4	<i>A. purpurea</i>	0.087	0.127	90.69	0.035	9.32	-0.050	0.027	Increasing
	2070	C4	<i>B. eriopoda</i>	0.019	0.015	37.84	0.017	62.16	-0.019	-0.005	Decreasing
	2070	C4	<i>B. gracilis</i>	0.198	0.129	24.81	0.001	75.19	-0.017	-0.013	Decreasing
	2070	C4	<i>P. jamesii</i>	0.020	0.020	93.54	0.014	6.46	-0.082	0.007	Increasing
	2070	C4	<i>S. airoides</i>	0.019	0.027	81.21	0.026	18.79	-0.004	0.020	Increasing
	2070	C4	<i>S. cryptandrus</i>	0.027	0.030	79.83	0.036	20.17	-0.111	0.013	Increasing

Table A.3.4 (continued). Changes in habitat suitability for the western United States. Habitat suitability (lambda) values for the 11 grass species for the western United States showing historical (1970–2000) lambda, future lambda for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations, overall mean robust change in lambda, the percent area (pixel-wise) where lambda is robustly increasing and decreasing, and the mean lambda values for regions of robust increase and decrease. Historical and future lambda values should not be compared among species. However, since robust change in habitat suitability was adjusted by the maximum historical habitat suitability for each species, mean changes in lambda values can be compared across species and can be used to infer relative changes in habitat suitability among species. Orange-, magenta-, and beige-labeled rows indicate robust decreases, increases, and neutral shifts in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% + λ)	Pos (+ λ)	Percent area decreasing (% - λ)	Neg (- λ)	Mean robust change λ	Direction of change
RCP 8.5	2050	C3	<i>A. hymenoides</i>	0.140	0.147	57.22	0.030	42.78	-0.042	0.000	Neutral
	2050	C3	<i>E. elymoides</i>	0.187	0.164	21.44	0.007	78.56	-0.005	-0.002	Decreasing
	2050	C3	<i>H. comata</i>	0.076	0.071	33.61	0.061	66.39	-0.028	0.002	Increasing
	2050	C3	<i>P. smithii</i>	0.068	0.042	18.61	0.008	81.39	-0.021	-0.015	Decreasing
	2050	C3	<i>P. secunda</i>	0.566	0.324	7.27	0.025	92.73	-0.024	-0.021	Decreasing
	2050	C4	<i>A. purpurea</i>	0.087	0.127	90.69	0.035	9.31	-0.047	0.028	Increasing
	2050	C4	<i>B. eriopoda</i>	0.019	0.016	37.83	0.019	62.17	-0.019	-0.004	Decreasing
	2050	C4	<i>B. gracilis</i>	0.198	0.128	24.81	0.001	75.19	-0.017	-0.013	Decreasing
	2050	C4	<i>P. jamesii</i>	0.020	0.021	92.89	0.015	7.11	-0.081	0.009	Increasing
	2050	C4	<i>S. airoides</i>	0.019	0.028	82.15	0.028	17.85	-0.004	0.022	Increasing
	2050	C4	<i>S. cryptandrus</i>	0.027	0.029	79.83	0.036	20.17	-0.111	0.006	Increasing
	2070	C3	<i>A. hymenoides</i>	0.140	0.150	77.16	0.037	22.84	-0.042	0.019	Increasing
	2070	C3	<i>E. elymoides</i>	0.187	0.144	15.36	0.010	84.64	-0.006	-0.004	Decreasing
	2070	C3	<i>H. comata</i>	0.076	0.054	19.71	0.067	80.29	-0.052	-0.029	Decreasing
	2070	C3	<i>P. smithii</i>	0.068	0.029	12.54	0.008	87.46	-0.027	-0.023	Decreasing
	2070	C3	<i>P. secunda</i>	0.566	0.211	3.22	0.021	96.78	-0.032	-0.030	Decreasing
	2070	C4	<i>A. purpurea</i>	0.087	0.141	91.77	0.044	8.23	-0.055	0.036	Increasing
	2070	C4	<i>B. eriopoda</i>	0.019	0.012	34.50	0.017	65.50	-0.024	-0.010	Decreasing
	2070	C4	<i>B. gracilis</i>	0.198	0.094	21.76	0.001	78.24	-0.022	-0.017	Decreasing
	2070	C4	<i>P. jamesii</i>	0.020	0.021	93.29	0.021	6.71	-0.109	0.012	Increasing

Table A.3.4 (continued). Changes in habitat suitability for the western United States. Habitat suitability (lambda) values for the 11 grass species for the western United States showing historical (1970–2000) lambda, future lambda for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations, overall mean robust change in lambda, the percent area (pixel-wise) where lambda is robustly increasing and decreasing, and the mean lambda values for regions of robust increase and decrease. Historical and future lambda values should not be compared among species. However, since robust change in habitat suitability was adjusted by the maximum historical habitat suitability for each species, mean changes in lambda values can be compared across species and can be used to infer relative changes in habitat suitability among species. Orange-, magenta-, and beige-labeled rows indicate robust decreases, increases, and neutral shifts in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% +λ)	Pos (+ λ)	Percent area decreasing (% -λ)	Neg (- λ)	Mean robust change λ	Direction of change
RCP 8.5 (cont.)	2070	C4	<i>S. airoides</i>	0.019	0.032	81.13	0.040	18.87	-0.002	0.032	Increasing
	2070	C4	<i>S. cryptandrus</i>	0.027	0.028	75.71	0.052	24.29	-0.146	0.004	Increasing

Table A.3.5. Changes in climate for the Colorado Plateau Ecoregion. Mean values for the six climatic covariates: mean annual precipitation (MAP; mm/yr), mean annual temperature (MAT; °C), the correlation between MAP and MAT (MM_Corr), precipitation seasonality (PSeas; coefficient of variation), annual temperature range (TRange; °C), and summer aridity index for the Colorado Plateau. Table shows historical (1970–2000) and future values (50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations), overall mean robust change in each covariate, the percent area (pixel-wise) where the covariate is robustly increasing and decreasing, and the mean values for regions of robust increase and decrease. Orange- and magenta-labeled rows indicate robust decreases and increases in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Environmental covariate	Historical (1970–2000)	Future (Ensem 50 th quant.)	Percent area increasing	Pos mean	Percent area decreasing	Neg mean	Robust change mean	Direction of change
RCP 4.5	2050	MAP	327.12	322.73	28.04	46.81	71.86	-28.17	-7.15	Decreasing
	2050	MAT	10.36	12.66	99.92	2.32	0.08	-3.57	2.31	Increasing
	2050	MM_Corr	0.40	0.29	90.67	0.09	9.33	-0.17	0.40	Increasing
	2050	PSeas	41.85	47.16	93.82	6.21	6.18	-2.22	5.69	Increasing
	2050	Trange	40.63	40.20	36.19	2.20	63.81	-2.44	-0.76	Decreasing
	2050	Summer_Aridity	0.20	0.18	1.07	0.01	98.93	-0.04	-0.04	Decreasing
	2070	MAP	327.12	330.86	50.84	50.84	49.16	-31.30	10.46	Increasing
	2070	MAT	10.36	13.22	99.94	2.86	0.06	-3.84	2.86	Increasing

Table A.3.5 (continued). Changes in climate for the Colorado Plateau Ecoregion. Mean values for the six climatic covariates: mean annual precipitation (MAP; mm/yr), mean annual temperature (MAT; °C), the correlation between MAP and MAT (MM_Corr), precipitation seasonality (PSeas; coefficient of variation), annual temperature range (TRange; °C), and summer aridity index for the Colorado Plateau. Table shows historical (1970–2000) and future values (50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations), overall mean robust change in each covariate, the percent area (pixel-wise) where the covariate is robustly increasing and decreasing, and the mean values for regions of robust increase and decrease. Orange- and magenta-labeled rows indicate robust decreases and increases in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Environmental covariate	Historical (1970–2000)	Future (Ensem 50 th quant.)	Percent area increasing	Pos mean	Percent area decreasing	Neg mean	Robust change mean	Direction of change
RCP 4.5 (cont.)	2070	MM_Corr	0.40	0.33	0.01	0.20	99.99	-0.29	-0.29	Decreasing
	2070	PSeas	41.85	47.19	99.83	8.01	0.17	-8.72	7.98	Increasing
	2070	Trange	40.63	40.20	36.19	2.20	63.81	-2.44	-0.76	Decreasing
	2070	Summer_Aridity	0.20	0.18	0.32	0.08	99.69	-0.04	-0.04	Decreasing
RCP 8.5	2050	MAP	327.12	324.48	35.64	63.89	64.36	-36.74	-0.87	Decreasing
	2050	MAT	10.36	13.13	99.93	2.77	0.07	-3.20	2.77	Increasing
	2050	MM_Corr	0.40	0.30	18.95	0.05	81.05	-0.14	-0.14	Decreasing
	2050	PSeas	41.85	47.50	99.45	8.55	0.55	-9.50	8.45	Increasing
	2050	Trange	40.63	40.48	22.25	3.47	77.75	-2.92	-1.50	Decreasing
	2050	Summer_Aridity	0.20	0.17	0.22	0.06	99.78	-0.04	-0.04	Decreasing
	2070	MAP	327.12	309.89	27.42	55.68	72.58	-46.49	-18.47	Decreasing
	2070	MAT	10.36	14.65	99.97	4.29	0.03	-3.69	4.29	Increasing
	2070	MM_Corr	0.40	0.27	0.02	0.18	99.98	-0.37	-0.37	Decreasing
	2070	PSeas	41.85	48.05	98.05	9.49	1.95	-9.00	9.13	Increasing
	2070	Trange	40.63	40.74	29.53	3.83	70.47	-2.93	-0.94	Decreasing
	2070	Summer_Aridity	0.20	0.15	0.16	0.04	99.84	-0.05	-0.05	Decreasing

Table A.3.6. Changes in habitat suitability for the Colorado Plateau ecoregion. Habitat suitability (lambda) values for the 11 grass species for the western United States showing historical (1970–2000) lambda, future lambda for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations, overall mean robust change in lambda, the percent area (pixel-wise) where lambda is robustly increasing (magenta) and decreasing (orange), and the mean lambda values for regions of robust increase and decrease.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% +λ)	Pos (+ λ)	Percent area decreasing (% -λ)	Neg (- λ)	Mean robust change (Δλ)	Direction of change
RCP 4.5	2050	C3	<i>A. hymenoides</i>	0.254	0.235	28.28	0.028	71.72	-0.028	-0.050	Decreasing
	2050	C3	<i>E. elymoides</i>	0.196	0.156	3.56	0.006	96.44	-0.004	-0.004	Decreasing
	2050	C3	<i>H. comata</i>	0.082	0.058	1.89	0.032	98.11	-0.030	-0.032	Decreasing
	2050	C3	<i>P. smithii</i>	0.051	0.026	1.09	0.008	98.91	-0.013	-0.014	Decreasing
	2050	C3	<i>P. secunda</i>	0.189	0.121	0.48	0.004	99.52	-0.005	-0.007	Decreasing
	2050	C4	<i>A. purpurea</i>	0.107	0.131	97.69	0.020	2.31	0.018	0.048	Increasing
	2050	C4	<i>B. eriopoda</i>	0.060	0.071	85.59	0.035	14.41	0.014	0.113	Increasing
	2050	C4	<i>B. gracilis</i>	0.379	0.212	0.43	0.007	99.57	-0.020	-0.021	Decreasing
	2050	C4	<i>P. jamesii</i>	0.040	0.036	48.18	0.021	51.81	-0.035	-0.087	Increasing
	2050	C4	<i>S. airoides</i>	0.020	0.024	92.83	0.012	7.17	0.011	0.003	Increasing
	2050	C4	<i>S. cryptandrus</i>	0.053	0.061	90.20	0.089	9.81	0.070	0.101	Increasing
	2070	C3	<i>A. hymenoides</i>	0.254	0.233	27.83	0.028	72.17	-0.029	-0.051	Decreasing
	2070	C3	<i>E. elymoides</i>	0.196	0.144	3.01	0.006	96.99	-0.004	-0.005	Decreasing
	2070	C3	<i>H. comata</i>	0.082	0.052	0.89	0.035	99.11	-0.037	-0.038	Decreasing
	2070	C3	<i>P. smithii</i>	0.051	0.024	1.01	0.008	98.99	-0.014	-0.014	Decreasing
	2070	C3	<i>P. secunda</i>	0.189	0.088	0.04	0.009	99.96	-0.007	-0.007	Decreasing
	2070	C4	<i>A. purpurea</i>	0.107	0.132	98.29	0.024	1.71	0.023	0.037	Increasing
	2070	C4	<i>B. eriopoda</i>	0.060	0.067	83.31	0.040	16.59	0.015	0.108	Increasing
	2070	C4	<i>B. gracilis</i>	0.379	0.199	0.36	0.009	99.64	-0.024	-0.024	Decreasing
	2070	C4	<i>P. jamesii</i>	0.040	0.038	41.84	0.031	58.16	-0.031	-0.077	Decreasing
	2070	C4	<i>S. airoides</i>	0.020	0.025	91.64	0.015	8.36	0.013	0.003	Increasing

Table A.3.6 (continued). Changes in habitat suitability for the Colorado Plateau ecoregion. Habitat suitability (λ) values for the 11 grass species for the western United States showing historical (1970–2000) λ , future λ for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) $\times$ time period (2050, 2070) combinations, overall mean robust change in λ , the percent area (pixel-wise) where λ is robustly increasing (magenta) and decreasing (orange), and the mean λ values for regions of robust increase and decrease.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% $+\lambda$)	Pos (+ λ)	Percent area decreasing (% $-\lambda$)	Neg (- λ)	Mean robust change ($\Delta\lambda$)	Direction of change
RCP 4.5 (cont.)	2070	C4	<i>S. cryptandrus</i>	0.053	0.064	90.19	0.110	9.81	0.088	0.114	Increasing
RCP 8.5	2050	C3	<i>A. hymenoides</i>	0.254	0.241	10.62	0.041	89.39	-0.048	-0.058	Decreasing
	2050	C3	<i>E. elymoides</i>	0.196	0.137	3.01	0.006	96.99	-0.005	-0.005	Decreasing
	2050	C3	<i>H. comata</i>	0.082	0.048	0.89	0.037	99.11	-0.041	-0.041	Decreasing
	2050	C3	<i>P. smithii</i>	0.051	0.022	1.01	0.007	98.99	-0.014	-0.016	Decreasing
	2050	C3	<i>P. secunda</i>	0.189	0.079	0.04	0.008	99.96	-0.007	-0.007	Decreasing
	2050	C4	<i>A. purpurea</i>	0.107	0.133	98.29	0.022	1.71	0.022	0.036	Increasing
	2050	C4	<i>B. eriopoda</i>	0.060	0.074	83.31	0.044	16.68	0.018	0.110	Increasing
	2050	C4	<i>B. gracilis</i>	0.379	0.184	0.36	0.009	99.64	-0.025	-0.025	Decreasing
	2050	C4	<i>P. jamesii</i>	0.039	0.037	54.13	0.030	48.87	-0.024	-0.090	Decreasing
	2050	C4	<i>S. airoides</i>	0.020	0.026	93.43	0.015	6.57	0.014	0.003	Increasing
	2050	C4	<i>S. cryptandrus</i>	0.053	0.060	88.65	0.107	11.35	0.080	0.132	Increasing
	2070	C3	<i>A. hymenoides</i>	0.254	0.243	49.52	0.033	50.48	-0.015	-0.006	Decreasing
	2070	C3	<i>E. elymoides</i>	0.196	0.111	1.11	0.010	98.89	-0.007	-0.007	Decreasing
	2070	C3	<i>H. comata</i>	0.082	0.032	0.41	0.035	99.59	-0.056	-0.057	Decreasing
	2070	C3	<i>P. smithii</i>	0.051	0.013	0.55	0.008	99.45	-0.019	-0.019	Decreasing
	2070	C3	<i>P. secunda</i>	0.189	0.211	0.03	0.006	99.97	-0.010	-0.010	Decreasing
	2070	C4	<i>A. purpurea</i>	0.107	0.150	98.96	0.032	1.04	0.031	0.054	Increasing
	2070	C4	<i>B. eriopoda</i>	0.060	0.055	65.06	0.042	34.94	-0.009	-0.103	Decreasing
	2070	C4	<i>B. gracilis</i>	0.379	0.110	0.42	0.009	99.58	-0.029	-0.030	Decreasing

Table A.3.6 (continued). Changes in habitat suitability for the Colorado Plateau ecoregion. Habitat suitability (λ) values for the 11 grass species for the western United States showing historical (1970–2000) λ , future λ for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) $\times$ time period (2050, 2070) combinations, overall mean robust change in λ , the percent area (pixel-wise) where λ is robustly increasing (magenta) and decreasing (orange), and the mean λ values for regions of robust increase and decrease.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% $+\lambda$)	Pos (+ λ)	Percent area decreasing (% $-\lambda$)	Neg (- λ)	Mean robust change ($\Delta\lambda$)	Direction of change
RCP 8.5 (cont.)	2070	C4	<i>P. jamesii</i>	0.039	0.038	67.75	0.043	32.25	-0.005	-0.107	Decreasing
	2070	C4	<i>S. airoides</i>	0.020	0.031	94.31	0.024	5.69	0.023	0.003	Increasing
	2070	C4	<i>S. cryptandrus</i>	0.053	0.056	60.92	0.147	39.08	0.032	0.148	Increasing

Table A.3.7. Changes in climate for Arches National Park. Mean values for the six climatic covariates: mean annual precipitation (MAP; mm/yr), mean annual temperature (MAT; °C), the correlation between MAP and MAT (MM_Corr), precipitation seasonality (PSeas; coefficient of variation), annual temperature range (Trange; °C), and summer aridity index for Arches National Park. Table shows historical (1970–2000) and future values (50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) $\times$ time period (2050, 2070) combinations), overall mean robust change in each covariate, the percent area (pixel-wise) where the covariate is robustly increasing and decreasing, and the mean values for regions of robust increase and decrease. Orange- and magenta-labeled rows indicate robust decreases and increases in habitat suitability, respectively, for each given species $\times$ RCP $\times$ time period combination.

RCP	Time period	Environmental covariate	Historical (1970–2000)	Future (Ensem 50th quant.)	Percent area increasing	Pos mean	Percent area decreasing	Neg mean	Robust change mean	Direction of change
RCP 4.5	2050	MAP	243.04	240.25	100.00	15.67	0.00	NA	15.67	Increasing
	2050	MAT	12.03	14.80	100.00	2.77	0.00	NA	2.77	Increasing
	2050	MM_Corr	0.09	0.09	95.62	0.09	4.38	-0.02	0.08	Increasing
	2050	PSeas	24.48	27.37	99.14	2.88	0.86	-0.17	2.85	Increasing
	2050	Trange	44.80	43.48	0.00	NA	100.00	-1.62	-1.62	Decreasing
	2050	Summer_Aridity	0.10	0.09	0.00	NA	100.00	-0.02	-0.02	Decreasing
	2070	MAP	243.04	247.19	100.00	21.60	0.00	NA	21.60	Increasing
	2070	MAT	12.03	15.36	100.00	3.33	0.00	NA	3.33	Increasing

Table A.3.7 (continued). Changes in climate for Arches National Park. Mean values for the six climatic covariates: mean annual precipitation (MAP; mm/yr), mean annual temperature (MAT; °C), the correlation between MAP and MAT (MM_Corr), precipitation seasonality (PSeas; coefficient of variation), annual temperature range (Trange; °C), and summer aridity index for Arches National Park. Table shows historical (1970–2000) and future values (50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations), overall mean robust change in each covariate, the percent area (pixel-wise) where the covariate is robustly increasing and decreasing, and the mean values for regions of robust increase and decrease. Orange- and magenta-labeled rows indicate robust decreases and increases in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Environmental covariate	Historical (1970–2000)	Future (Ensem 50th quant.)	Percent area increasing	Pos mean	Percent area decreasing	Neg mean	Robust change mean	Direction of change
RCP 4.5 (cont.)	2070	MM_Corr	0.08	0.13	NA	NA	NA	NA	NA	Increasing
	2070	PSeas	24.48	28.79	NA	NA	NA	NA	NA	Increasing
	2070	Trange	44.80	43.48	0.00	NA	100.00	-1.62	-1.62	Decreasing
	2070	Summer_Aridity	0.10	0.08	NA	NA	NA	NA	NA	Decreasing
RCP 8.5	2050	MAP	243.04	245.71	NA	NA	NA	NA	NA	Increasing
	2050	MAT	12.03	15.26	100.00	3.23	0.00	NA	3.23	Increasing
	2050	MM_Corr	0.08	0.11	65.21	0.05	34.79	-0.03	0.02	Increasing
	2050	PSeas	24.48	28.74	100.00	5.78	0.00	NA	5.78	Increasing
	2050	Trange	44.80	43.67	0.00	NA	100.00	-1.80	-1.80	Decreasing
	2050	Summer_Aridity	0.10	0.09	NA	NA	NA	NA	NA	Decreasing
	2070	MAP	243.04	237.16	NA	NA	NA	NA	NA	Decreasing
	2070	MAT	12.03	17.07	100.00	5.03	0.00	NA	5.03	Increasing
	2070	MM_Corr	0.08	0.05	NA	NA	NA	NA	NA	Decreasing
	2070	PSeas	24.48	29.67	92.04	10.28	7.96	-8.35	8.80	Increasing
	2070	Trange	44.80	43.48	0.00	NA	100.00	-2.27	-2.27	Decreasing
	2070	Summer_Aridity	0.10	0.07	0.00	NA	100.00	-0.02	-0.02	Decreasing

Table A.3.8. Changes in habitat suitability for Arches National Park. Habitat suitability (lambda) values for the 11 grass species for Arches National Park showing historical (1970–2000) lambda, future lambda for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations, overall mean robust change in lambda, the percent area (pixel-wise) where lambda is robustly increasing (magenta), decreasing (orange), or staying neutral (beige), and the mean lambda values for regions of robust increase and decrease.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% +λ)	Pos (+ λ)	Percent area decreasing (% -λ)	Neg (- λ)	Mean robust change (Δλ)	Direction of change
RCP 4.5	2050	C3	<i>A. hymenoides</i>	0.663	0.511	0.00	NA	100.00	-0.092	-0.092	Decreasing
	2050	C3	<i>E. elymoides</i>	0.105	0.073	0.00	NA	100.00	-0.002	-0.002	Decreasing
	2050	C3	<i>H. comata</i>	0.032	0.020	0.00	NA	100.00	-0.013	-0.013	Decreasing
	2050	C3	<i>P. smithii</i>	0.005	0.002	0.00	NA	100.00	-0.001	-0.001	Decreasing
	2050	C3	<i>P. secunda</i>	0.030	0.008	0.00	NA	100.00	-0.002	-0.002	Decreasing
	2050	C4	<i>A. purpurea</i>	0.040	0.051	NA	NA	NA	NA	NA	Neutral
	2050	C4	<i>B. eriopoda</i>	0.044	0.047	57.14	0.077	11.63	-0.016	0.014	Decreasing
	2050	C4	<i>B. gracilis</i>	0.130	0.055	0.00	NA	100.00	-0.009	-0.009	Decreasing
	2050	C4	<i>P. jamesii</i>	0.044	0.046	NA	NA	NA	NA	NA	Neutral
	2050	C4	<i>S. airoides</i>	0.015	0.018	100.00	0.006	0.00	NA	0.006	Increasing
	2050	C4	<i>S. cryptandrus</i>	0.024	0.030	100.00	0.077	0.00	NA	0.077	Increasing
	2070	C3	<i>A. hymenoides</i>	0.663	0.511	0.00	NA	100.00	-0.107	-0.107	Decreasing
	2070	C3	<i>E. elymoides</i>	0.105	0.066	0.00	NA	100.00	-0.003	-0.003	Decreasing
	2070	C3	<i>H. comata</i>	0.032	0.015	0.00	NA	100.00	-0.018	-0.018	Decreasing
	2070	C3	<i>P. smithii</i>	0.005	0.001	0.00	NA	100.00	-0.002	-0.002	Decreasing
	2070	C3	<i>P. secunda</i>	0.030	0.006	0.00	NA	100.00	-0.002	-0.002	Decreasing
	2070	C4	<i>A. purpurea</i>	0.040	0.064	100.00	0.017	0.00	NA	0.017	Increasing
	2070	C4	<i>B. eriopoda</i>	0.044	0.037	8.33	0.057	27.78	-0.017	-0.021	Decreasing
	2070	C4	<i>B. gracilis</i>	0.130	0.042	0.00	NA	100.00	-0.010	-0.010	Decreasing
	2070	C4	<i>P. jamesii</i>	0.044	0.058	NA	NA	NA	NA	NA	Neutral
	2070	C4	<i>S. airoides</i>	0.015	0.021	100.00	0.007	0.00	NA	0.007	Increasing

Table A.3.8 (continued). Changes in habitat suitability for Arches National Park. Habitat suitability (lambda) values for the 11 grass species for Arches National Park showing historical (1970–2000) lambda, future lambda for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations, overall mean robust change in lambda, the percent area (pixel-wise) where lambda is robustly increasing (magenta), decreasing (orange), or staying neutral (beige), and the mean lambda values for regions of robust increase and decrease.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% $+\lambda$)	Pos (+ λ)	Percent area decreasing (% $-\lambda$)	Neg (- λ)	Mean robust change ($\Delta\lambda$)	Direction of change
RCP 8.5	2070	C4	<i>S. cryptandrus</i>	0.024	0.027	100.00	0.058	NA	NA	0.058	Increasing
	2050	C3	<i>A. hymenoides</i>	0.663	0.531	0.00	NA	100.00	-0.109	-0.109	Decreasing
	2050	C3	<i>E. elymoides</i>	0.105	0.057	0.00	NA	100.00	-0.004	-0.004	Decreasing
	2050	C3	<i>H. comata</i>	0.032	0.013	0.00	NA	100.00	-0.020	-0.020	Decreasing
	2050	C3	<i>P. smithii</i>	0.005	0.002	0.00	NA	100.00	-0.001	-0.001	Decreasing
	2050	C3	<i>P. secunda</i>	0.030	0.005	0.00	NA	100.00	-0.002	-0.002	Decreasing
	2050	C4	<i>A. purpurea</i>	0.040	0.076	100	0.022	0	NA	0.022	Increasing
	2050	C4	<i>B. eriopoda</i>	0.044	0.039	8.33	0.071	27.78	-0.018	-0.020	Decreasing
	2050	C4	<i>B. gracilis</i>	0.130	0.055	0.00	NA	100	-0.009	-0.009	Decreasing
	2050	C4	<i>P. jamesii</i>	0.044	0.051	NA	NA	NA	NA	NA	Neutral
	2050	C4	<i>S. airoides</i>	0.015	0.023	100.00	0.010	0.00	NA	0.010	Increasing
	2050	C4	<i>S. cryptandrus</i>	0.024	0.031	NA	NA	NA	NA	NA	Neutral
	2070	C3	<i>A. hymenoides</i>	0.663	0.497	0.00	NA	100.00	-0.130	-0.130	Decreasing
	2070	C3	<i>E. elymoides</i>	0.105	0.039	0.00	NA	100.00	-0.005	-0.005	Decreasing
	2070	C3	<i>H. comata</i>	0.032	0.007	0.00	NA	100.00	-0.026	-0.026	Decreasing
	2070	C3	<i>P. smithii</i>	0.005	0.000	0.00	NA	100.00	-0.002	-0.002	Decreasing
	2070	C3	<i>P. secunda</i>	0.030	0.002	0.00	NA	100.00	-0.002	-0.002	Decreasing
	2070	C4	<i>A. purpurea</i>	0.040	0.074	NA	NA	NA	NA	NA	Increasing
	2070	C4	<i>B. eriopoda</i>	0.044	0.015	0.00	NA	63.69	-0.018	-0.032	Decreasing
	2070	C4	<i>B. gracilis</i>	0.130	0.015	0.00	NA	100.00	-0.012	-0.012	Decreasing
	2070	C4	<i>P. jamesii</i>	0.044	0.0400	NA	NA	NA	NA	NA	Neutral

Table A.3.8 (continued). Changes in habitat suitability for Arches National Park. Habitat suitability (lambda) values for the 11 grass species for Arches National Park showing historical (1970–2000) lambda, future lambda for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations, overall mean robust change in lambda, the percent area (pixel-wise) where lambda is robustly increasing (magenta), decreasing (orange), or staying neutral (beige), and the mean lambda values for regions of robust increase and decrease.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% +λ)	Pos (+ λ)	Percent area decreasing (% -λ)	Neg (- λ)	Mean robust change (Δλ)	Direction of change
RCP 8.5 (cont.)	2070	C4	<i>S. airoides</i>	0.015	0.022	100.00	0.009	0.00	NA	0.009	Increasing
	2070	C4	<i>S. cryptandrus</i>	0.024	0.013	0.00	NA	100.00	-0.065	-0.065	Decreasing

Table A.3.9. Changes in climate for Canyonlands National Park. Mean values for the six climatic covariates: mean annual precipitation (MAP; mm/yr), mean annual temperature (MAT; °C), the correlation between MAP and MAT (MM_Corr), precipitation seasonality (PSeas; coefficient of variation), annual temperature range (Trange; °C), and summer aridity index for Canyonlands National Park. Table shows historical (1970–2000) and future values (50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations), overall mean robust change in each covariate, the percent area (pixel-wise) where the covariate is robustly increasing and decreasing, and the mean values for regions of robust increase and decrease. Orange- and magenta-labeled rows indicate robust decreases and increases in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Environmental covariate	Historical (1970–2000)	Future (Ensem 50th quant.)	Percent area increasing	Pos mean	Percent area decreasing	Neg mean	Robust change mean	Direction of change
RCP 4.5	2050	MAP	232.68	229.60	9.00	21.68	91.00	-14.41	-11.16	Decreasing
	2050	MAT	11.88	14.69	100.00	2.81	0.00	NA	2.81	Increasing
	2050	MM_Corr	0.09	0.12	90.42	0.10	9.58	-0.02	0.09	Increasing
	2050	PSeas	26.47	31.50	100.00	5.87	0.00	NA	5.87	Increasing
	2050	Trange	42.28	43.16	93.21	2.08	6.79	-1.66	1.83	Increasing
	2050	Summer_Aridity	0.10	0.09	0.00	NA	100.00	-0.02	-0.02	Decreasing
	2070	MAP	232.68	235.23	74.63	22.66	0.00	NA	22.66	Increasing
	2070	MAT	11.88	15.27	100.00	3.38	0.00	NA	3.38	Increasing
	2070	MM_Corr	0.09	0.04	NA	NA	NA	NA	NA	Decreasing

Table A.3.9 (continued). Changes in climate for Canyonlands National Park. Mean values for the six climatic covariates: mean annual precipitation (MAP; mm/yr), mean annual temperature (MAT; °C), the correlation between MAP and MAT (MM_Corr), precipitation seasonality (PSeas; coefficient of variation), annual temperature range (Trange; °C), and summer aridity index for Canyonlands National Park. Table shows historical (1970–2000) and future values (50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations), overall mean robust change in each covariate, the percent area (pixel-wise) where the covariate is robustly increasing and decreasing, and the mean values for regions of robust increase and decrease. Orange- and magenta-labeled rows indicate robust decreases and increases in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Environmental covariate	Historical (1970–2000)	Future (Ensem 50th quant.)	Percent area increasing	Pos mean	Percent area decreasing	Neg mean	Robust change mean	Direction of change
RCP 4.5 (cont.)	2070	PSeas	26.47	31.60	100.00	6.39	0.00	NA	6.39	Increasing
	2070	Trange	42.28	43.16	93.21	2.08	6.79	-1.66	1.83	Increasing
	2070	Summer_Aridity	0.10	0.09	0.00	NA	100.00	-0.03	-0.03	Decreasing
RCP 8.5	2050	MAP	232.68	233.01	77.78	23.71	22.22	-22.33	13.48	Increasing
	2050	MAT	11.88	15.16	100.00	3.28	0.00	NA	3.28	Increasing
	2050	MM_Corr	0.09	0.14	78.24	0.07	21.76	-0.03	0.05	Increasing
	2050	PSeas	26.47	31.73	100.00	5.89	0.00	NA	5.89	Increasing
	2050	Trange	42.28	43.25	80.00	3.18	20.00	-2.22	2.10	Increasing
	2050	Summer_Aridity	0.10	0.09	0.00	NA	100.00	-0.02	-0.02	Decreasing
	2070	MAP	232.68	223.40	77.78	13.42	22.22	-30.17	3.74	Increasing
	2070	MAT	11.88	16.77	100.00	4.88	0.00	NA	4.88	Increasing
	2070	MM_Corr	0.09	0.10	NA	NA	NA	NA	NA	Increasing
	2070	PSeas	26.47	33.06	100.00	7.46	0.00	NA	7.46	Increasing
	2070	Trange	42.28	43.06	96.00	2.98	4.00	-3.40	2.73	Increasing
	2070	Summer_Aridity	0.10	0.08	0.00	NA	100.00	-0.03	-0.03	Decreasing

Table A.3.10. Changes in habitat suitability for Canyonlands National Park. Habitat suitability (lambda) values for the 11 grass species for Canyonlands National Park showing historical (1970–2000) lambda, future lambda for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations, overall mean robust change in lambda, the percent area (pixel-wise) where lambda is robustly increasing and decreasing, and the mean lambda values for regions of robust increase and decrease. Orange- and magenta-labeled rows indicate robust decreases and increases in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% + λ)	Pos (+ λ)	Percent area decreasing (% - λ)	Neg (- λ)	Mean robust change ($\Delta\lambda$)	Direction of change
RCP 4.5	2050	C3	<i>A. hymenoides</i>	0.447	0.436	80.70	0.056	19.30	-0.092	0.027	Increasing
	2050	C3	<i>E. elymoides</i>	0.124	0.080	0.00	NA	100.00	0.080	-0.003	Decreasing
	2050	C3	<i>H. comata</i>	0.036	0.020	0.00	NA	100.00	-0.017	-0.017	Decreasing
	2050	C3	<i>P. smithii</i>	0.008	0.003	0.00	NA	100.00	-0.003	-0.003	Decreasing
	2050	C3	<i>P. secunda</i>	0.068	0.013	0.00	NA	100.00	-0.004	-0.004	Decreasing
	2050	C4	<i>A. purpurea</i>	0.055	0.089	100.00	0.016	0.00	0.000	0.016	Increasing
	2050	C4	<i>B. eriopoda</i>	0.026	0.068	88.37	0.071	11.63	-0.016	0.061	Increasing
	2050	C4	<i>B. gracilis</i>	0.121	0.057	0.00	NA	100.00	-0.009	-0.009	Decreasing
	2050	C4	<i>P. jamesii</i>	0.040	0.050	100.00	0.047	0.00	NA	0.047	Increasing
	2050	C4	<i>S. airoides</i>	0.016	0.023	100.00	0.010	0.00	NA	0.010	Increasing
	2050	C4	<i>S. cryptandrus</i>	0.043	0.037	40.51	0.060	59.49	-0.078	-0.022	Decreasing
	2070	C3	<i>A. hymenoides</i>	0.447	0.436	88.03	0.039	11.96	-0.110	0.021	Increasing
	2070	C3	<i>E. elymoides</i>	0.124	0.075	0.00	NA	100.00	-0.004	-0.004	Decreasing
	2070	C3	<i>H. comata</i>	0.036	0.014	0.00	NA	100.00	-0.023	-0.023	Decreasing
	2070	C3	<i>P. smithii</i>	0.008	0.002	0.00	NA	100.00	-0.003	-0.003	Decreasing
	2070	C3	<i>P. secunda</i>	0.068	0.010	0.00	NA	100.00	-0.004	-0.004	Decreasing
	2070	C4	<i>A. purpurea</i>	0.055	0.106	100.00	0.025	0.00	NA	0.025	Increasing
	2070	C4	<i>B. eriopoda</i>	0.026	0.048	72.22	0.059	27.78	-0.017	0.038	Increasing
	2070	C4	<i>B. gracilis</i>	0.121	0.047	0.00	NA	100.00	-0.010	-0.010	Decreasing
	2070	C4	<i>P. jamesii</i>	0.040	0.058	100.00	0.096	0.00	NA	0.096	Increasing
	2070	C4	<i>S. airoides</i>	0.016	0.025	100.00	0.012	0.00	NA	0.012	Increasing

Table A.3.10 (continued). Changes in habitat suitability for Canyonlands National Park. Habitat suitability (λ) values for the 11 grass species for Canyonlands National Park showing historical (1970–2000) λ , future λ for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) $\times$ time period (2050, 2070) combinations, overall mean robust change in λ , the percent area (pixel-wise) where λ is robustly increasing and decreasing, and the mean λ values for regions of robust increase and decrease. Orange- and magenta-labeled rows indicate robust decreases and increases in habitat suitability, respectively, for each given species $\times$ RCP $\times$ time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% $+\lambda$)	Pos (+ λ)	Percent area decreasing (% $-\lambda$)	Neg (- λ)	Mean robust change ($\Delta\lambda$)	Direction of change
RCP 4.5 (cont.)	2070	C4	<i>S. cryptandrus</i>	0.043	0.037	40.51	0.102	59.49	-0.080	-0.006	Decreasing
RCP 8.5	2050	C3	<i>A. hymenoides</i>	0.447	0.474	72.22	0.063	27.78	-0.106	0.016	Increasing
	2050	C3	<i>E. elymoides</i>	0.124	0.064	0.00	NA	100.00	-0.004	-0.004	Decreasing
	2050	C3	<i>H. comata</i>	0.036	0.013	0.00	NA	100.00	-0.023	-0.023	Decreasing
	2050	C3	<i>P. smithii</i>	0.008	0.003	0.00	NA	100.00	-0.027	-0.027	Decreasing
	2050	C3	<i>P. secunda</i>	0.068	0.009	0.00	NA	100.00	-0.004	-0.004	Decreasing
	2050	C4	<i>A. purpurea</i>	0.055	0.100	100.00	0.023	0.00	NA	0.023	Increasing
	2050	C4	<i>B. eriopoda</i>	0.026	0.055	72.22	0.073	27.78	-0.018	0.048	Increasing
	2050	C4	<i>B. gracilis</i>	0.121	0.058	0.00	NA	100.00	-0.009	-0.009	Decreasing
	2050	C4	<i>P. jamesii</i>	0.040	0.051	100.00	0.030	0.00	NA	0.030	Increasing
	2050	C4	<i>S. airoides</i>	0.016	0.026	100.00	0.014	0.00	NA	0.014	Increasing
	2050	C4	<i>S. cryptandrus</i>	0.043	0.031	83.33	0.090	16.67	-0.111	0.057	Increasing
	2070	C3	<i>A. hymenoides</i>	0.447	0.465	83.78	0.056	16.22	-0.104	0.030	Increasing
	2070	C3	<i>E. elymoides</i>	0.124	0.046	0.00	NA	100.00	-0.006	-0.006	Decreasing
	2070	C3	<i>H. comata</i>	0.036	0.007	0.00	NA	100.00	-0.030	-0.030	Decreasing
	2070	C3	<i>P. smithii</i>	0.008	0.006	0.00	NA	100.00	-0.004	-0.004	Decreasing
	2070	C3	<i>P. secunda</i>	0.068	0.003	0.00	NA	100.00	-0.005	-0.005	Decreasing
	2070	C4	<i>A. purpurea</i>	0.055	0.121	100.00	0.036	0.00	NA	0.036	Increasing
	2070	C4	<i>B. eriopoda</i>	0.026	0.031	36.31	0.056	63.69	-0.018	0.009	Increasing
	2070	C4	<i>B. gracilis</i>	0.121	0.019	0.00	NA	100.00	-0.011	-0.011	Decreasing

Table A.3.10 (continued). Changes in habitat suitability for Canyonlands National Park. Habitat suitability (λ) values for the 11 grass species for Canyonlands National Park showing historical (1970–2000) λ , future λ for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) $\times$ time period (2050, 2070) combinations, overall mean robust change in λ , the percent area (pixel-wise) where λ is robustly increasing and decreasing, and the mean λ values for regions of robust increase and decrease. Orange- and magenta-labeled rows indicate robust decreases and increases in habitat suitability, respectively, for each given species $\times$ RCP $\times$ time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% $+\lambda$)	Pos (+ λ)	Percent area decreasing (% $-\lambda$)	Neg (- λ)	Mean robust change ($\Delta\lambda$)	Direction of change
RCP 8.5 (cont.)	2070	C4	<i>P. jamesii</i>	0.040	0.043	NA	NA	NA	NA	NA	Increasing
	2070	C4	<i>S. airoides</i>	0.016	0.028	100.00	0.015	0.00	NA	0.015	Increasing
	2070	C4	<i>S. cryptandrus</i>	0.043	0.022	0.90	0.140	99.10	-0.109	-0.107	Decreasing

Table A.3.11. Changes in climate for Natural Bridges National Monument. Mean values for the six climatic covariates: mean annual precipitation (MAP; mm/yr), mean annual temperature (MAT; °C), the correlation between MAP and MAT (MM_Corr), precipitation seasonality (PSeas; coefficient of variation), annual temperature range (Trange; °C), and summer aridity index for Natural Bridges National Monument. Table shows historical (1970–2000) and future values (50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) $\times$ time period (2050, 2070) combinations), overall mean robust change in each covariate, the percent area (pixel-wise) where the covariate is robustly increasing and decreasing, and the mean values for regions of robust increase and decrease. Orange-, magenta-, and beige-labeled rows indicate robust decreases, increases, and neutral shifts in habitat suitability, respectively, for each given species $\times$ RCP $\times$ time period combination.

RCP	Time period	Environmental covariate	Historical (1970–2000)	Future (Ensem 50th quant.)	Percent area increasing	Pos mean	Percent area decreasing	Neg mean	Robust change mean	Direction of change
RCP 4.5	2050	MAP	278.26	273.88	0.00	NA	100.00	-9.33	-9.33	Decreasing
	2050	MAT	10.47	13.58	100.00	3.11	0.00	NA	3.11	Increasing
	2050	MM_Corr	0.11	0.01	100.00	0.11	0.00	NA	0.11	Increasing
	2050	PSeas	27.68	36.30	NA	NA	NA	NA	NA	Increasing
	2050	Trange	39.72	39.83	NA	NA	NA	NA	NA	Decreasing
	2050	Summer_Aridity	0.14	0.12	0.00	NA	100.00	-0.03	-0.03	Decreasing
	2070	MAP	278.26	279.37	NA	NA	NA	NA	NA	Increasing
	2070	MAT	10.47	14.18	100.00	3.71	0.00	NA	3.71	Increasing

Table A.3.11 (continued). Changes in climate for Natural Bridges National Monument. Mean values for the six climatic covariates: mean annual precipitation (MAP; mm/yr), mean annual temperature (MAT; °C), the correlation between MAP and MAT (MM_Corr), precipitation seasonality (PSeas; coefficient of variation), annual temperature range (Trange; °C), and summer aridity index for Natural Bridges National Monument. Table shows historical (1970–2000) and future values (50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations), overall mean robust change in each covariate, the percent area (pixel-wise) where the covariate is robustly increasing and decreasing, and the mean values for regions of robust increase and decrease. Orange-, magenta-, and beige-labeled rows indicate robust decreases, increases, and neutral shifts in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Environmental covariate	Historical (1970–2000)	Future (Ensem 50th quant.)	Percent area increasing	Pos mean	Percent area decreasing	Neg mean	Robust change mean	Direction of change
RCP 4.5 (cont.)	2070	MM_Corr	0.11	0.04	NA	NA	NA	NA	NA	Decreasing
	2070	PSeas	27.68	34.60	100.00	6.97	0.00	NA	6.97	Decreasing
	2070	Trange	39.72	39.83	NA	NA	NA	NA	NA	Neutral
	2070	Summer_Aridity	0.14	0.12	NA	NA	NA	NA	NA	Decreasing
RCP 8.5	2050	MAP	278.26	278.09	NA	NA	NA	NA	NA	Neutral
	2050	MAT	10.47	14.03	100.00	3.56	0.00	NA	3.56	Increasing
	2050	MM_Corr	0.11	0.05	0.00	NA	100.00	-0.03	-0.03	Decreasing
	2050	PSeas	27.68	35.74	100.00	8.07	0.00	NA	8.07	Increasing
	2050	Trange	39.72	39.43	NA	NA	NA	NA	NA	Neutral
	2050	Summer_Aridity	0.14	0.12	0.00	NA	100.00	-0.02	-0.02	Decreasing
	2070	MAP	278.26	267.00	NA	NA	NA	NA	NA	Decreasing
	2070	MAT	10.47	15.49	100.00	5.02	0.00	NA	5.02	Increasing
	2070	MM_Corr	0.11	0.03	NA	NA	NA	NA	NA	Decreasing
	2070	PSeas	27.68	36.72	100.00	9.05	0.00	NA	9.05	Increasing
	2070	Trange	39.72	39.34	NA	NA	NA	NA	NA	Decreasing
	2070	Summer_Aridity	0.14	0.11	0.00	NA	100.00	-0.04	-0.04	Decreasing

Table A.3.12. Changes in habitat suitability for Natural Bridges National Monument. Habitat suitability (lambda) values for the 11 grass species for the Natural Bridges National Monument showing historical (1970–2000) lambda, future lambda for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations, overall mean robust change in lambda, the percent area (pixel-wise) where lambda is robustly increasing and decreasing and the mean lambda values across areas of increase and decrease. Orange-, magenta-, and beige-labeled rows indicate robust decreases, increases, and neutral shifts in habitat suitability respectively for each given species × RCP × time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% +λ)	Pos (+ λ)	Percent area decreasing (% -λ)	Neg (- λ)	Mean robust change (Δλ)	Direction of change
RCP 4.5	2050	C3	<i>A. hymenoides</i>	0.348	0.333	NA	NA	NA	NA	NA	Decreasing
	2050	C3	<i>E. elymoides</i>	0.199	0.135	0.00	NA	100.00	-0.005	-0.005	Decreasing
	2050	C3	<i>H. comata</i>	0.073	0.046	0.00	NA	100.00	-0.028	-0.028	Decreasing
	2050	C3	<i>P. smithii</i>	0.013	0.005	0.00	NA	100.00	-0.004	-0.004	Decreasing
	2050	C3	<i>P. secunda</i>	0.134	0.030	0.00	NA	100.00	-0.008	-0.008	Decreasing
	2050	C4	<i>A. purpurea</i>	0.036	0.075	100.00	0.016	0.00	NA	0.016	Increasing
	2050	C4	<i>B. eriopoda</i>	0.023	0.126	100.00	0.074	0.00	NA	0.074	Increasing
	2050	C4	<i>B. gracilis</i>	0.122	0.060	0.00	NA	100.00	-0.008	-0.008	Decreasing
	2050	C4	<i>P. jamesii</i>	0.029	0.028	NA	NA	NA	NA	NA	Decreasing
	2050	C4	<i>S. airoides</i>	0.011	0.018	100.00	0.009	0.00	NA	0.009	Increasing
	2050	C4	<i>S. cryptandrus</i>	0.043	0.047	100.00	0.045	0.00	NA	0.045	Increasing
	2070	C3	<i>A. hymenoides</i>	0.348	0.318	NA	NA	NA	NA	NA	Decreasing
	2070	C3	<i>E. elymoides</i>	0.199	0.123	0.00	NA	100.00	-0.005	-0.005	Decreasing
	2070	C3	<i>H. comata</i>	0.073	0.037	0.00	NA	100.00	-0.038	-0.038	Decreasing
	2070	C3	<i>P. smithii</i>	0.013	0.004	0.00	NA	100.00	-0.005	-0.005	Decreasing
	2070	C3	<i>P. secunda</i>	0.134	0.023	0.00	NA	100.00	-0.008	-0.008	Decreasing
	2070	C4	<i>A. purpurea</i>	0.036	0.087	100.00	0.016	0.00	NA	0.016	Increasing
	2070	C4	<i>B. eriopoda</i>	0.023	0.114	100.00	0.066	0.00	NA	0.066	Increasing
	2070	C4	<i>B. gracilis</i>	0.122	0.063	0.00	NA	100.00	-0.009	-0.009	Decreasing
	2070	C4	<i>P. jamesii</i>	0.029	0.037	NA	NA	NA	NA	NA	Increasing

Table A.3.12 (continued). Changes in habitat suitability for Natural Bridges National Monument. Habitat suitability (lambda) values for the 11 grass species for the Natural Bridges National Monument showing historical (1970–2000) lambda, future lambda for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations, overall mean robust change in lambda, the percent area (pixel-wise) where lambda is robustly increasing and decreasing and the mean lambda values across areas of increase and decrease. Orange-, magenta-, and beige-labeled rows indicate robust decreases, increases, and neutral shifts in habitat suitability respectively for each given species × RCP × time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% + λ)	Pos (+ λ)	Percent area decreasing (% - λ)	Neg (- λ)	Mean robust change ($\Delta\lambda$)	Direction of change
RCP 4.5 (cont.)	2070	C4	<i>S. airoides</i>	0.011	0.020	100.00	0.012	0.00	NA	0.012	Increasing
	2070	C4	<i>S. cryptandrus</i>	0.043	0.050	100.00	0.063	0.00	NA	0.063	Increasing
RCP 8.5	2050	C3	<i>A. hymenoides</i>	0.348	0.317	NA 0.00	NA	NA	NA	NA	Decreasing
	2050	C3	<i>E. elymoides</i>	0.199	0.108	0.00	NA	100.00	-0.007	-0.007	Decreasing
	2050	C3	<i>H. comata</i>	0.073	0.039	0.00	NA	100.00	-0.036	-0.036	Decreasing
	2050	C3	<i>P. smithii</i>	0.013	0.004	0.00	NA	100.00	-0.004	-0.004	Decreasing
	2050	C3	<i>P. secunda</i>	0.134	0.022	0.00	NA	100.00	-0.008	-0.008	Decreasing
	2050	C4	<i>A. purpurea</i>	0.036	0.076	100.00	0.017	0.00	NA	0.017	Increasing
	2050	C4	<i>B. eriopoda</i>	0.023	0.137	100.00	0.082	0.00	NA	0.082	Increasing
	2050	C4	<i>B. gracilis</i>	0.122	0.066	0.00	NA	100.00	-0.008	-0.008	Decreasing
	2050	C4	<i>P. jamesii</i>	0.029	0.033	NA	NA	NA	NA	NA	Increasing
	2050	C4	<i>S. airoides</i>	0.011	0.022	100.00	0.014	0.00	NA	0.014	Increasing
	2050	C4	<i>S. cryptandrus</i>	0.043	0.046	NA	NA	NA	NA	NA	Increasing
	2070	C3	<i>A. hymenoides</i>	0.348	0.339	NA	NA	NA	NA	NA	Neutral
	2070	C3	<i>E. elymoides</i>	0.199	0.085	0.00	NA	100.00	-0.008	-0.008	Decreasing
	2070	C3	<i>H. comata</i>	0.073	0.019	0.00	NA	100.00	-0.056	-0.056	Decreasing
	2070	C3	<i>P. smithii</i>	0.013	0.001	0.00	NA	100.00	-0.006	-0.006	Decreasing
	2070	C3	<i>P. secunda</i>	0.134	0.009	0.00	NA	100.00	-0.009	-0.009	Decreasing
	2070	C4	<i>A. purpurea</i>	0.036	0.099	100.00	0.027	0.00	NA	0.027	Increasing
	2070	C4	<i>B. eriopoda</i>	0.023	0.105	100.00	0.065	0.00	NA	0.065	Increasing

Table A.3.12 (continued). Changes in habitat suitability for Natural Bridges National Monument. Habitat suitability (λ) values for the 11 grass species for the Natural Bridges National Monument showing historical (1970–2000) λ , future λ for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) $\times$ time period (2050, 2070) combinations, overall mean robust change in λ , the percent area (pixel-wise) where λ is robustly increasing and decreasing and the mean λ values across areas of increase and decrease. Orange-, magenta-, and beige-labeled rows indicate robust decreases, increases, and neutral shifts in habitat suitability respectively for each given species $\times$ RCP $\times$ time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% $+\lambda$)	Pos (+ λ)	Percent area decreasing (% $-\lambda$)	Neg (- λ)	Mean robust change ($\Delta\lambda$)	Direction of change
RCP 8.5 (cont.)	2070	C4	<i>B. gracilis</i>	0.122	0.025	0.00	NA	100.00	-0.010	-0.010	Decreasing
	2070	C4	<i>P. jamesii</i>	0.029	0.028	NA	NA	NA	NA	NA	Neutral
	2070	C4	<i>S. airoides</i>	0.011	0.025	100.00	0.018	0.00	NA	0.018	Increasing
	2070	C4	<i>S. cryptandrus</i>	0.043	0.040	NA	NA	NA	NA	NA	Neutral

Table A.3.13. Changes in climate for Hovenweep National Monument. Mean values for the six climatic covariates: mean annual precipitation (MAP; mm/yr), mean annual temperature (MAT; °C), the correlation between MAP and MAT (MM_Corr), precipitation seasonality (PSeas; coefficient of variation), annual temperature range (Trange; °C), and summer aridity index for Hovenweep National Monument. Table shows historical (1970–2000) and future values (50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) $\times$ time period (2050, 2070) combinations), overall mean robust change in each covariate, the percent area (pixel-wise) where the covariate is robustly increasing and decreasing, and the mean values for regions of robust increase and decrease. Orange- and magenta-labeled rows indicate robust decreases and increases in habitat suitability, respectively, for each given species $\times$ RCP $\times$ time period combination.

RCP	Time period	Environmental covariate	Historical (1970–2000)	Future (Ensem 50th quant.)	Percent area increasing	Pos mean	Percent area decreasing	Neg mean	Robust change mean	Direction of change
RCP 4.5	2050	MAP	309.00	307.25	NA	NA	NA	NA	NA	Decreasing
	2050	MAT	10.73	13.48	100.00	2.75	0.00	NA	2.75	Increasing
	2050	MM_Corr	-0.13	-0.22	25.00	0.04	75.00	-0.19	-0.13	Decreasing
	2050	PSeas	26.37	32.70	NA	NA	NA	NA	NA	Increasing
	2050	Trange	43.38	43.38	NA	NA	NA	NA	NA	Neutral
	2050	Summer_Aridity	0.13	0.11	0.00	NA	100.00	-0.02	-0.02	Decreasing
	2070	MAP	309.00	312.75	NA	NA	NA	NA	NA	Increasing

Table A.3.13 (continued). Changes in climate for Hovenweep National Monument. Mean values for the six climatic covariates: mean annual precipitation (MAP; mm/yr), mean annual temperature (MAT; °C), the correlation between MAP and MAT (MM_Corr), precipitation seasonality (PSeas; coefficient of variation), annual temperature range (Trange; °C), and summer aridity index for Hovenweep National Monument. Table shows historical (1970–2000) and future values (50th quantile of the ensemble of 17 global circulation models (GCMs) for all representative concentration pathways (RCP) (4.5, 8.5) × time period (2050, 2070) combinations), overall mean robust change in each covariate, the percent area (pixel-wise) where the covariate is robustly increasing and decreasing, and the mean values for regions of robust increase and decrease. Orange- and magenta-labeled rows indicate robust decreases and increases in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Environmental covariate	Historical (1970–2000)	Future (Ensem 50th quant.)	Percent area increasing	Pos mean	Percent area decreasing	Neg mean	Robust change mean	Direction of change
RCP 4.5 (cont.)	2070	MAT	10.73	14.18	100.00	3.46	0.00	NA	3.46	Increasing
	2070	MM_Corr	-0.13	-0.11	NA	NA	NA	NA	NA	Increasing
	2070	PSeas	26.37	31.66	100.00	5.30	0.00	NA	5.30	Increasing
	2070	Trange	43.38	43.48	NA	NA	NA	NA	NA	Neutral
	2070	Summer_Aridity	0.13	0.11	NA	NA	NA	NA	NA	Decreasing
RCP 8.5	2050	MAP	309.00	311.00	NA	NA	NA	NA	NA	Increasing
	2050	MAT	10.73	13.73	100.00	3.01	0.00	NA	3.01	Increasing
	2050	MM_Corr	-0.13	-0.17	0.00	NA	100.00	-0.03	-0.03	Decreasing
	2050	PSeas	26.37	33.71	100.00	7.35	0.00	NA	7.35	Increasing
	2050	Trange	43.38	42.85	NA	NA	NA	NA	NA	Decreasing
	2050	Summer_Aridity	0.13	0.11	0.00	NA	100.00	-0.02	-0.02	Decreasing
	2070	MAP	309.00	301.00	NA	NA	NA	NA	NA	Decreasing
	2070	MAT	10.73	15.61	100.00	4.88	0.00	NA	4.88	Increasing
	2070	MM_Corr	-0.13	-0.20	NA	NA	NA	NA	NA	Decreasing
	2070	PSeas	26.37	34.75	100.00	8.39	0.00	NA	8.39	Increasing
	2070	Trange	43.38	43.35	NA	NA	NA	NA	NA	Decreasing
	2070	Summer_Aridity	0.13	0.09	0.00	NA	100.00	-0.03	-0.03	Decreasing

Table A.3.14. Changes in habitat suitability for Hovenweep National Monument. Habitat suitability (lambda) values for the 11 grass species for Hovenweep National Monument showing historical (1970–2000) lambda, long term future (2070) lambda for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for representative concentration pathway (RCP) 8.5, overall mean robust change in lambda, the percent area (pixel-wise) where lambda is robustly increasing and decreasing, and the mean lambda values for regions of robust increase and decrease. Orange-, magenta-, and beige-labeled rows indicate robust decreases, increases, and neutral shifts in habitat suitability, respectively, for each given species × RCP × time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% + λ)	Pos (+ λ)	Percent area decreasing (% - λ)	Neg (- λ)	Mean robust change ($\Delta\lambda$)	Direction of change
RCP 4.5	2050	C3	<i>A. hymenoides</i>	0.339	0.330	NA	NA	NA	NA	NA	Decreasing
	2050	C3	<i>E. elymoides</i>	0.225	0.148	0.00	NA	100.00	-0.006	-0.006	Decreasing
	2050	C3	<i>H. comata</i>	0.052	0.032	0.00	NA	100.00	-0.019	-0.019	Decreasing
	2050	C3	<i>P. smithii</i>	0.013	0.006	0.00	NA	100.00	-0.004	-0.004	Decreasing
	2050	C3	<i>P. secunda</i>	0.166	0.056	0.00	NA	100.00	-0.008	-0.008	Decreasing
	2050	C4	<i>A. purpurea</i>	0.016	0.040	100.00	0.012	0.00	NA	0.012	Increasing
	2050	C4	<i>B. eriopoda</i>	0.043	0.082	100.00	0.038	0.00	NA	0.038	Increasing
	2050	C4	<i>B. gracilis</i>	0.072	0.037	NA	NA	NA	NA	NA	Decreasing
	2050	C4	<i>P. jamesii</i>	0.018	0.018	NA	NA	NA	NA	NA	Neutral
	2050	C4	<i>S. airoides</i>	0.010	0.014	100.00	0.008	0.00	NA	0.008	Increasing
	2050	C4	<i>S. cryptandrus</i>	0.022	0.027	100.00	0.053	0.00	NA	0.053	Increasing
	2070	C3	<i>A. hymenoides</i>	0.339	0.321	NA	NA	NA	NA	NA	Decreasing
	2070	C3	<i>E. elymoides</i>	0.225	0.132	0.00	NA	100.00	-0.007	-0.007	Decreasing
	2070	C3	<i>H. comata</i>	0.052	0.029	0.00	NA	100.00	-0.023	-0.023	Decreasing
	2070	C3	<i>P. smithii</i>	0.013	0.005	0.00	NA	100.00	-0.004	-0.004	Decreasing
	2070	C3	<i>P. secunda</i>	0.166	0.036	0.00	NA	100.00	-0.009	-0.009	Decreasing
	2070	C4	<i>A. purpurea</i>	0.016	0.047	NA	NA	NA	NA	NA	Increasing
	2070	C4	<i>B. eriopoda</i>	0.043	0.096	100.00	0.047	0.00	NA	0.047	Increasing
	2070	C4	<i>B. gracilis</i>	0.072	0.049	NA	NA	NA	NA	NA	Decreasing
	2070	C4	<i>P. jamesii</i>	0.018	0.023	NA	NA	NA	NA	NA	Increasing
	2070	C4	<i>S. airoides</i>	0.010	0.018	NA	NA	NA	NA	NA	Increasing

Table A.3.14 (continued). Changes in habitat suitability for Hovenweep National Monument. Habitat suitability (λ) values for the 11 grass species for Hovenweep National Monument showing historical (1970–2000) λ , long term future (2070) λ for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for representative concentration pathway (RCP) 8.5, overall mean robust change in λ , the percent area (pixel-wise) where λ is robustly increasing and decreasing, and the mean λ values for regions of robust increase and decrease. Orange-, magenta-, and beige-labeled rows indicate robust decreases, increases, and neutral shifts in habitat suitability, respectively, for each given species $\times$ RCP $\times$ time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% $+\lambda$)	Pos (+ λ)	Percent area decreasing (% $-\lambda$)	Neg (- λ)	Mean robust change ($\Delta\lambda$)	Direction of change
RCP 4.5 (cont.)	2070	C4	<i>S. cryptandrus</i>	0.022	0.024	100.00	0.031	00.00	NA	0.031	Increasing
RCP 8.5	2050	C3	<i>A. hymenoides</i>	0.339	0.315	NA	NA	NA	NA	NA	Decreasing
	2050	C3	<i>E. elymoides</i>	0.225	0.124	0.00	NA	100.00	-0.008	-0.008	Decreasing
	2050	C3	<i>H. comata</i>	0.052	0.027	0.00	NA	100.00	-0.023	-0.023	Decreasing
	2050	C3	<i>P. smithii</i>	0.013	0.005	0.00	NA	100.00	-0.004	-0.004	Decreasing
	2050	C3	<i>P. secunda</i>	0.166	0.034	0.00	NA	100.00	-0.010	-0.010	Decreasing
	2050	C4	<i>A. purpurea</i>	0.016	0.044	NA	NA	NA	NA	NA	Increasing
	2050	C4	<i>B. eriopoda</i>	0.043	0.089	100.00	0.043	0.00	NA	0.043	Increasing
	2050	C4	<i>B. gracilis</i>	0.072	0.036	NA	NA	NA	NA	NA	Decreasing
	2050	C4	<i>P. jamesii</i>	0.018	0.021	NA	NA	NA	NA	NA	Increasing
	2050	C4	<i>S. airoides</i>	0.010	0.017	100.00	0.012	0.00	NA	0.012	Increasing
	2050	C4	<i>S. cryptandrus</i>	0.022	0.023	NA	NA	NA	NA	NA	Increasing
	2070	C3	<i>A. hymenoides</i>	0.339	0.320	NA	NA	NA	NA	NA	Neutral
	2070	C3	<i>E. elymoides</i>	0.225	0.091	0.00	NA	100.00	-0.010	-0.010	Decreasing
	2070	C3	<i>H. comata</i>	0.052	0.016	0.00	NA	100.00	-0.038	-0.038	Decreasing
	2070	C3	<i>P. smithii</i>	0.013	0.002	0.00	NA	100.00	-0.006	-0.006	Decreasing
	2070	C3	<i>P. secunda</i>	0.166	0.014	0.00	NA	100.00	-0.011	-0.011	Decreasing
	2070	C4	<i>A. purpurea</i>	0.016	0.058	100.00	0.021	0.00	NA	0.021	Increasing
	2070	C4	<i>B. eriopoda</i>	0.043	0.043	NA	NA	NA	NA	NA	Neutral
	2070	C4	<i>B. gracilis</i>	0.072	0.014	0.00	NA	100.00	-0.006	-0.006	Decreasing

Table A.3.14 (continued). Changes in habitat suitability for Hovenweep National Monument. Habitat suitability (λ) values for the 11 grass species for Hovenweep National Monument showing historical (1970–2000) λ , long term future (2070) λ for the 50th quantile of the ensemble of 17 global circulation models (GCMs) for representative concentration pathway (RCP) 8.5, overall mean robust change in λ , the percent area (pixel-wise) where λ is robustly increasing and decreasing, and the mean λ values for regions of robust increase and decrease. Orange-, magenta-, and beige-labeled rows indicate robust decreases, increases, and neutral shifts in habitat suitability, respectively, for each given species $\times$ RCP $\times$ time period combination.

RCP	Time period	Carbon fixation pathway	Species	Historical λ (1970–2000)	Future λ (Ensem 50th quant.)	Percent area increasing (% $+\lambda$)	Pos (+ λ)	Percent area decreasing (% $-\lambda$)	Neg (- λ)	Mean robust change ($\Delta\lambda$)	Direction of change
RCP 8.5 (cont.)	2070	C4	<i>P. jamesii</i>	0.018	0.022	NA	NA	NA	NA	NA	Increasing
	2070	C4	<i>S. airoides</i>	0.010	0.021	100.00	0.018	0.00	NA	0.018	Increasing
	2070	C4	<i>S. cryptandrus</i>	0.022	0.021	NA	NA	NA	NA	NA	Neutral

Table A.3.15. Environmental covariates included in the final species distribution models (SDMs) for 11 grassland species in the western United States. C₃ species are the top 5 rows; C₄ species are the bottom six rows. MAP = mean annual precipitation; PTcorr = correlation between monthly mean precipitation and temperature; MAT = mean annual temperature; PSeas = coefficient of variation in monthly precipitation; TRange = difference between maximum and minimum monthly temperature. This table is a more accessible version of Figure 19.

Species	Functional Type	Covariates included in the distribution models (Yes or No)								
		MAP	PTcorr	MAT	PSeas	Summer aridity	TRange	Soil depth	Soil sand	Soil clay
<i>A. hymenoides</i>	C ₃	Yes	Yes	No	No	No	Yes	Yes	No	Yes
<i>E. elymoides</i>	C ₃	No	Yes	Yes	Yes	No	Yes	No	Yes	Yes
<i>H. comata</i>	C ₃	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
<i>P. smithii</i>	C ₃	No	Yes	Yes	No	No	Yes	Yes	Yes	No
<i>P. Secunda</i>	C ₃	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<i>A. purpurea</i>	C ₄	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes
<i>B. eriopoda</i>	C ₄	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes
<i>B. gracillis</i>	C ₄	Yes	Yes	Yes	No	No	No	No	Yes	Yes
<i>P. jamesii</i>	C ₄	No	Yes	No	No	Yes	No	No	Yes	Yes
<i>S. airoides</i>	C ₄	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes
<i>S. cryptandrus</i>	C ₄	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes

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