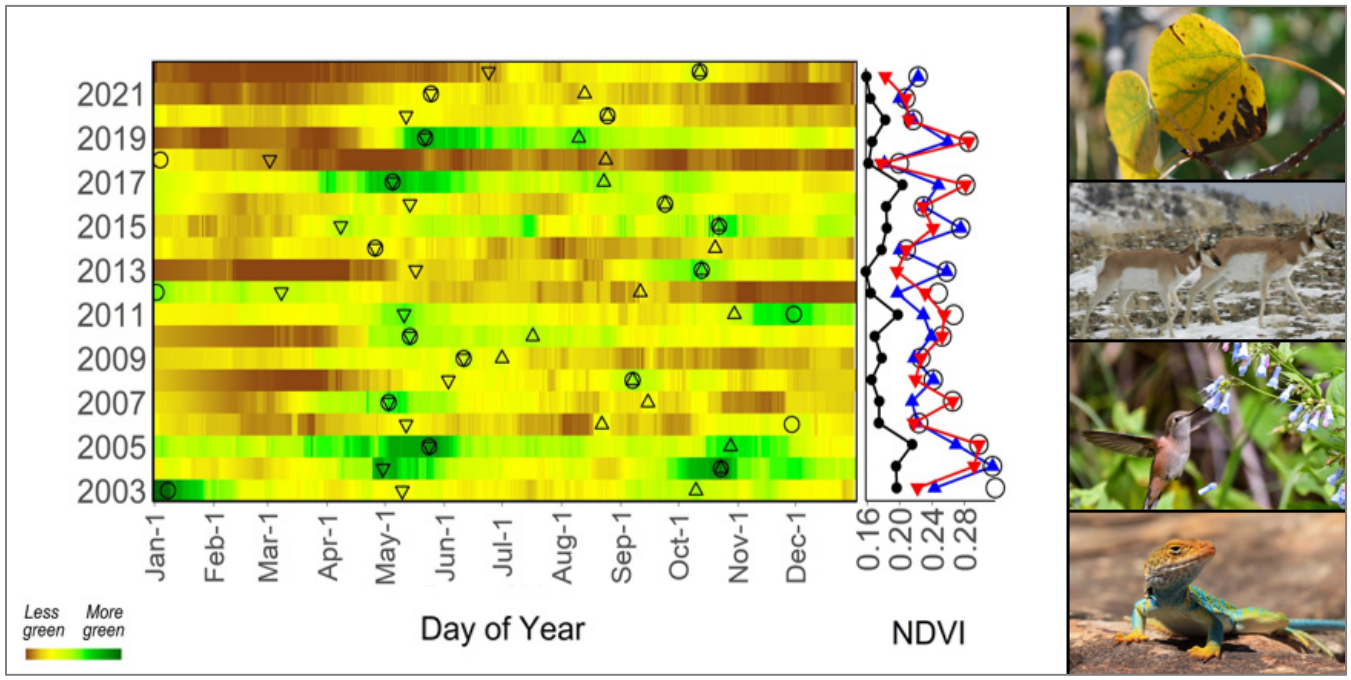
National Park Service
U.S. Department of the Interior

Science Report NPS/SR—2025/319
https://doi.org/10.36967/2312720

Trends in Satellite-Derived Phenology in Grasslands and Shrublands of Southern Colorado Plateau Network Parks



Utilizing heat maps to monitor vegetation phenology shows the variability from year to year of peak greenness and when seasonal changes begin, like with Quaking Aspen (*Populus tremuloides*) trees. Wildlife, such as the pronghorn *(Antilocapra americana*), rufous hummingbirds (*Selasphorus rufus*), and common collared lizards (*Crotaphytus collaris*) depends on the timing and abundance of vegetation for survival.

CLOCKWISE FROM LEFT: NPS / JODI NORRIS; D. LEHLE; JIM PEACO; DYLAN HANOR; NPS / CARLA DE KALB

Trends in satellite-derived phenology in grasslands and shrublands of Southern Colorado Plateau Network parks

Science Report NPS/SR—2025/319

Jodi R. Norris[1]

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

Christopher Calvo[1], editor

Please cite this publication as:

Norris, J. R. 2025. Trends in satellite-derived phenology in grasslands and shrublands of Southern Colorado Plateau Network parks. Science Report NPS/SR—2025/319. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/2312720

NPS 960/197295, June 2025

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

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

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

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

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

Contents

Page

Figures v
Tables x
Abstract xi
List of Terms or Acronyms xii
Park Units xii
Acknowledgments xiii
Introduction and Background 1
Drivers of Dryland Phenology 1
Average Phenological Pattern 2
Interannual Variability 3
Projected Shifts with Climate Change and Current Megadrought 3
Study Areas 6
Target Ecosystems 6
Study Area Delineation 9
Climate 9
Climate Averages and Historical Record 12
Vegetation 14
Methods 16
Season Definitions 16
MODIS Satellite Data Processing and Trend Analysis 16
Overview 16
Compilation of Daily NDVI Record for Each 250 m Pixel 17
Calculation of Daily NDVI for Three Productivity Levels 17
Trend Analyses 17
Raster Graph Visualizations 21
Results and Discussion 22
Daily and Peak Seasonal NDVI Values 22
Die-Off and Disturbance Indicators 25

Contents (continued)

Page

Relative Size of Spring and Monsoon NDVI Peaks 26
Ranked-Day NDVI Trends 27
Overview 27
Ranked-Day Trend Analysis 32
Likelihood vs. Threshold p-values 32
Seasonal Differences in Ranked-Day Trends 32
More and Less Productive Study Area Pixels 32
Further Topics of Investigation 33
Conclusions 34
Study Area Phenological Characteristics 34
Trend Analyses 34
Management Implications and Future Research 34
Study Area Phenology Visualizations and Covariates 34
Disturbance and Multiyear Drought Event Recording 35
Utility of Trend Information 35
Literature Cited 37
Appendix 43

Figures

Page

Figure 1. Typical Colorado Plateau grassland and shrubland phenological cycles showing average patterns, patterns of interannual variability, and projected future patterns of greenness. 2

Figure 2. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in Petrified Forest National Park. 5

Figure 3. Map of park units and study areas included in this report. 8

Figure 4. Historical record of winter/spring- and monsoon-season precipitation for each study area. 10

Figure 5. Historical record of spring- and monsoon-season temperature for each study area. 11

Figure 6. Spring and monsoon season climate patterns across the study areas. 13

Figure 7. Average relative percent cover of grasses, shrubs, and forbs for the study areas. 14

Figure 8. Conceptual diagram of the steps used in ranked-day trend analysis. 19

Figure 9. Raster graphs showing phenological patterns of smoothed NDVI for the 20-year analysis period for 6 of the 12 study areas including the park units AZRU, CHCU, GLCA, and PETR. 23

Figure 10. Raster graph showing phenological patterns of smoothed NDVI for the 20-year period of record for 6 of the 12 study areas including the park units PEFO and WUPA. 24

Figure 11. Size and frequency of spring-season vs. monsoon-season NDVI peaks. 26

Figure 12. Ranked-day NDVI trend estimates for the spring season for 6 of the 12 study areas including the park units AZRU, CHCU, GLCA and PEFO. 28

Figure 13. Ranked-day NDVI trend estimates for the spring season for 6 of the 12 study areas including the park units PEFO, PETR, and WUPA. 29

Figure 14. Ranked-day trend estimation results for the monsoon season for 6 of the 12 study areas including the park units AZRU, CHCU, GLCA and PEFO. 30

Figure 15. Ranked-day trend estimation results for the monsoon season for 6 of the 12 study areas including the park units PEFO, PETR and WUPA. 31

Figure 16. Conceptual diagram of the steps used in ranked-day trend analysis. 44

Figure 17. Map of MODIS pixel centers used for analysis at Aztec Ruins NM. 46

Figures (continued)

Page

Figure 18. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Aztec Ruins NM Limy Upland Shrubland study area. 47

Figure 19. Ranked-day NDVI trend estimates for the spring season for the Aztec Ruins Limy Upland Shrubland study area. 48

Figure 20. Ranked-day NDVI trend estimates for the monsoon season for the Aztec Ruins NM Limy Upland Shrubland study area. 49

Figure 21. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in Aztec Ruins NM. 50

Figure 22. Map of MODIS pixel centers used for analysis at Chaco Culture NHP. 51

Figure 23. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Chaco Culture NHP Sandy Loam Upland Grassland study area. 52

Figure 24. Ranked-day NDVI trend estimates for the spring season for the Chaco Culture NHP Sandy Loam Upland Grassland study area. 53

Figure 25. Ranked-day NDVI trend estimates for the monsoon season for the Chaco Culture NHP Sandy Loam Upland Grassland study area. 54

Figure 26. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in Chaco Culture NHP. 55

Figure 27. Map of MODIS pixel centers used for analysis at Glen Canyon NRA. 56

Figure 28. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Bullfrog Area of the Glen Canyon NRA Desert Sand Shrubland study area. 57

Figure 29. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Hole in the Rock Area of the Glen Canyon NRA Desert Sand Shrubland study area. 58

Figure 30. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Page Area of the Glen Canyon NRA Desert Sand Shrubland study area. 59

Figure 31. Ranked-day NDVI trend estimates for the spring season for the Bullfrog Area of the Glen Canyon NRA Desert Sand Shrubland study area. 60

Figure 32. Ranked-day NDVI trend estimates for the spring season for the Hole in the Rock area of the Glen Canyon NRA Desert Sand Shrubland study area. 61

Figures (continued)

Page

Figure 33. Ranked-day NDVI trend estimates for the spring season for the Page Area of the Glen Canyon NRA Desert Sand Shrubland study area. 62

Figure 34. Ranked-day NDVI trend estimates for the monsoon season for the Bullfrog Area of the Glen Canyon NRA Desert Sand Shrubland study area. 63

Figure 35. Ranked-day NDVI trend estimates for the monsoon season for the Hole in the Rock Area of the Glen Canyon NRA Desert Sand Shrubland study area. 64

Figure 36. Ranked-day NDVI trend estimates for the monsoon season for the Page Area of the Glen Canyon NRA Desert Sand Shrubland study area. 65

Figure 37. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Bullfrog Area of the Glen Canyon NRA Desert Sand Shrubland study area. 66

Figure 38. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Hole in the Rock Area of the Glen Canyon NRA Desert Sand Shrubland study area. 67

Figure 39. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Page Area of the Glen Canyon NRA Desert Sand Shrubland study area. 68

Figure 40. Map of MODIS pixel centers used for analysis at Petrified Forest NP. 69

Figure 41. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Petrified Forest NP Clayey Fan Grassland, Expansion Lands study area. 70

Figure 42. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Petrified Forest NP Clayey Fan Grassland, Pre-expansion Area study area. 71

Figure 43. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Petrified Forest NP Sandy Loam Upland Grassland, Expansion Lands study area. 72

Figure 44. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Petrified Forest NP Sandy Loam Upland Grassland, Pre-expansion Area study area. 73

Figure 45. Ranked-day NDVI trend estimates for the spring season for the Petrified Forest NP Clayey Fan Grassland, Expansion Lands study area. 74

Figures (continued)

Page

Figure 46. Ranked-day NDVI trend estimates for the spring season for the Petrified Forest NP Clayey Fan Grassland, Pre-expansion Area study area. 75

Figure 47. Ranked-day NDVI trend estimates for the spring season for the Petrified Forest NP Sandy Loam Upland Grassland, Expansion Lands study area. 76

Figure 48. Ranked-day NDVI trend estimates for the spring season for the Petrified Forest NP Sandy Loam Upland Grassland, Pre-expansion Area study area..... 77

Figure 49. Ranked-day NDVI trend estimates for the monsoon season for the Petrified Forest NP Clayey Fan Grassland, Expansion Lands study area. 78

Figure 50. Ranked-day NDVI trend estimates for the monsoon season for the Petrified Forest NP Clayey Fan Grassland, Pre-expansion Area study area. 79

Figure 51. Ranked-day NDVI trend estimates for the monsoon season for the Petrified Forest NP Sandy Loam Upland Grassland, Expansion Lands study area. 80

Figure 52. Ranked-day NDVI trend estimates for the monsoon season for the Petrified Forest NP Sandy Loam Upland Grassland, Pre-expansion Area study area..... 81

Figure 53. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Petrified Forest NP Clayey Fan Grassland study area. 82

Figure 54. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Petrified Forest NP Sandy Loam Upland Grassland study area. 83

Figure 55. Map of MODIS pixel centers used for analysis at Petroglyph NM. 84

Figure 56. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Petroglyph NM Malpais Grassland study area..... 85

Figure 57. Ranked-day NDVI trend estimates for the spring season for the Petroglyph NM Malpais Grassland study area. 86

Figure 58. Ranked-day NDVI trend estimates for the monsoon season for the Petroglyph NM Malpais Grassland study area. 87

Figure 59. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Petroglyph NM Malpais Grassland study area. 88

Figure 60. Map of MODIS pixel centers used for analysis at Wupatki NM..... 89

Figures (continued)

Page

Figure 61. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Wupatki NM Loamy Upland Shrubland study area. 90

Figure 62. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Wupatki NM Volcanic Upland Grassland study area. 91

Figure 63. Ranked-day NDVI trend estimates for the spring season for the Wupatki NM Loamy Upland Shrubland study area. 92

Figure 64. Ranked-day NDVI trend estimates for the spring season for the Wupatki NM Volcanic Upland Grassland study area. 93

Figure 65. Ranked-day NDVI trend estimates for the monsoon season for the Wupatki NM Loamy Upland Shrubland study area. 94

Figure 66. Ranked-day NDVI trend estimates for the monsoon season for the Wupatki NM Volcanic Upland Grassland study area. 95

Figure 67. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Wupatki NM Loamy Upland Shrubland study area. 96

Figure 68. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Wupatki NM Volcanic Upland Grassland study area. 97

Tables

Page

Table 1. SCPN Phenology study area names and identifiers, including park name, ecosystem name, subarea name, and study area identifiers. 7

Table 2. Predominant plant taxa found in corresponding upland plots within the study areas. 15

Abstract

Purpose: The Southern Colorado Plateau Network (SCPN) used satellite-derived normalized difference vegetation index (NDVI) data over a 20-year period (2003–2022) to examine trends and patterns of variability in 12 grassland and shrubland study areas within SCPN park units.

Methods: SCPN developed daily NDVI records for each study area, from which analyses and visualizations were derived. Raster graphs were created to facilitate data interpretation. Trends were calculated for each ranked day of the spring and monsoon seasons: For each study area, season, and year, each day was ranked from the highest NDVI value to the lowest. Total NDVI change was then estimated for the spring and monsoon season NDVI peaks (day-rank = 1) as well as all other non-peak day ranks for each season. The same analyses were also applied to subsets of pixels corresponding to more productive and less productive pixels within each study area.

Results: The study areas had many “likely” trends in NDVI for ranked-daily values, with a smaller number of “very likely” and “highly likely” trends. Monsoon season trends were consistently negative or neutral for more northerly parks—Aztec Ruins National Monument (NM), Chaco Culture National Historical Park (NHP), and Glen Canyon National Recreation Area (NRA); and consistently positive or neutral for more southerly parks—Petrified Forest National Park (NP), Petroglyph NM, and Wupatki NM. Spring season trends varied spatially and included both positive and negative trends. Aztec Ruins NM and Glen Canyon NRA exhibited consistently negative or neutral trends for both seasons.

Raster graphs revealed patterns including the variability in timing and intensity of seasonal greenness peaks and multi-year patterns. The raster graphs and associated data release can be used to evaluate the potential for the phenological patterns to correlate with on-the-ground conditions for wildlife resources that depend on vegetation. These data may also be used to parameterize models that relate climate to vegetation condition.

Multi-year consecutive seasons of below-average NDVI were found in some records: At Wupatki NM, low NDVI from spring 2017 to spring 2021 corresponded in time with a widespread juniper dieback in 2021 in the adjacent pinyon-juniper woodlands of the area. Consecutive seasons of low NDVI also occurred in Petroglyph NM from 2008 to 2013 and at Aztec Ruins NM from 2020 to 2022. These records show the potential to link plant community stress to disturbance response thresholds, which is a subject of ongoing SCPN research.

List of Terms or Acronyms

NDVI: Normalized Difference Vegetation Index

MODIS: Moderate Resolution Imaging Spectroradiometer

NHP: National Historical Park

NM: National Monument

NP: National Park

NPS: National Park Service

NRCS: Natural Resources Conservation Service

PRISM: Parameter-elevation Regressions on Independent Slopes Model

SCPN: Southern Colorado Plateau Network

SSURGO: Soil Survey Geographic Database

NRA: National Recreation Area

Park Units

AZRU: Aztec Ruins National Monument

CHCU: Chaco Culture National Historical Park

GLCA: Glen Canyon National Recreation Area

PEFO: Petrified Forest National Park

PETR: Petroglyph National Monument

WUPA: Wupatki National Monument

Acknowledgments

This report greatly benefited from comments and suggestions of Michael Hamman, Dana Hawkins, Matthew Johnson, and David Thoma. Kristin Straka created and improved each of the numerous maps in the report and appendix. Jean Palumbo (volunteer) provided many hours of editorial assistance, helping to reduce technical language and improve the organization and explanation of technical concepts. Christopher Calvo edited and provided improvements to figures, layout, and wording. Cindy Parker assisted in maintaining the SQL Server database instances used to store and process data. Laura Ploughe guided the creation of the associated data release.

Introduction and Background

The Southern Colorado Plateau Network (SCPN) of the National Park Service (NPS) Inventory and Monitoring Program is composed of 19 separate park units covering over 1.2 million hectares. Grassland and shrubland plant communities cover large areas of the SCPN (Thomas et al. 2006). Like most dryland plant communities, SCPN communities are vulnerable to changing climate, invasive species, and local stressors (Miller 2005). Monitoring the phenology and condition of grasslands and shrublands using satellite data is one of the goals of the SCPN Inventory and Monitoring Program. Satellite-derived phenology (also called "land surface phenology") refers to annual seasonal timing and intensity of vegetation greenness, as measured by satellites. Land surface phenology data provide useful information about plant communities' condition through time and their responses to climate variability and change (White et al. 2005, White et al. 2009).

This study summarizes and analyzes satellite-derived phenology data in order to provide status and trend information for twelve grassland and shrubland study areas within eight ecosystems of six SCPN park units. These study areas correspond to ecosystems selected for SCPN ground-based upland vegetation monitoring (DeCoster 2009, DeCoster and Swan 2009a and b, Swan 2024).

Drivers of Dryland Phenology

In the southwestern United States, measuring phenology in drylands can be particularly challenging because plant growth is not only controlled by seasonal temperatures but also by moisture availability, which is often variable in both amount and timing (Jolly et al. 2005, White et al. 2009, Hereford and Webb 1992, Leung et al. 2023), as depicted in Figure 1.

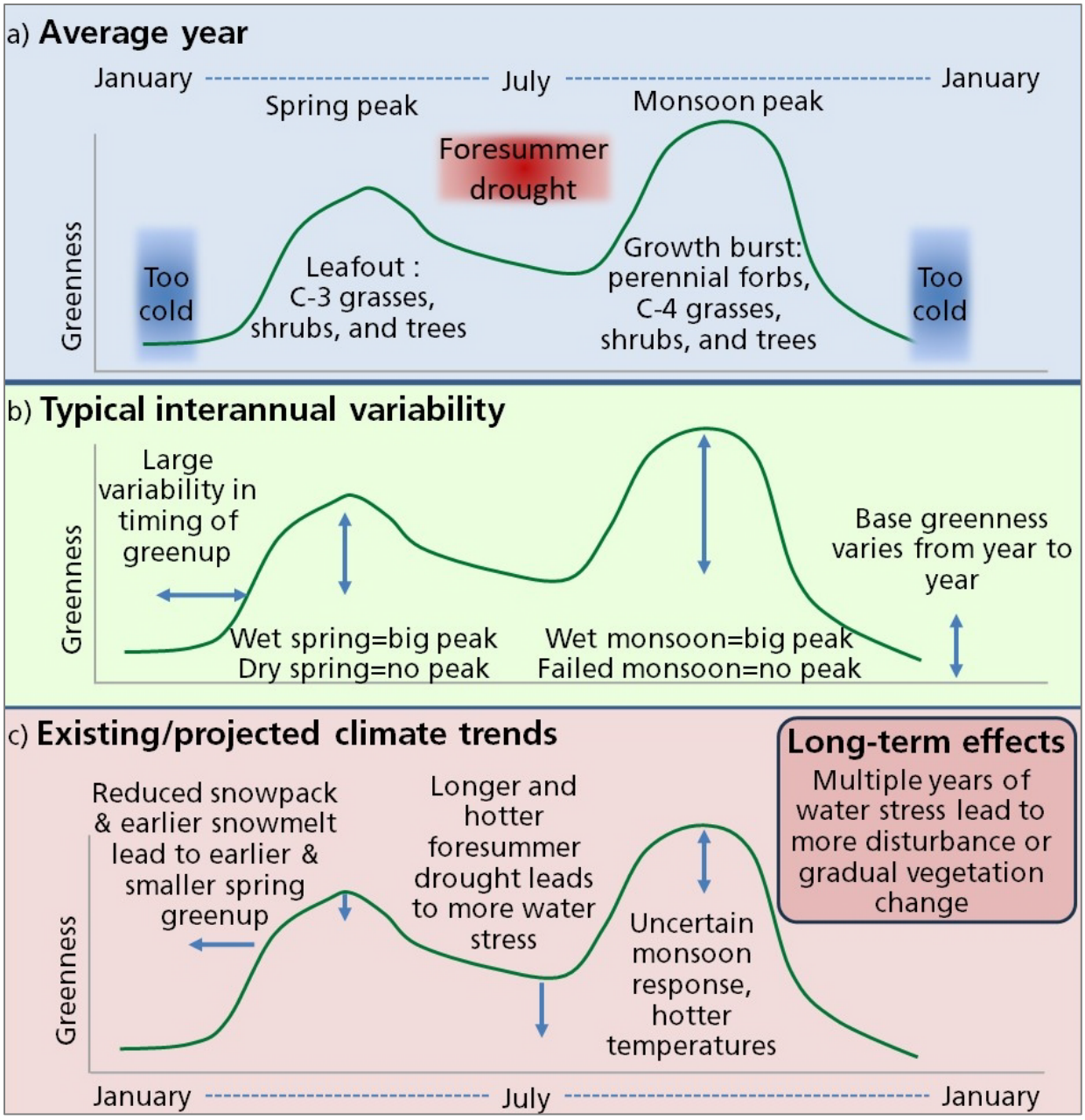


Figure 1. Typical Colorado Plateau grassland and shrubland phenological cycles showing average patterns, patterns of interannual variability, and projected future patterns of greenness. a) example of the average annual greenness cycle on the Southern Colorado Plateau, b) common forms of interannual variability on the Southern Colorado Plateau, and c) projected effects of climate change on land surface phenology. Figure modified from Thoma et al. (2017).
NPS / JODI NORRIS

Average Phenological Pattern

On the Southern Colorado Plateau, precipitation is commonly bimodal, occurring mostly in winter and late summer (Garfin et al. 2010, Leung et al. 2023). In winter, nights often have subfreezing temperatures, and soil moisture is typically at its highest. In both summer and winter, air moisture

(humidity) varies on a daily-to-weekly scale with diurnal variations and passing weather fronts (winter) or monsoon moisture incursions (summer). This pattern of temperature and moisture availability leads to a generally bimodal pattern of vegetation growth (Figure 1, Thoma et al. (2017)). The first growth period occurs in spring as temperatures increase enough to allow plant growth, and before the winter soil moisture has been depleted. The second period of growth occurs during the late summer and early autumn, due to the precipitation and humidity provided by the North American Monsoon.

Interannual Variability

Highly variable precipitation from year to year leads to high variability in vegetation response (Thoma et al. 2017). Because of this variability, both the spring and monsoon vegetation peaks can range from very strong to completely absent (Figure 1b).

Projected Shifts with Climate Change and Current Megadrought

Figure 1c shows the projected effects of climate change on Colorado Plateau grasslands and shrublands. Climate and soil moisture projections exist for each of the ecosystems associated with the study areas (Andrews et al. 2019a, b, c, d, e, f, g, h, i). All the study areas are projected to have warmer temperatures, while precipitation projections are inconsistent among different climate models, with both positive and negative projections for both the winter and monsoon seasons. In springtime, soils are consistently predicted to dry earlier, limiting plant growth.

Although warming temperatures and drier springs are consistently predicted, interpretation of recent changes through time is complicated because the analysis period of this study began during a drought that was severe enough to cause a regional die-off of *Pinus edulis* in 2003 (Breshears et al. 2005). Overlapping with that drought, much of the southwestern U.S. has experienced a 22-year megadrought that encompasses this study's 20-year analysis period of record (Williams et al. 2022). This megadrought is estimated to be the driest 22-year period of record since at least 800 CE.

Plant species distributions can be expected to shift with climate change, and even within the range of individual species, there are typically populations genetically adapted to local climate conditions (Bothwell et al. 2021, Rehfeldt et al. 2006, Richardson et al. 2014). Examples can be found in the wide range of seedling survival rates when, in common garden studies, seeds from one location are planted in a climatically different location (Neale and Wheeler 2019). Thus, there is no assurance that a population will survive in a future climate, even if the future climate is within the overall climate niche of the species as a whole. To better identify climate similarities, St. Clair et al. (2022) developed the "Seedlot Selection Tool" to visualize how the climate conditions associated with local plant communities might shift with climate change. Their visualization tool lets users identify a reference site, and map locations whose existing climate conditions match predicted future conditions at the reference site. The output from this tool is shown for each study area in the Appendix (See example, Figure 2). The Seedlot Selection Tool results suggest that it may be necessary to look dozens to hundreds of miles away for plant populations that are genetically adapted to the expected future climate conditions.

A common feature among the projections derived from the Seedlot Selection Tool is that our study areas are predicted to become more climatically similar to Mojave Desert areas in southern Nevada and Northwestern Arizona, as well as some areas in south central New Mexico (Appendix). The Seedlot Selection Tool projections for the study areas are consistent with models and analyses made by Tercek at al. (2023), which examine areas where growing season dryness is severe enough that plant growth is expected to cease entirely for a portion of the growing season. Tercek et al. (2023) map these areas as occurring today largely in the Sonoran and Mojave deserts of the United States, with smaller areas present around Glen Canyon NRA and adjacent portions the lower Little Colorado drainage. However, they project the areas to expand by the end of the century, with most of their model analyses suggesting that areas with an episode of severe growing season dryness could expand across much of the Southern Colorado Plateau. When paired with the Seedlot Selection Tool visualizations, this suggests that SCPN park resource managers at the six NPS parks in our study may encounter conditions similar to those of the Mojave Desert or south-central New Mexico in the coming decades.

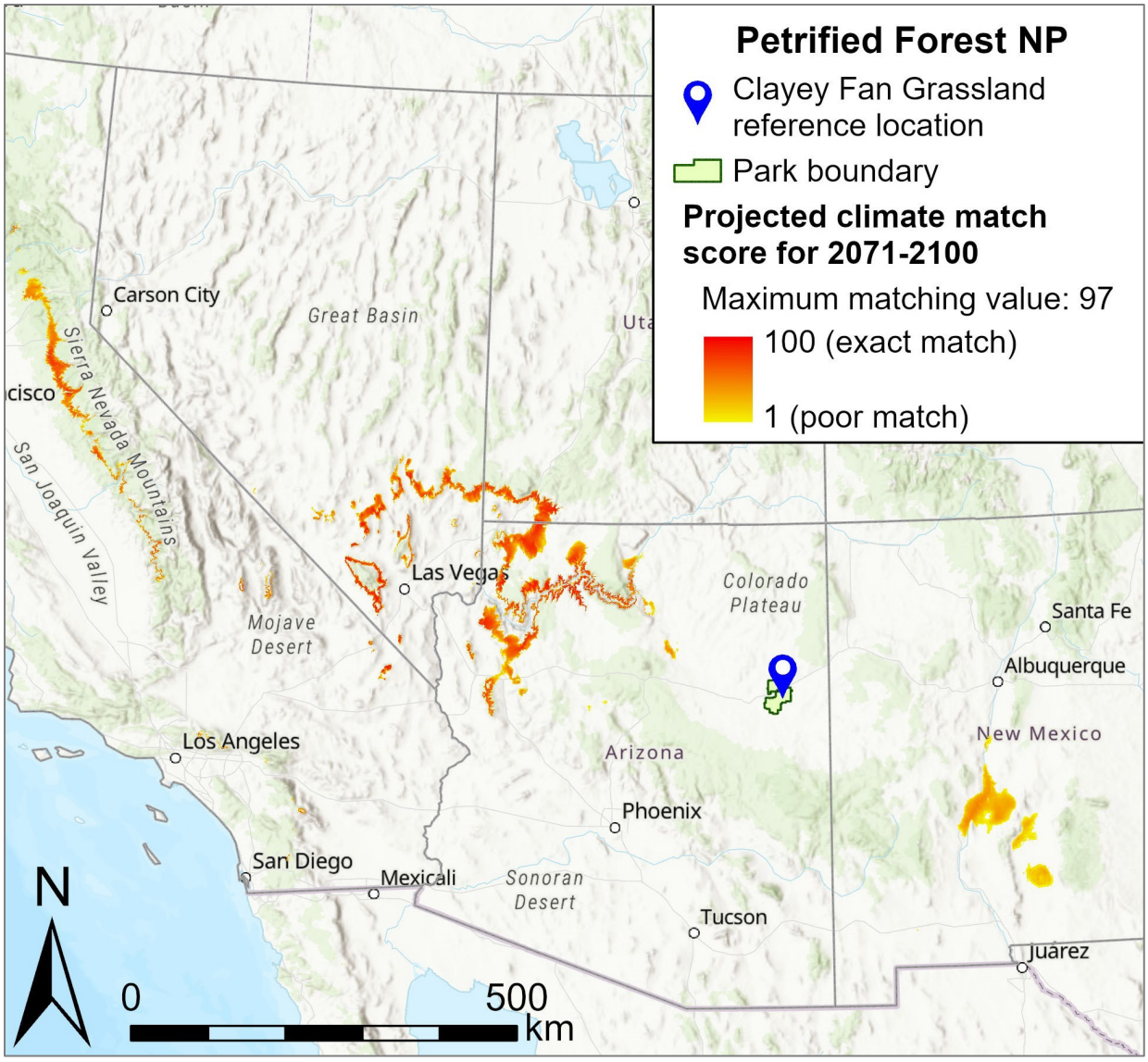


Figure 2. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in Petrified Forest National Park. Data are derived from Seedlot Selection Tool scores (St. Clair et al. 2022). Current climate was based on 1981–2010 normals. Projected climate was based on the years 2071–2100 using the Representative Concentration Pathways (RCP) 8.5 scenario. Settings used allowed liberal definitions of matches, requiring similarity in only three variables: Mean Coldest Month Temperature, Summer Heat Moisture Index, and Frost-Free Period. More conservative matches (using additional climate variables) resulted in little or no area with similar projected climate for most study areas. Settings and additional maps are provided in Appendix.

NPS / KRISTIN STRAKA

Study Areas

Target Ecosystems

A total of twelve study areas across eight ecosystems in six NPS park units were selected for analysis (Table 1, Figure 3). Ten of the twelve study areas were chosen to correspond with the extent of ecosystems and subareas monitored by SCPN using ground-based plots (DeCoster et al. 2012). The original ecosystem boundaries selected for ground-based monitoring were derived from the Natural Resources Conservation Service (NRCS) Ecological Site concept. An ecological site is a class of land with similar potential vegetation, soil, geomorphology, topographic position, and microclimate (Salley et al. 2016). Specific ecological sites chosen for monitoring were based on prioritization made by resource managers at each park (DeCoster et al. 2012). In two parks, ecosystem sub-areas were identified based on geography or park history. At Glen Canyon National Recreation Area (NRA), SCPN divided analysis of the Desert Sand Shrubland into three geographic areas because of its wide extent (Table 1, Figure 3). Petrified Forest National Park (NP) underwent significant expansion in 2004. Ownership of land within the expansion area was not conferred to the NPS by the boundary change, and ownership of these lands has changed gradually. Much of the expansion land area was grazed prior to the ownership change. To account for possible differences in response, both of the target ecosystems within Petrified Forest NP were divided for analysis into areas within the pre-2004 park boundary ("Pre-expansion Lands"), and areas acquired as a result of the 2004 expansion legislation ("Expansion Lands").

Table 1. SCPN Phenology study area names and identifiers, including park name, ecosystem name, subarea name, and study area identifiers.

Park	Ecosystem name	Subarea name	Study area identifier (for some figures)	Study area identifier correlating with ground-based integrated upland ecosystem monitoring
Aztec Ruins NM	Limy Upland Shrubland	–	AZRU_A_X	AZRU_A
Chaco Culture NHP	Sandy Loam Upland Grassland	–	CHCU_S_X	CHCU_S
Glen Canyon NRA	Desert Sand Shrubland	Bullfrog Area	GLCA_D_B	GLCA_B
Glen Canyon NRA	Desert Sand Shrubland	Hole-in-the-Rock Area	GLCA_D_H	GLCA_H
Glen Canyon NRA	Desert Sand Shrubland	Page Area	GLCA_D_P	GLCA_P
Petrified Forest NP	Sandy Loam Upland Grassland	Pre-expansion Lands	PEFO_S_O	PEFO_S
Petrified Forest NP	Sandy Loam Upland Grassland	Expansion Lands	PEFO_S_N	not monitored
Petrified Forest NP	Clayey Fan Grassland	Pre-expansion Lands	PEFO_C_O	PEFO_C
Petrified Forest NP	Clayey Fan Grassland	Expansion Lands	PEFO_C_N	not monitored
Petroglyph NM	Malpais Grassland	–	PETR_P_X	PETR_P
Wupatki NM	Volcanic Upland Grassland	–	WUPA_L_X	WUPA_L [A]
Wupatki NM	Loamy Upland Shrubland	–	WUPA_S_X	WUPA_S [B]

[A] The designation WUPA_L corresponds to the WUPA_V designation in some SCPN reports.

[B] The designation WUPA_S corresponds to the WUPA_L designation in some SCPN reports.

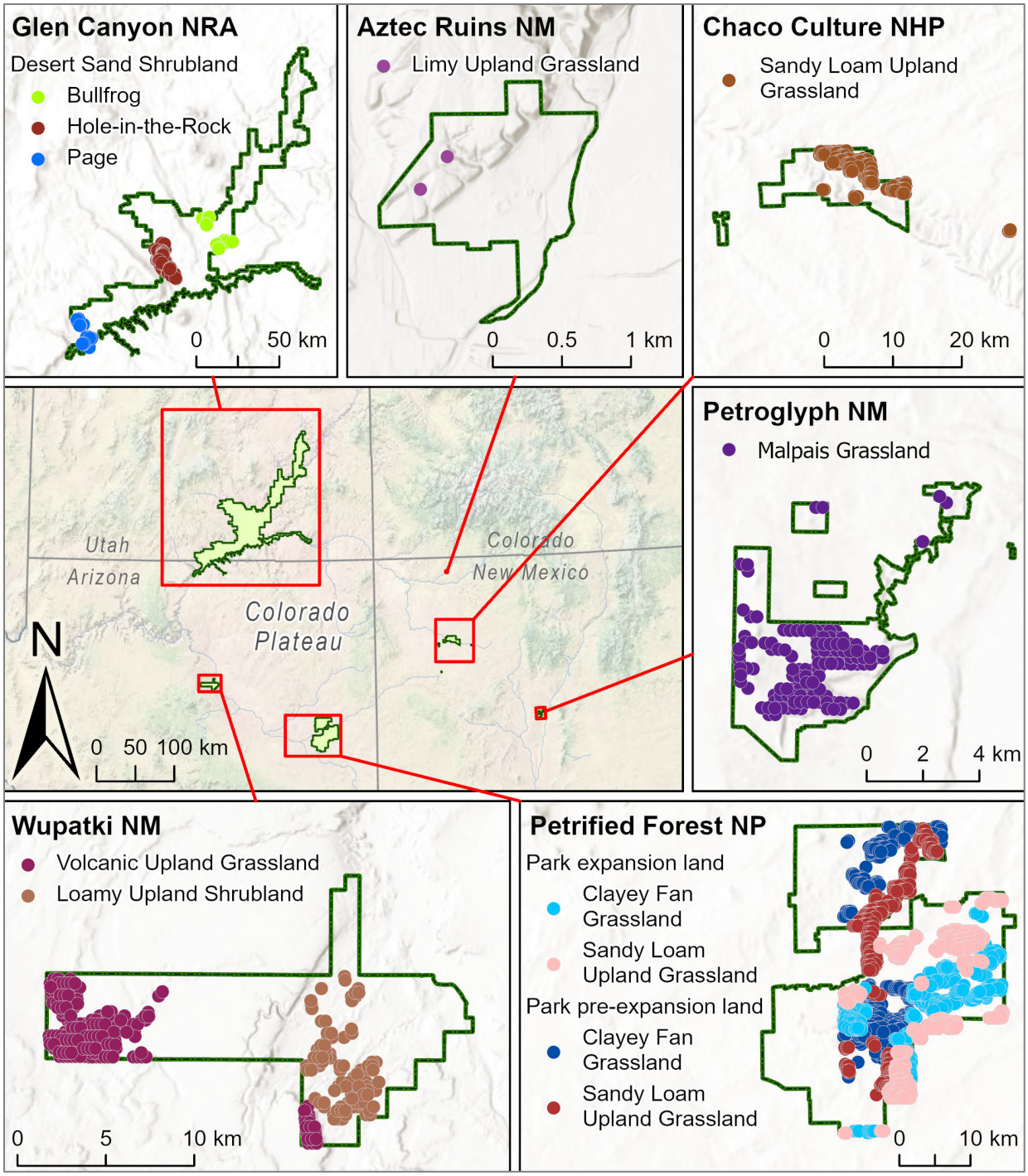


Figure 3. Map of park units and study areas included in this report. MODIS pixel centers are shown for each study area. Key includes park, ecosystem name, and subarea (if present). Base map sources include Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, USFWS.

NPS / KRISTIN STRAKA

Study Area Delineation

Study areas were delineated using the target soil (SSURGO) map units identified with the NRCS ecological sites chosen for ground-based monitoring (DeCoster et al. 2012, Norris 2020). Individual 250-m Moderate Resolution Imaging Spectroradiometer (MODIS) pixels were included in the analysis if at least 80% of an individual pixel's area was covered by the target SSURGO soil map unit(s) within the corresponding park (Norris 2020). A complete table of the MODIS pixel centers for each study area is included in the data release for this report (Norris and Ploughe 2025).

Climate

Climate across the study area varies seasonally and between years. Increases in temperature have consistently been observed across the region over the last century (Garfin et al. 2013), although for shorter, decadal scale periods the amount and direction of trend vary considerably (Figures 4 and 5, Parker et al. 2007, Johnson et al. 2020).

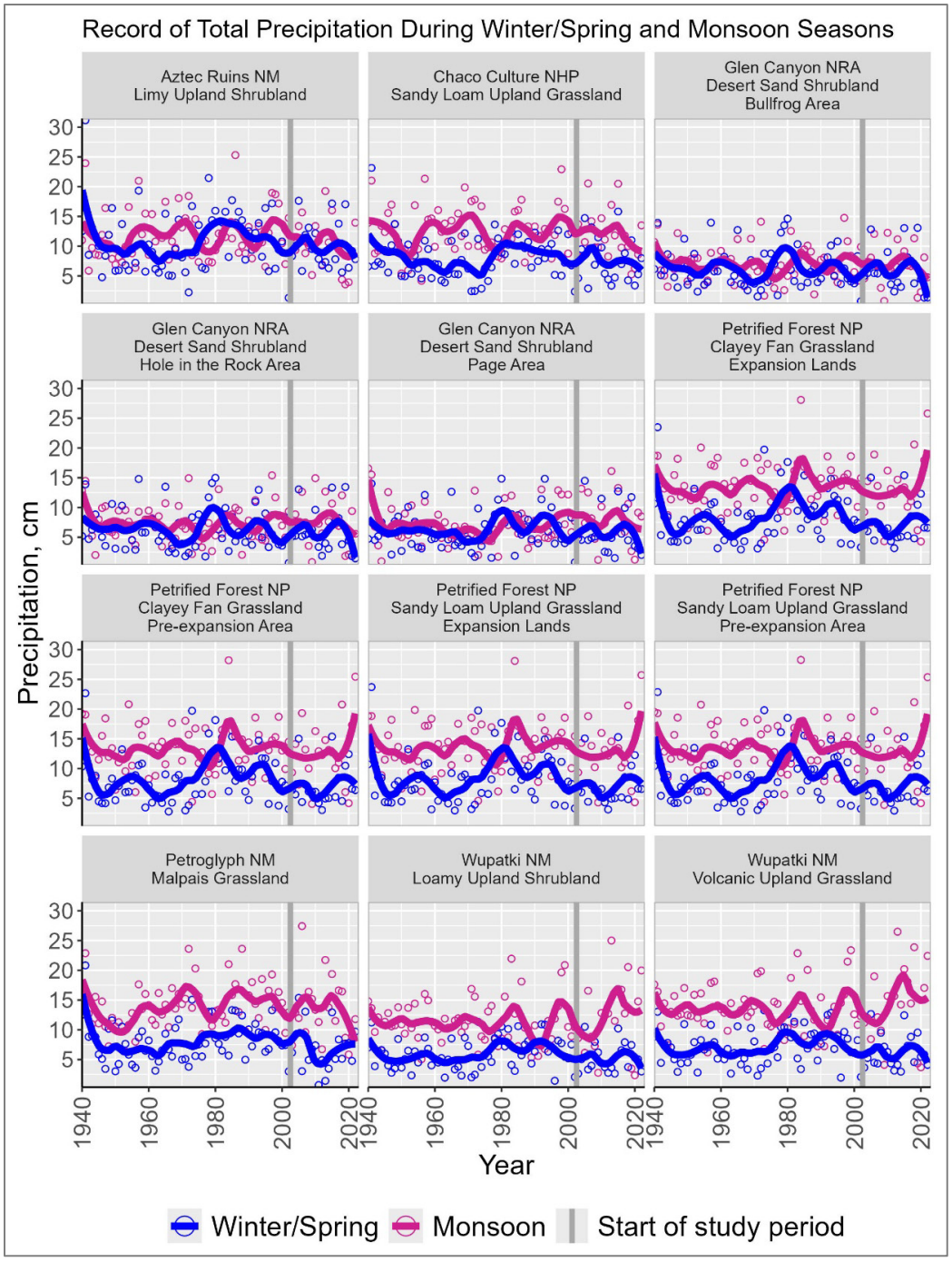


Figure 4. Historical record of winter/spring- and monsoon-season precipitation for each study area. Data derived from nClimGrid (~5 km gridded data, Vose et al., 2014). The nClimGrid dataset is suitable for viewing trends because it is adjusted to correct for non-climate-related shifts through time, such as shifts caused by instrument changes. Precipitation units are sums across the season in cm. “Winter/Spring” season refers to January, February, March, April, May, and June; “monsoon” season refers to July, August, September, October. Data are available in associated data release (Norris and Ploughe 2024). Early years of record (~1900–1939) were not included in the graphs because of the poor overall weather station data record in the region at that time.

NPS / JODI NORRIS

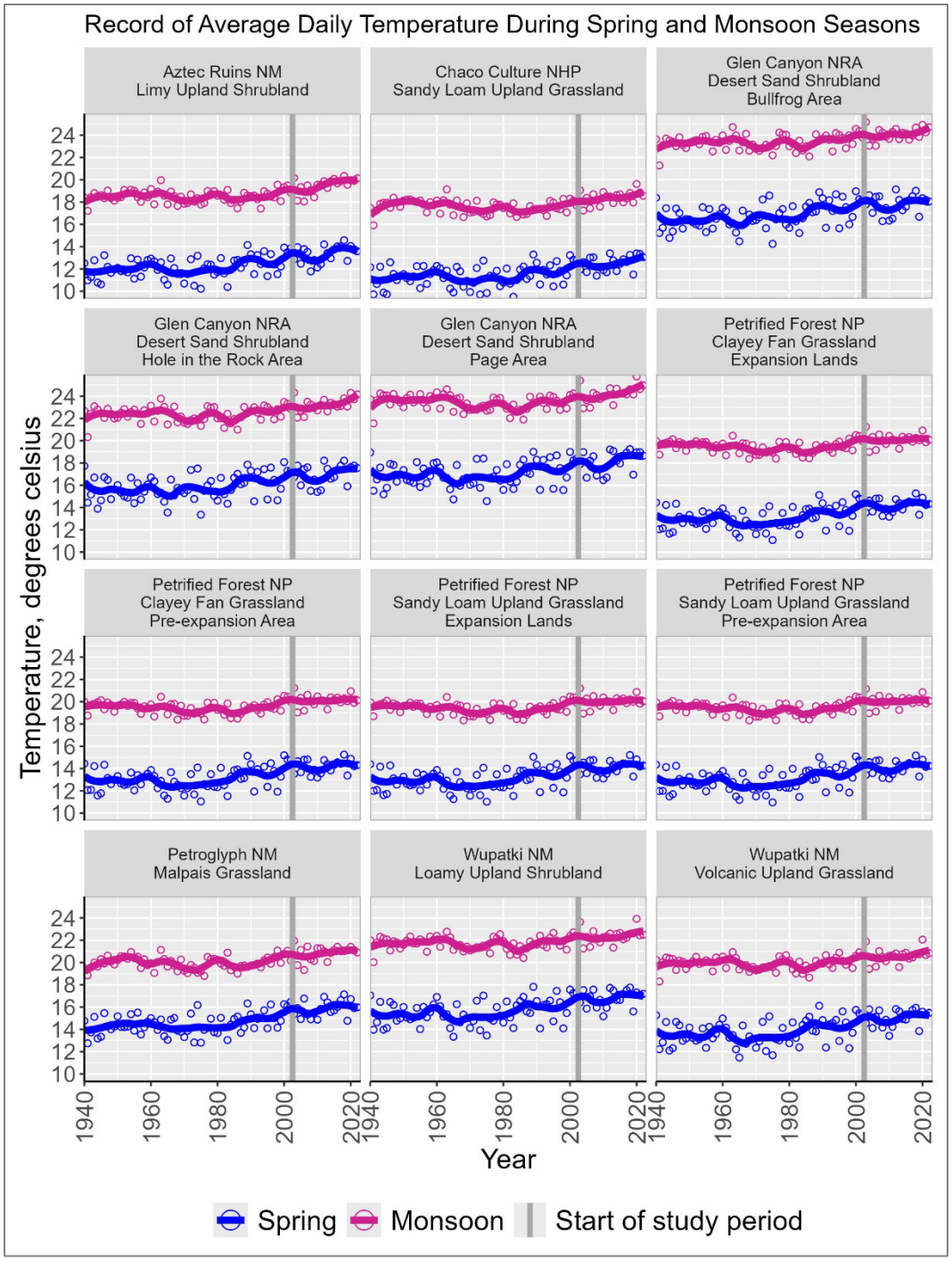


Figure 5. Historical record of spring- and monsoon-season temperature for each study area. Data derived from nClimGrid (~5 km gridded data, Vose et al., 2014). The nClimGrid dataset is suitable for viewing trends because it is adjusted to correct for non-climate-related shifts through time, such as shifts caused by instrument changes. Temperature units are in degrees C. “Spring” season refers to March, April, May, and June; “monsoon” season refers to July, August, September, and October. Data are available in associated data release (Norris and Ploughe 2025). Early years of record (~1900–1939) were not included in the graphs because of the poor overall weather station data record in the region at that time.
NPS / JODI NORRIS

Climate Averages and Historical Record

All of the study areas show an increasing pattern of temperature through time, which is consistent with regional climate patterns (Garfin et al. 2013) (Figure 5). Precipitation patterns through time have high interannual variability in precipitation (Figure 4).

Minimum and maximum temperature patterns (Figure 6) show a correlation between spring and monsoon temperature between individual study areas. Precipitation and dewpoint are much less correlated between the spring and monsoon seasons, and the relative pattern (higher vs. lower) of study areas does not match the pattern of study areas seen in the temperature conditions. Vapor pressure deficit provides a way to integrate the effects of both precipitation and temperature and may provide a better way to estimate what moisture availability the vegetation is experiencing and could thereby limit vegetation growth. Vapor pressure deficit measures the deficit in how much moisture the air could hold vs. how much moisture is present in the air, with higher vapor pressure deficit values representing drier conditions. The relative positions of the study areas on the minimum and maximum daily vapor pressure axes closely match the relative positions of the study areas on the minimum and maximum daily temperature axes. This suggests that in these ecosystems, temperature is providing a stronger control than precipitation on patterns of vapor pressure deficit among the study areas.

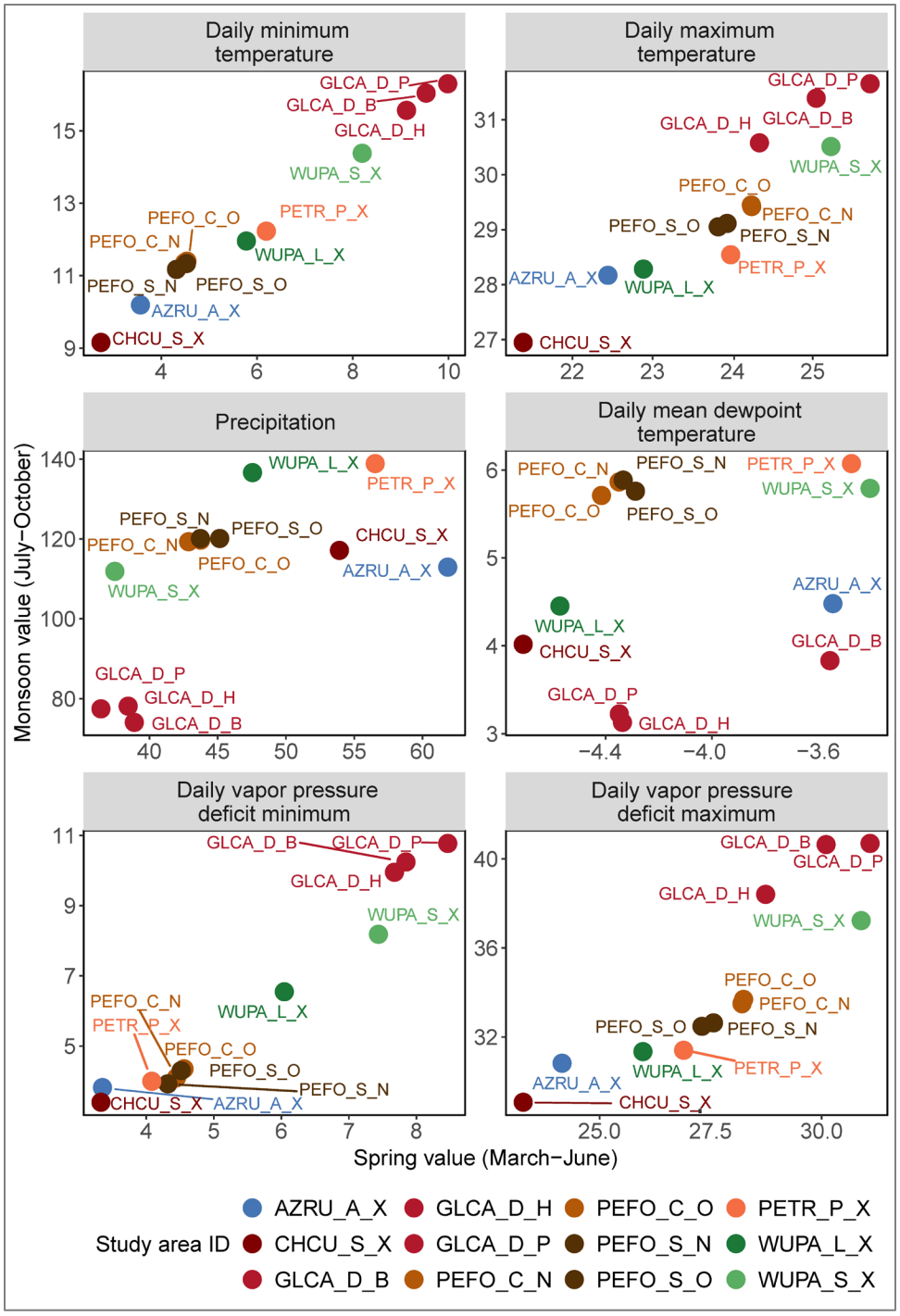


Figure 6. Spring and monsoon season climate patterns across the study areas. Study area IDs correspond to designations in Table 1. Data derived from Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate normals, 1991–2020. (PRISM Climate Group at Oregon State University 2022). Temperature units are in degrees C. Precipitation units are sums across the season in mm. Vapor pressure deficit units are in hPa, with higher vapor pressure deficits corresponding to drier conditions for plants. “Spring” season refers to March, April, May, and June; “monsoon” season refers to July, August, September, and October.

NPS / JODI NORRIS

Vegetation

Vegetation varied by study area and was a mix of grasses, shrubs, and a lesser proportion of forbs (Figure 7). Predominant plant taxa at each site are shown in Table 2. Data collected at the ground-based plots include species-specific plant cover estimates collected on an annual or biennial basis (DeCoster et al. 2012). Taxa included in this table are those with ≥ 10% relative cover in at least one of the study areas. Relative cover estimates are based on plot averages across varying years of data collection (data from Swan and Ploughe 2022). Taxa present across all six park units include the species *Salsola tragus*, *Hilaria jamesii*, *Gutierrezia sarothrae*, and two taxa identified to the genus level: *Sporobolus spp.* and *Euphorbia spp.*

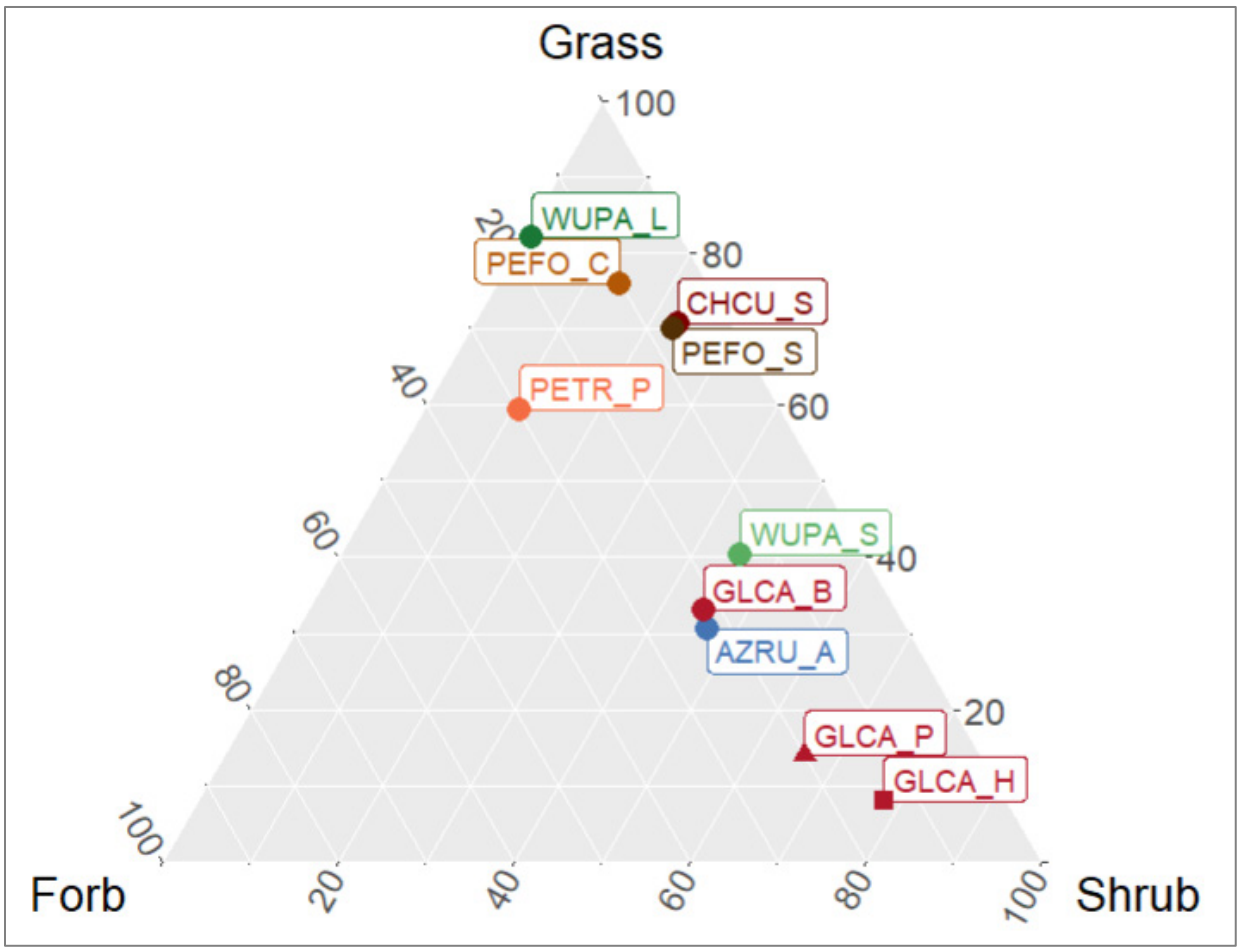


Figure 7. Average relative percent cover of grasses, shrubs, and forbs for the study areas. The two Petrified Forest NP expansion land study areas are not included in this diagram because SCPN has no ground plots in those areas. Study area IDs correspond to designations in Table 1. Data are summarized from Swan and Ploughe (2022).

NPS / JODI NORRIS

Table 2. Predominant plant taxa found in corresponding upland plots within the study areas. Cover estimates are based on plot averages across varying numbers of years of data collection. The two Petrified Forest NP "Expansion Lands" study areas are not included in this table because they are not a part of the ground-based long-term monitoring program. Color coding is used to highlight higher relative percents of taxa, with more intense colors indicating higher relative percent cover. Taxa included are those with ≥ 10% relative cover in at least one of the study areas. Thus, the relative percent covers for individual study areas do not sum to 100 for each study area, because many additional taxa occur that are not shown here. Study area IDs correspond to designations in Table 1. Data summarized from Swan and Ploughe (2022).

Life-form	Species	AZRU_A_X	CHCU_S_X	GLCA_D_B	GLCA_D_H	GLCA_D_P	PEFO_C_O	PEFO_S_O	PETR_P_X	WUPA_L_X	WUPA_S_X
Forb	*Euphorbia* spp.	4.1	0.2	<0.1	<0.1	<0.1	2.0	0.7	0.2	1.1	11.0
	Salsola tragus	8.3	0.3	1.3	0.1	0.6	3.1	1.1	20.3	13.4	0.2
	Bouteloua eriopoda	0	0	0	0	0.1	0.1	3.8	16.3	19.9	3.8
	Bouteloua gracilis	<0.1	32.0	0	0	0	12.1	28.1	0	<0.1	0
Grass	*Hilaria jamesii*	22.6	24.8	1.5	0.3	0.4	10.7	13.7	12.3	53.8	28.9
	Schismus barbatus	0	0	10.4	0.2	0.7	0	0	0	0	0
	Sporobolus spp.	3.7	7.0	14.3	5.6	6.2	41.5	16.6	20.9	0.6	1.2
	Artemisia filifolia	0	0.9	5.1	9.6	8.9	0.4	3.8	<0.1	0	10.7
	Artemisia tridentata	23.9	0.2	0	0	0	0	0	0	0	0
	Coleogyne ramosissima	0	0	4.0	5.7	16.5	0	0	0	0	0
	Ephedra cutleri	0	0.1	4.8	9.8	13.2	0.3	0.4	0	0	0
Shrub	*Ephedra torreyana*	1.1	1.1	7.0	0	0	0.2	1.2	0.1	0	14.6
	Ephedra viridis	5.3	0.1	4.4	21.0	13.1	0.1	0.2	0	0	1.1
	Fallugia paradoxa	0	0	0	0	0	0	0	0	0	11.0
	Gutierrezia sarothrae	14.7	2.9	2.4	6.0	4.9	0.8	3.8	6.9	0	<0.1
	Psorothamnus fremontii	0	0	11.3	13.3	0.5	0	0	0	0	0

Methods

Season Definitions

Some of the analyses summarize data by season to better delineate when changes are occurring. To encompass most of the inter-year and across-ecosystem variability, we are using broad spring and monsoon season definitions, with the spring period including the months of March through June, and the monsoon period including the months of July through October. Green-up in spring vegetation occurs when moisture that has built up over the previous winter is combined with warming growing-season temperatures. A second period of growth in the monsoon season occurs in response to precipitation and humidity increases due to the North American Monsoon. The inclusion of October allows for non-monsoon season moisture events that may contribute to longer late summer and autumn plant growth that is common in these ecosystems.

MODIS Satellite Data Processing and Trend Analysis

Satellite phenology records can be obtained by calculating vegetation index values from sensor reflectance data. Vegetation indices are designed to be a measure of increases or decreases in vegetation greenness. The MODIS sensor provides red and near infrared reflectance data, from which the Normalized Difference Vegetation Index (NDVI) can be calculated. NDVI (Tucker 1979) is a commonly used vegetation index and can be calculated from satellite sensors that measure reflectance in the red and near infrared bands (Equation 1).

$$\text{NDVI} = (\rho\boldsymbol{NIR} - \rho\boldsymbol{red})/(\rho\boldsymbol{NIR} + \rho\boldsymbol{red}) \quad (1)$$

where **ρNIR** is reflectance in the near infrared band, and **ρred** is reflectance in the red band. NDVI data were obtained from products created from the MODIS sensors on the Aqua and Terra satellites. Both satellites provide daily overpasses across the globe, with Terra passing over the United States in multiple orbits that provide overlapping coverage each morning, and Aqua passing over the U.S. in multiple orbits that provide overlapping coverage each afternoon. For most MODIS products, including the products used by SCPN, a single value per pixel is provided daily for each satellite's data series (one for Aqua and one for Terra), even if multiple values are available due to the overlapping nature of the overpasses.

Overview

NDVI data processing, trend analysis and visualization consisted of four major steps, which will be discussed in detail.

1. Compile a daily NDVI data record for each 250-m MODIS pixel within each study area.
2. Calculate a daily NDVI record for each of three productivity levels within each study area:
    a. median across all ecosystem pixels
    b. less productive pixels as measured by average NDVI value
    c. more productive pixels as measured by average NDVI value

3. Perform trend analyses of the study area median values for each ranked day within an individual season/year. Days were ranked based on NDVI value, with rank 1 being the seasonal NDVI peak.
4. Create raster graph visualizations of the phenological patterns.

Compilation of Daily NDVI Record for Each 250 m Pixel

Study area phenological statistics and visualizations were calculated from statistical summaries of the daily data. SCPN uses the MOD09GQ and MOD09GA satellite reflectance products (Vermote 2020). The MOD09GQ data were used to calculate the NDVI values and further phenology metrics derived from the NDVI, such as the timing and intensity of annual or seasonal peaks for each pixel. The MOD09GQ product provides adjusted reflectance values for each 250-m pixel. The MOD09GA product provides linked quality information that was used to screen out values that are affected by snow, clouds, and high levels of aerosols.

Data were downloaded for the period of record for each satellite for each 250-m pixel that was at least 80% occupied by one of the 12 study areas. Data were median smoothed using a 15-day moving window. Median smooth values were retained if at least three high-quality source values contributed to the median, and a linear interpolation was made for those days without at least three contributing values. The 15-day median smooth window is used by SCPN for all MODIS data processing (Norris, 2020). The 15-day window length was chosen because of its balance in detecting changes relatively quickly (desirable for fast-responding, moisture-limited ecosystems) and the need to have some data smoothing to protect against the effects of sometimes large outliers present in satellite data. These outliers can be caused by data misregistration (spatial shifts) or by incomplete screening of data affected by poor atmospheric or unusual ground conditions (snow, clouds, dust, aerosols). Further details of the satellite data processing steps can be found in standard operating procedure #1 of the SCPN Land Surface Phenology protocol (Norris 2020).

Calculation of Daily NDVI for Three Productivity Levels

To represent the overall study area, the study area median NDVI value was calculated from all the selected pixels in the study area for each day across the period of record. However, it can be expected that trends through time might be different for median than for the most and least productive parts of the study area. Therefore, daily NDVI estimates were also calculated for two subsets of pixels representing the more and less productive parts of each study area, using the 20^{th} and 80^{th} percentiles of productivity as estimated by average NDVI of the pixels within each study area. To avoid possible problems with mis-mapped pixels, we did not use pixels representing extremes in study area NDVI. Instead, percentiles were limited to the 5% around the target upper and lower percentiles: 17.5 – 22.5 percentile and 77.5–82.5 percentile for the 20^{th} and 80^{th} percentiles respectively. All daily statistical analyses were run on these three groupings and are referred to as study area median, less productive pixels and more productive pixels.

Trend Analyses

Trends and estimations of total change in NDVI were calculated across the 20-year period for each study area. Inputs for this analysis were the daily NDVI values calculated for the study area medians,

as well as for the pixels selected for the more and less productive areas. To measure trends in NDVI, we could have calculated just the trend in the peak seasonal NDVI values (day rank = 1); however, this could have missed important trends in non-peak days and in measuring the duration of greenness. To account for the variety of possible trends, we tested for and measured trend in NDVI for each ranked day within the spring and monsoon seasons, where the day ranks ranged from the NDVI peak for that year (rank = 1) and minimum NDVI rank for that year. The minimum rank value is based on the number of days in the season (spring = 122, monsoon = 123). Calculations and data preparation were done following the methods described for quantile Kendall exploratory analysis by Choquette et al. (2019).

Steps

For 10 of the 12 study areas, we created 3 daily datasets, one set each for the study area median, more productive pixels, and less productive pixels. Daily datasets were then divided into seasons, and ranked by NDVI value within that season, with 122 days in the spring season and the 123 days in the monsoon season. Each of the derived rank-day datasets consists of 20 NDVI values (one value for each year). This results in a total of 735 datasets for each study area, except for the two study areas which did not have enough pixels to designate more and less productive pixels: the Aztec Ruins NM Limy Upland Shrubland and the Glen Canyon NRA Desert Sand Shrubland Bullfrog Area. Thus, a total of 7,840 trend analyses were performed. The large number of trend analyses comes from the multiple possible combinations: day rank, season, study area, and productivity level.

The following steps were performed to calculate strength and significance of trends. See Figure 8 for a conceptual example. We used scripts modified from Hirsch (2023) and from supplementary material in Choquette et al. (2019). Tables of results are presented in the data release for this report (Norris and Ploughe 2025).

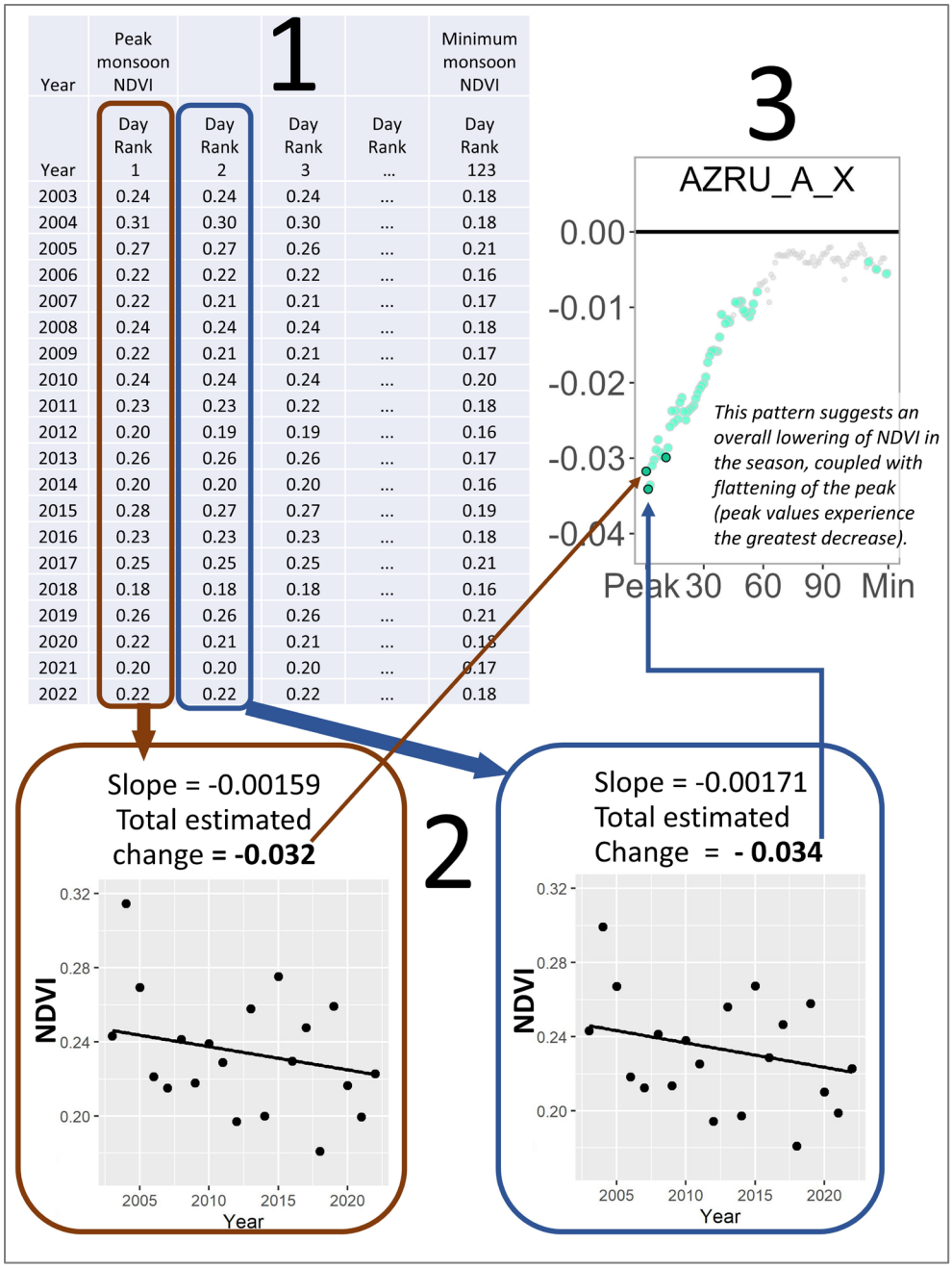


Figure 8. Conceptual diagram of the steps used in ranked-day trend analysis. Step 1 shows individual day ranks as columns, where Day Rank 1 is the seasonal peak NDVI value for the year; Day Rank 2 is the second-highest NDVI value, etc. proceeding down to the seasonal minimum NDVI value for the year. Step 2 shows a graphical example of the regression analysis of NDVI against year, the calculation of the slope of the regression, and conversion of slope to the total estimated NDVI change through time. Step 3 shows how the total estimated change through time is represented as a value on a graph, which shows corresponding trend values for each ranked day of the season. A lowering and flattening of the overall phenological curve in the monsoon season is suggested by the large decreases around the peak dates and smaller decreases on the higher-rank days. Color coding used on the plot in Step 3 reflects statistical significance and is described further in the methods.

NPS / JODI NORRIS

Steps:

1. For each study area, 6 matrices were created of daily NDVI values (2 seasons × 3 productivity levels). Each matrix was ordered by day-rank for each year (see example Figure 8, step 1), such that a list of NDVI values for a particular rank (e.g., rank #1 = the seasonal peaks) could be extracted and analyzed across the period of record.
2. For each ranked day, the Thiel-Sen slope was calculated for that ranked day's NDVI against year (Figure 8, step 2). This slope value estimates the amount of change in NDVI through time using a method that is minimally affected by outliers. This resulted in 122 slope calculations for each of the 122 spring season days and 123 slope values for each of the 123 monsoon season days.
3. For each ranked day, the slope was converted from NDVI change-per-year to total estimated NDVI change over the 20-year period of record (Figure 8, step 2); this provides the size and direction of the trend. The conversion is made by multiplying the slope by 20.
4. For each ranked day, the significance of the trend was determined by calculating an adjusted p-value using a Mann-Kendall test, modified for use in potentially autocorrelated data by using the Zhang method of data pre-whitening using the Zyp R package (Zhang et al. 2000, Bronaugh and Schoeneberg 2023). Time series data are often autocorrelated because adjacent days typically have more similar values than days further apart in time.
5. For each ranked day, the adjusted p-values were converted to likelihood values. Likelihood values estimate the likelihood that the trend direction is correct. Likelihood was calculated following Choquette et al. (2019) using the equation $L_k = 1 - (p_k/2)$, where the subscript k represents the daily rank (e.g., for the spring season, k values range from 1 to 122). L_k is the likelihood for the kth ranked day, and p_k is the adjusted p-value for the kth ranked day calculated from the Zhang method within the Zyp package.
6. Graphs were created showing the magnitude of the total estimated change in NDVI. (Figure 8, step 3). These graphs have symbols color-coded by their likelihood of being in the correct direction, following the likelihood boundaries used by Choquette et al. (2019) and described in their supplementary information.

How Methods Were Modified

The methods described above were modified from the methods described by Choquette et al. (2019) in these ways:

NDVI data were not log-transformed because NDVI data typically do not have a distribution needing log transformation. This assumption was tested against distribution diagrams for a sample of data from each study area. The best distribution match varied from normal to reciprocal. We chose the normal distribution (i.e., untransformed data) because the resulting cumulative change through time could be more intuitively expressed and because the Thiel-Sen slope estimation does not depend on an assumption of a particular distribution.

Similarly, instead of calculating slope as percent change per year (appropriate for log-transformed data), slope was instead converted to the total estimated change in NDVI value over the 20-year period of record.

To provide more conservative estimates, the larger of the two p-values (unadjusted and adjusted) was chosen for use in likelihood calculations. In most cases this was the adjusted p-value.

Calculation of Likelihood for Ranked-Day Trend Direction

To aid in results interpretation, we estimated the likelihood of correct trend direction (increasing or decreasing) using terminology and thresholds explained by Mastrandrea et al. (2010) and applied previously to ranked-day Mann-Kendall analyses by Choquette et al. (2019). Four categories of likelihood were used:

- **"Uncertain":** < 67% likely that the trend direction is correct.
- **"Likely":** 67% to < 90% likely that the trend direction is correct.
- **"Very likely":** 90% to < 95% likely that the trend direction is correct.
- **"Highly likely":** ≥ 95% likely that the trend direction is correct.

This terminology is designed to give an earlier indication for trends that do not meet the more conservative significance thresholds (e.g., p-value < 0.05). This is because by the time a trend meets the strict threshold, it is likely to be well underway; consequences may already be experienced; and the window for effective management action may have already passed. Caution must be used in ascribing trends to long term climate change rather than other sources, such as multidecadal climate variability. However, studies on the relative contributions of climate change provide evidence that anthropogenic climate change has already intensified recent droughts in the southwestern United States (Williams et al. 2022, Leung et al. 2023). In this report, the categories "very likely" and "highly likely" are combined into "very or highly likely" in the results, discussion, and conclusion text to improve readability. The four categories of likelihood are portrayed with distinct color shading and symbols in the figures.

Raster Graph Visualizations

Raster graphs (also known as heatmaps) were created to facilitate data visualization. Methods and color boundary selections are based on percentile statistics calculated from the 20-year period of record of NDVI for each study area. Spring peak timing and intensity values are calculated from daily spring (March–June) study area values. Monsoon peak timing and intensity values are calculated from daily monsoon (July–October) study area values. Further details about statistical calculations and plotting methods can be found in Norris (2020). Daily data and annual statistics are available in the data release associated with this report (Norris and Ploughe 2025).

Results and Discussion

Daily and Peak Seasonal NDVI Values

An overview of the daily and peak seasonal NDVI values is provided here. Due to space constraints, not all data are visible in the multi-park figures. For more detailed park-specific graphs, see the Appendix.

Phenological raster graphs of NDVI over time (Figures 9 and 10) provide a visualization tool to interpret seasonal and interannual changes in NDVI. Daily raster graphs provide a way for viewers to examine several patterns through time, including timing and intensity of seasonal peaks, duration of greenness, extent and amount of winter senescence, interannual variability, and short- or long-term disturbance events. Visualizing data in this way has proven important for resource managers and scientists in other fields to better understand patterns, identify important parameters for models, and to promote scientific hypothesis generation (Koehler 2004, Yanai and Lercher 2021, Zhu et al. 2021).

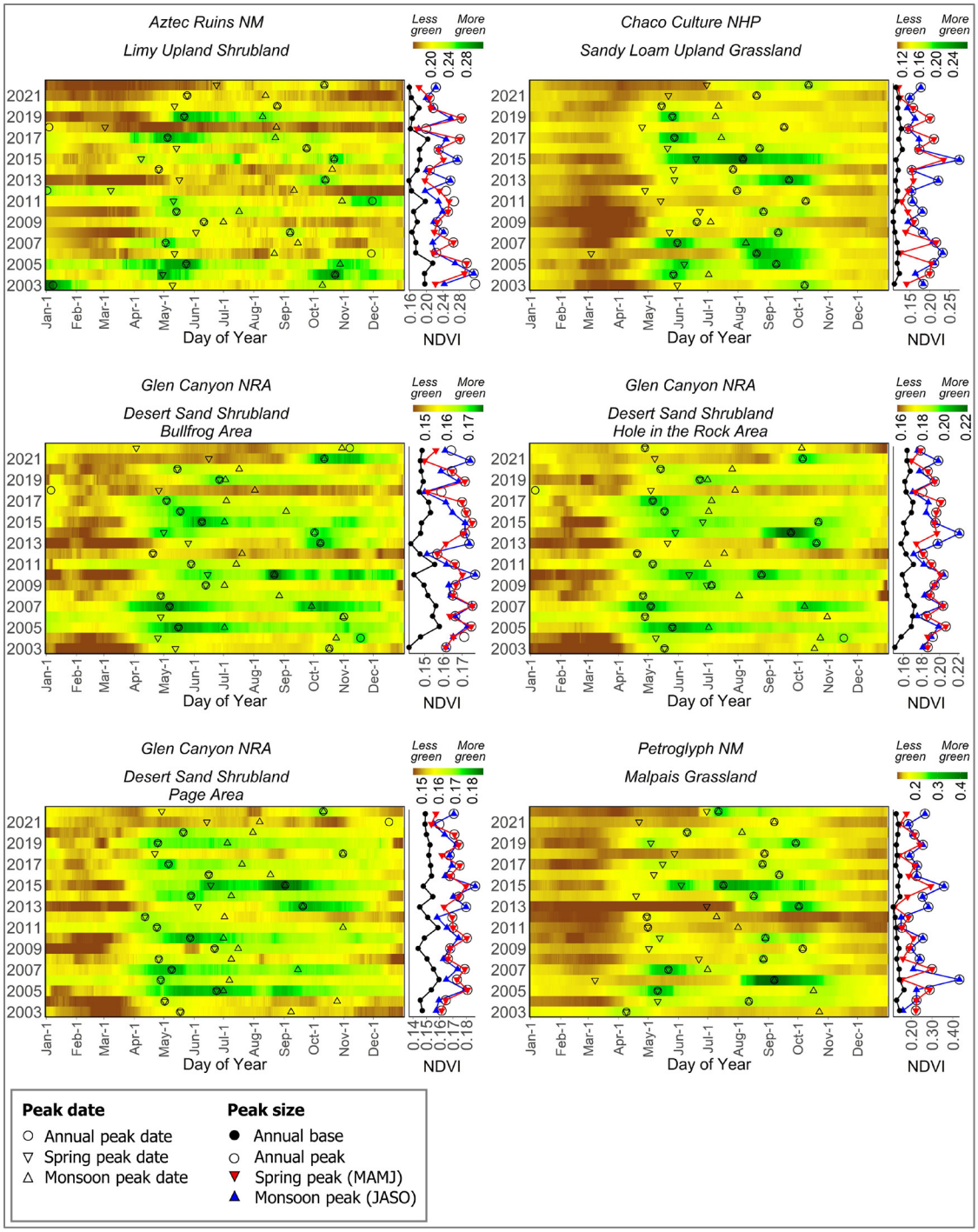


Figure 9. Raster graphs showing phenological patterns of smoothed NDVI for the 20-year analysis period for 6 of the 12 study areas including the park units AZRU, CHCU, GLCA, and PETR. Color ramps of greenness are adjusted to individual study areas' range of NDVI values. Therefore, the color ramps can be compared within a study area for both the timing and intensity of events. Timing of events can also be compared across study areas using the raster graphs. However, to compare intensity (e.g., seasonal peak size) among the study areas, the quantitative peak NDVI values shown in the marginal graphs must be used.

NPS / JODI NORRIS

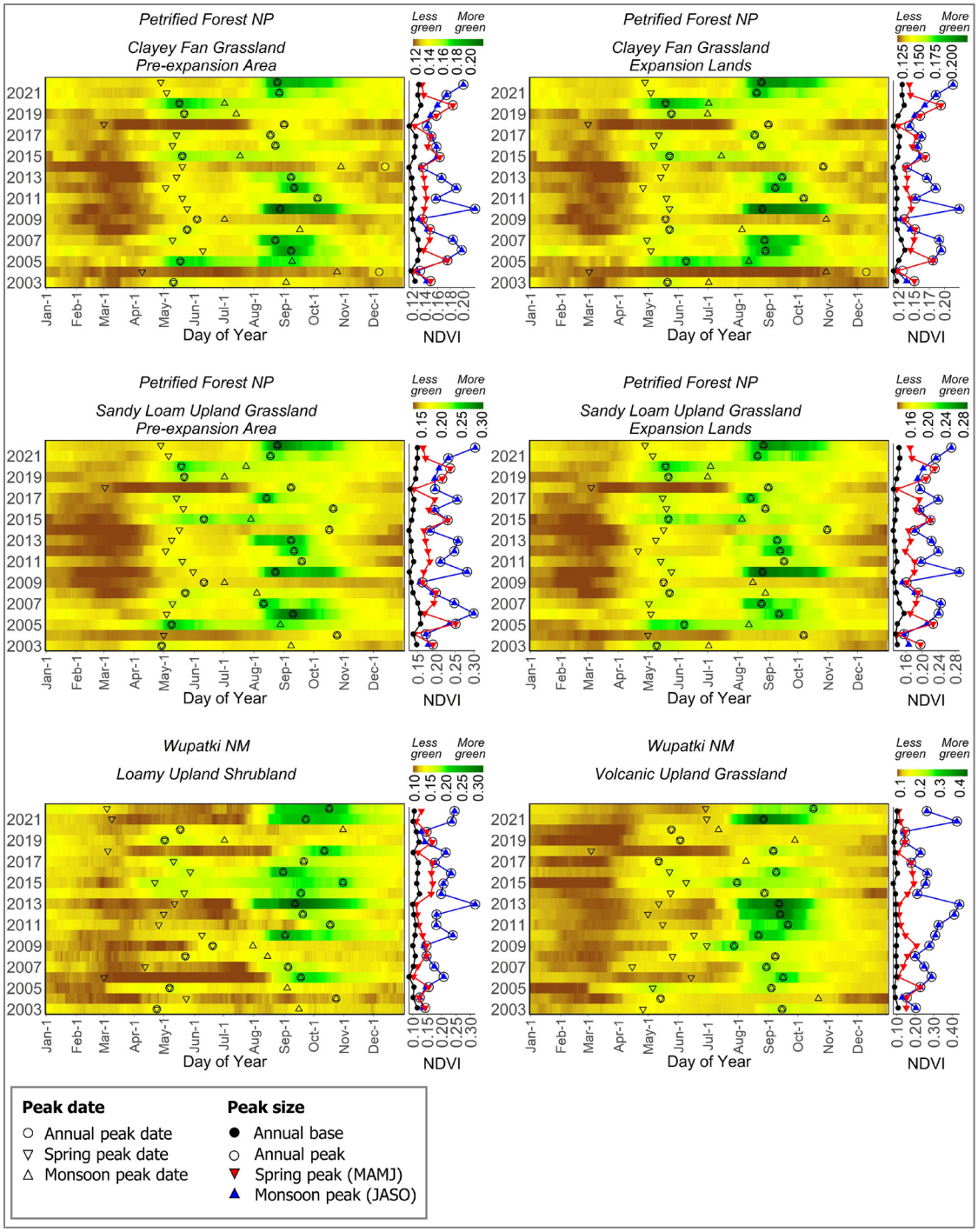


Figure 10. Raster graph showing phenological patterns of smoothed NDVI for the 20-year period of record for 6 of the 12 study areas including the park units PEFO and WUPA. Color ramps of greenness are adjusted to individual study areas' range of NDVI values. Therefore, the color ramps can be compared within a study area for both the timing and intensity of events. Timing of events can also be compared across study areas using the raster graphs. However, to compare intensity (e.g., seasonal peak size) across the study areas, the quantitative peak NDVI values shown in the marginal graphs must be used.

NPS / JODI NORRIS

Although the study areas show different patterns through time, all study areas showed a large variability in the timing, intensity, and duration of spring and monsoon season green-ups. The more northerly parks (Aztec Ruins NM and Glen Canyon NRA) have fewer years with high monsoon peaks. Park-specific consideration of phenology patterns can be used to inform park management and help to interpret past patterns of vegetation and wildlife abundance. As a result, park managers can consider early or preventative management responses for resources of special concern. For example, increased vegetation stress could cause a die-off of a threatened or endangered species. On a larger scale, a trend towards earlier timing of green-up could signal the expansion of an invasive annual species like cheat grass (Singh and Glenn 2009).

Die-Off and Disturbance Indicators

Several parks show multiple consecutive seasons of low NDVI values, suggesting periods of vegetation stress or die-off that may be associated with drought. For example, multiple consecutive seasons of low NDVI values extending from spring 2017 to spring 2021 at the two Wupatki NM study areas (Figure 10) correspond with a widespread juniper die-off/die-back in adjacent pinyon-juniper woodlands that was observed by resource managers in early spring of 2021 (Noel et al. 2023). Similar extended low NDVI periods occur in other parks, including from 2008–2013 at the Petroglyph NM Malpais Grassland study area, and from 2020–2022 at the Aztec Ruins NM Limy Upland Shrubland study area (Figures 9 and 10).

Recording these multi-season events is important in three ways:

1. The events provide context to explain past patterns of abundance of other resources such as wildlife populations.
2. The events provide quantitative information that can be used to parameterize models to link climate and vegetation disturbance. Models that link climate and disturbance thresholds form a foundation for providing accurate predictions of how ecosystems will respond to ongoing and future climate change.
3. If the events can be identified in near real-time, they will provide information about current conditions that can be used to inform anticipatory efforts or to better time already-planned restoration efforts.

Anticipatory efforts could include scenario planning for the case of disturbance and its effect on resources of special concern. It could also include mitigation efforts such as thinning or maintenance of fire breaks that could be immediately prioritized to the most impacted locations or to high-value resource areas.

Improving the timing of already planned restoration efforts (e.g., reseeding after construction projects or reintroducing wildlife) can result in less money wasted on an effort that is unlikely to succeed given current conditions if those conditions are particularly dry and poor. Under these conditions, managers should consider monitoring climate projections or waiting for improvements in humidity or soil moisture conditions before reseeding/replanting. They may also consider other mitigating

arrangements, such as supplemental watering of plants or feeding of reintroduced wildlife, to improve the likelihood of success.

Relative Size of Spring and Monsoon NDVI Peaks

For most study areas, the monsoon peak was larger than the spring peak in most years (Figure 11). The Aztec Ruins NM and Glen Canyon NRA study areas were exceptions. For most years at the Glen Canyon NRA study areas, the spring NDVI peak was higher than that year's monsoon NDVI peak, with only 25–35% of years having higher monsoon peaks than spring peaks. For Aztec Ruins NM, the years were evenly split between years with higher spring peaks and years with higher monsoon peaks. The study areas with the highest proportion of monsoon-peak dominated years were at Petroglyph NM and Wupatki NM, with 70–80% of the years having monsoon peaks that were larger than spring peaks.

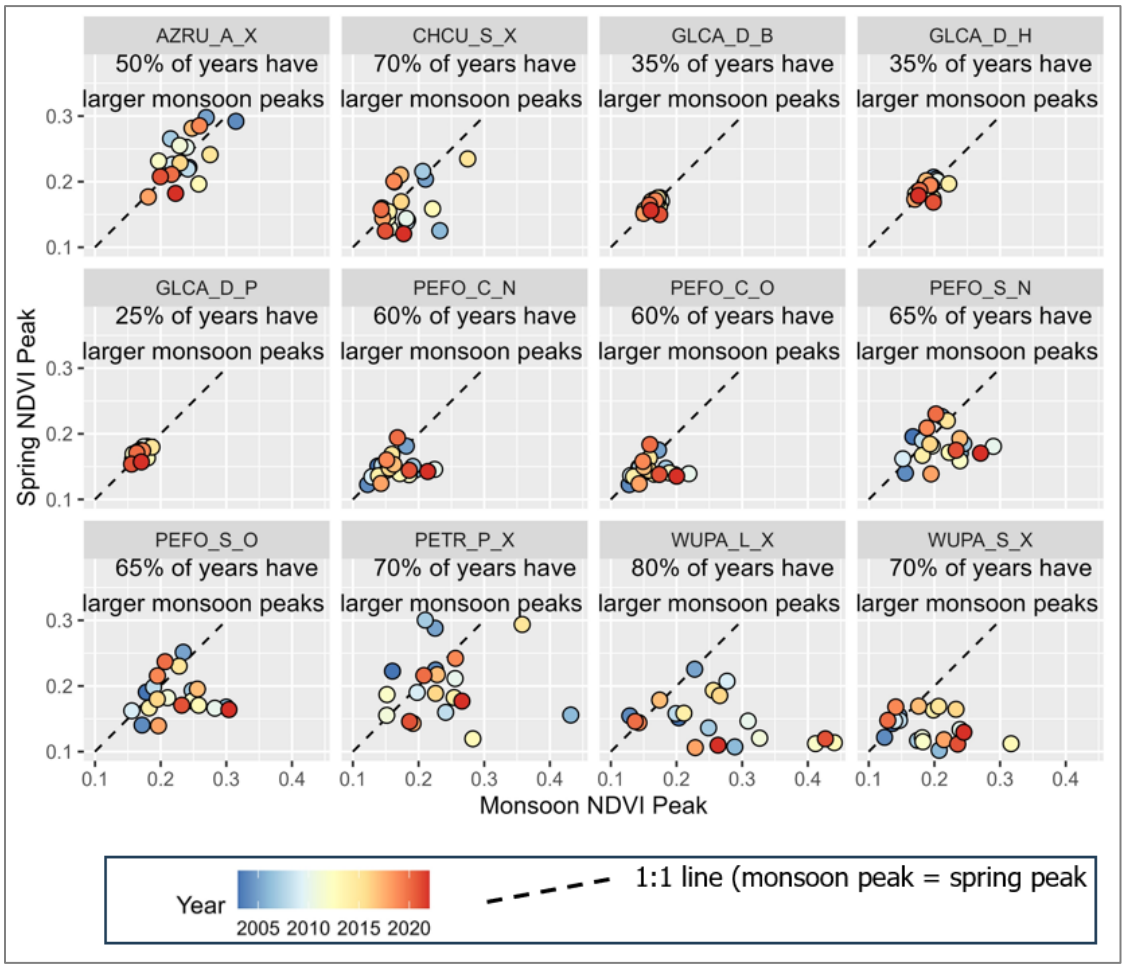


Figure 11. Size and frequency of spring-season vs. monsoon-season NDVI peaks. Study area IDs correspond to designations in Table 1. All study areas had a mix of years with monsoon and spring dominated peaks. Most parks have more years of monsoon-dominated NDVI peaks. Exceptions are Glen Canyon NRA, which has more years of spring-dominated peaks and Aztec Ruins NM, which has evenly divided years of spring- and monsoon- dominated peaks.

NPS / JODI NORRIS

Ranked-Day NDVI Trends

Overviews of the ranked-daily NDVI trends are provided here. Due to space constraints, not all data are visible on the multi-park figures. For more detailed park-specific graphs, see the Appendix.

Overview

Multiple aspects of the ranked-day trend analyses (Figures 12–15) will be discussed individually. Broadly, the results indicate that there were regionally consistent trends in monsoon season greenness over the last 20 years, with southern parks (Petrified Forest NP, Petroglyph NM, and Wupatki NM) experiencing positive or neutral trends, and northern parks (Aztec Ruins NM, Chaco Culture NHP, and Glen Canyon NRA) experiencing negative or neutral trends (Figures 14–15). Spring ranked-day trend patterns were more spatially variable. All parks had variability in the timing and intensity of trends and variability in trends among the more and less productive parts of the study areas. Two parks had negative trends for both spring and monsoon seasons: Glen Canyon NRA and Aztec Ruins NM. Among the 12 study areas, the Aztec Ruins NM study area had the greatest number of days with “very or highly likely” trends, all of which were negative (Figures 12–13).

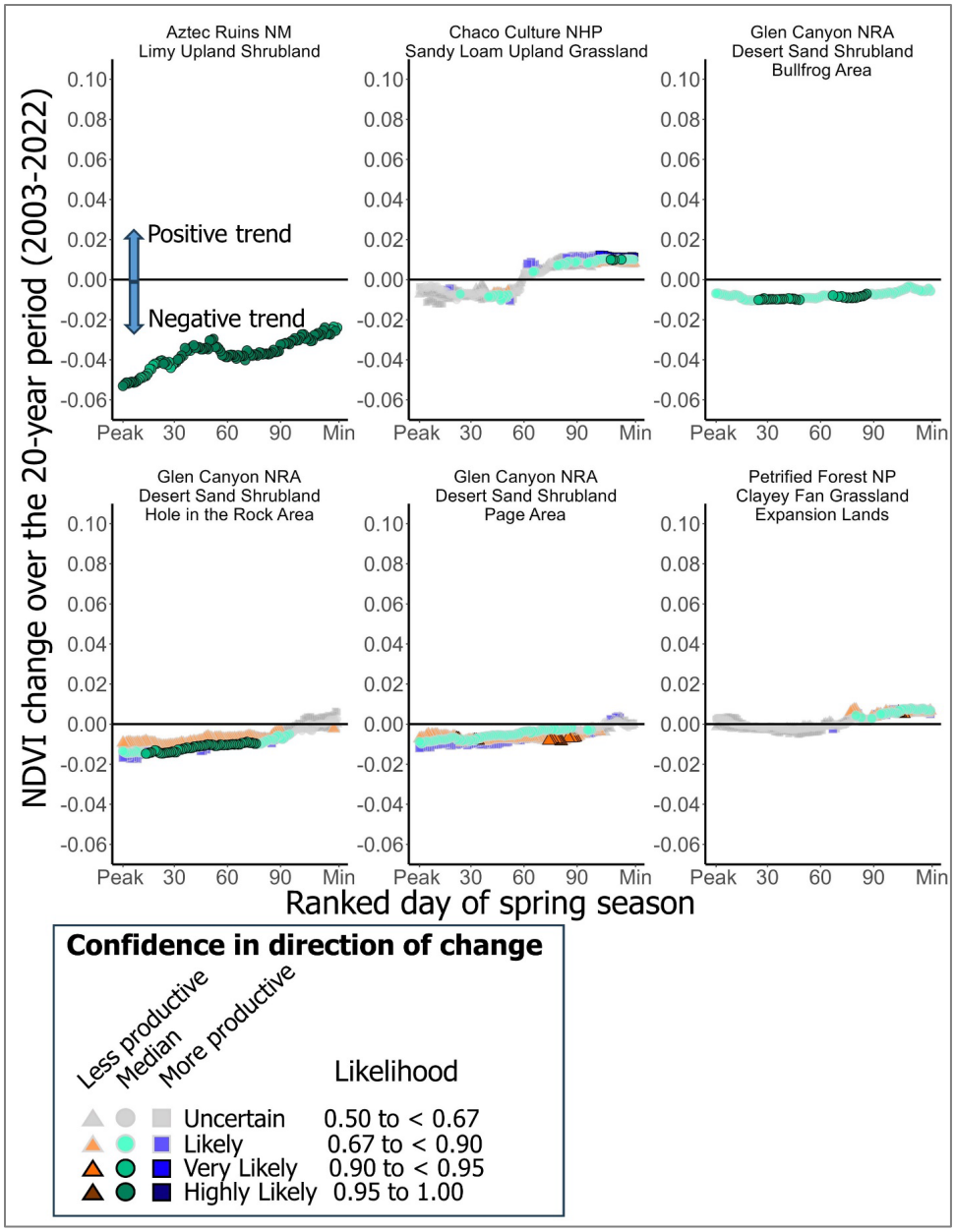


Figure 12. Ranked-day NDVI trend estimates for the spring season for 6 of the 12 study areas including the park units AZRU, CHCU, GLCA and PEFO. For conceptual example, see Figure 8. These graphs show estimates of total change through time (2003–2022) for each ranked day of the spring season (March–June), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the spring season is rank 122 (number of days in the spring season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

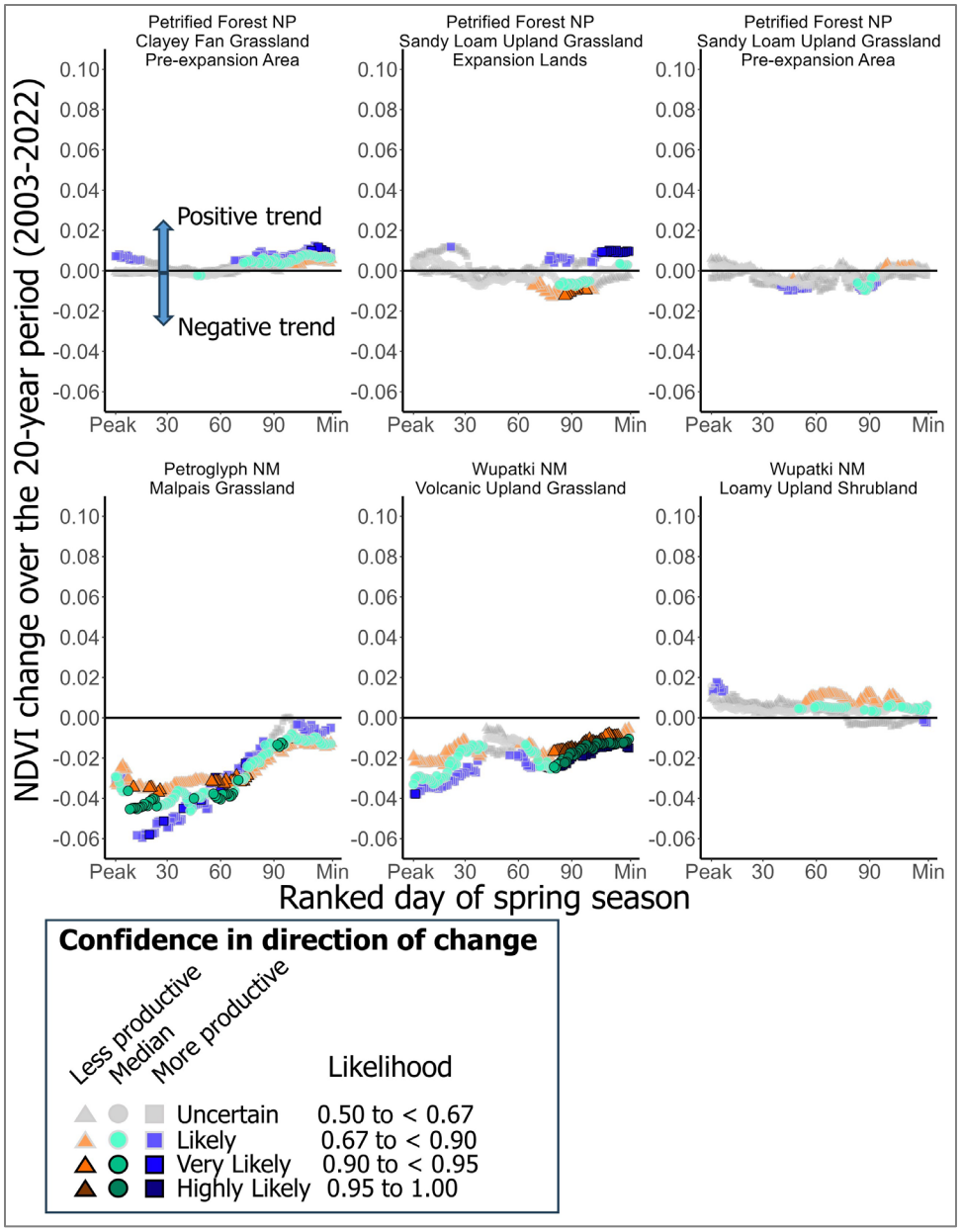


Figure 13. Ranked-day NDVI trend estimates for the spring season for 6 of the 12 study areas including the park units PEFO, PETR, and WUPA. For conceptual example, see Figure 8. These graphs show estimates of total change through time (2003–2022) for each ranked day of the spring season (March–June), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the spring season is rank 122 (number of days in the spring season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

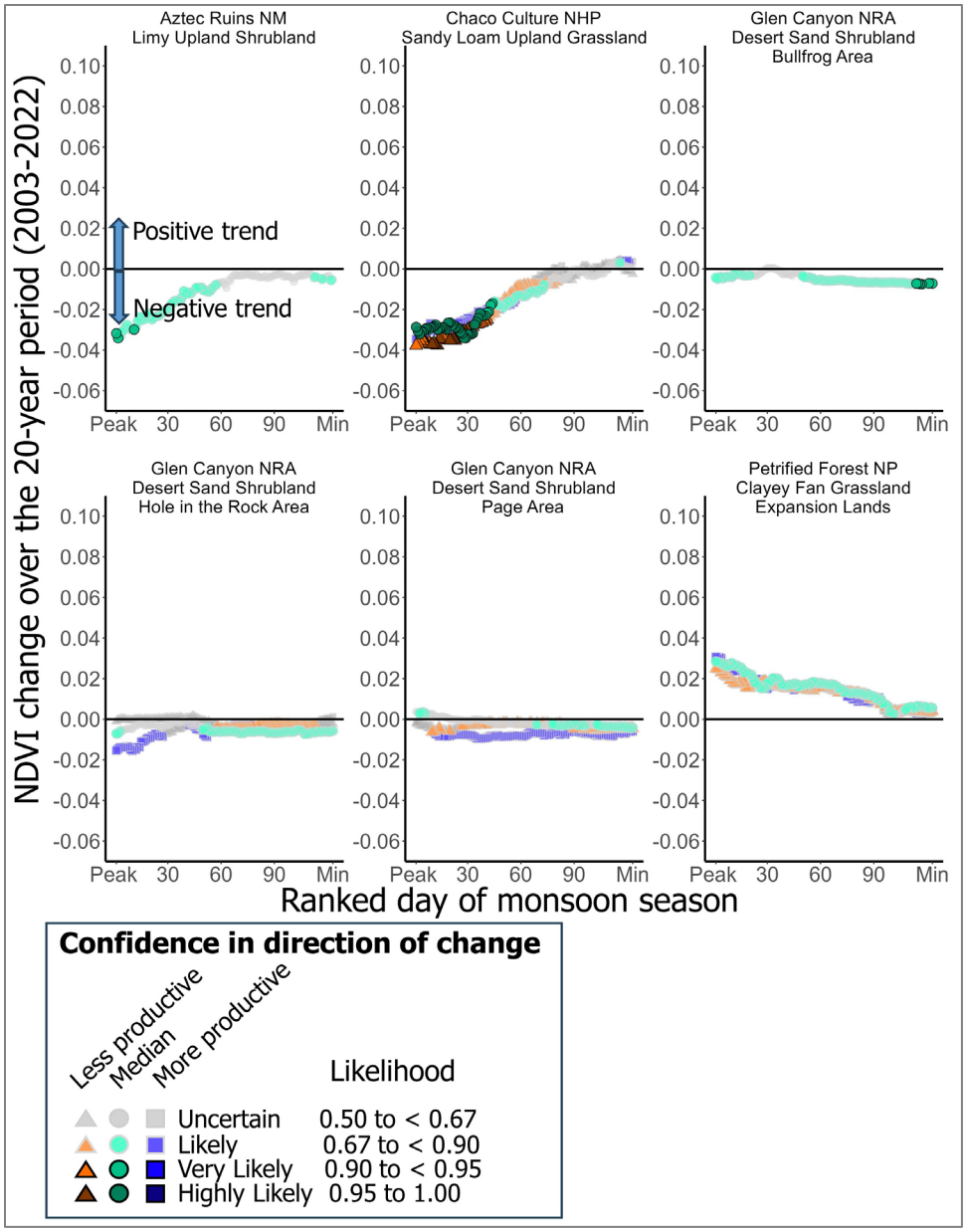


Figure 14. Ranked-day trend estimation results for the monsoon season for 6 of the 12 study areas including the park units AZRU, CHCU, GLCA and PEFO. For conceptual example, see Figure 8. Graph shows estimates of total change through time (2003–2022) for each ranked day of the monsoon season (July–October), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the monsoon season is rank 123 (number of days in the monsoon season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

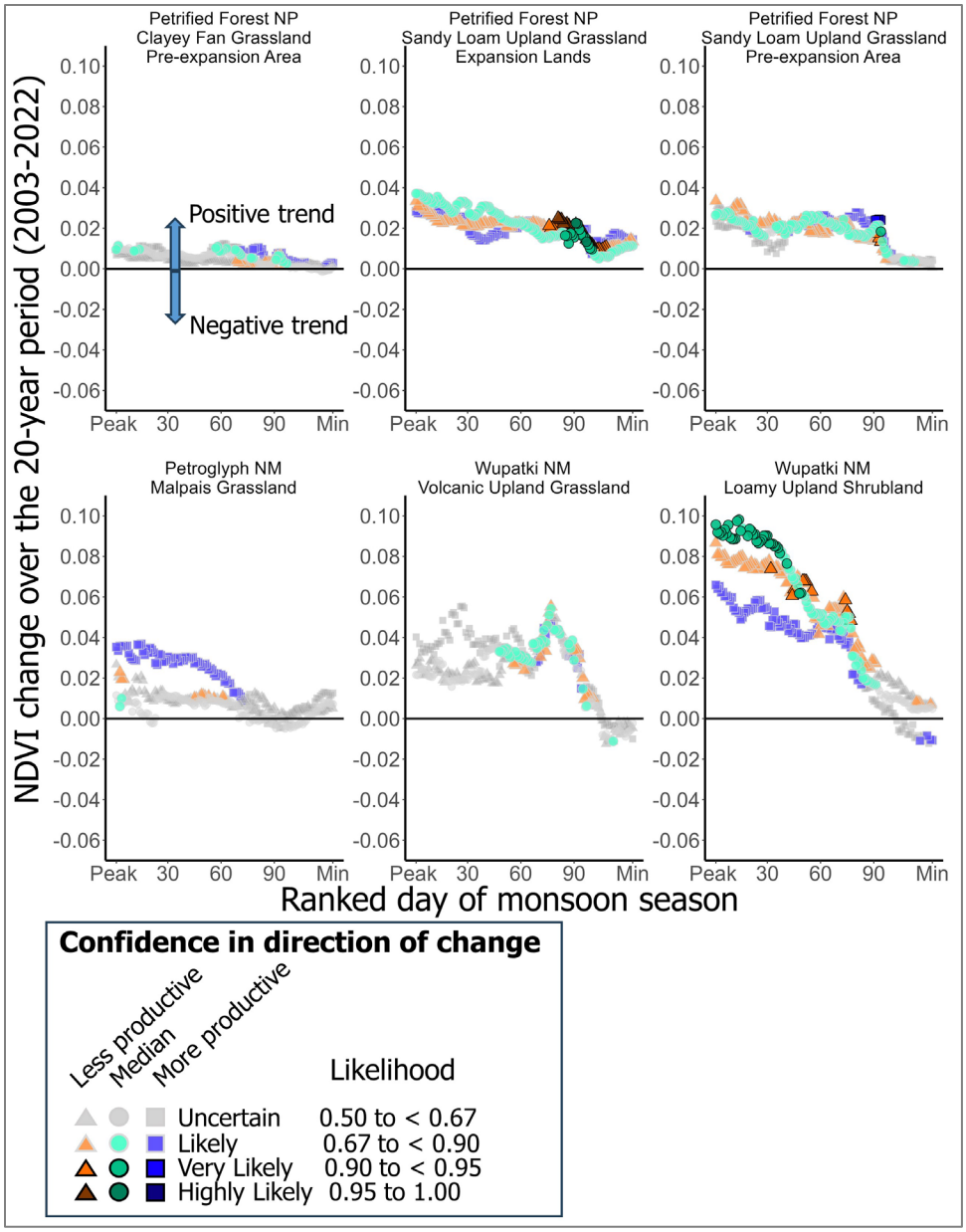


Figure 15. Ranked-day trend estimation results for the monsoon season for 6 of the 12 study areas including the park units PEFO, PETR and WUPA. For conceptual example, see Figure 8. Graph shows estimates of total change through time (2003–2022) for each ranked day of the monsoon season (July–October), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the monsoon season is rank 123 (number of days in the monsoon season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

Ranked-Day Trend Analysis

Ranked-day analysis provided more detailed trend information than simple seasonal peak analysis would have. For the spring season, ranked-day analysis had "very or highly likely" trends for 10 study areas, while peak days had only two study areas with "very or highly likely" trends. (Figures 12 and 13).

Likelihood vs. Threshold p-values

Using likelihood categories instead of a strict p-value threshold provided more information about trends that may be in the earlier stages of detectability. For the spring season analysis, all 12 study areas had trends whose directions were identified to the "likely" level or higher, as compared to 2 study areas which had trends whose directions were identified to the "highly likely" level (Figures 12 and 13). For the monsoon season analysis, all 12 study areas had trends whose directions were identified to the "likely" level or higher, compared to 2 study areas which had trends whose directions were identified to the "highly likely" level (Figures 14 and 15).

Seasonal Differences in Ranked-Day Trends

Spring and monsoon season NDVI trends differed in direction and location (Figures 12–15). Neither seasons' trend directions were consistently associated with shrubland or grassland vegetation types: Although the grasslands generally had more positive spring trends, this may have been due to the over-representation of the Petrified Forest NP grasslands (4 study areas).

Spring (March through June) trends had a locally variable pattern: there was no obvious geographic pattern, and two of the three parks with multiple study areas had both positive and negative trends within the same park (Petrified Forest NP and Wupatki NM, Figures 12 and 13). Spring season NDVI trends were generally negative: 7 out of 12 study areas had negative trends that were "very or highly likely", compared to 4 out of 12 study areas with positive "very or highly likely" trends. The number of rank-days with negative "very or highly likely" trends was also much larger than the few rank-days with positive "very or highly likely" trends.

Monsoon season (July through October) trends had a more regional pattern: the northern park units (Aztec Ruins NM, Chaco Culture NHP, and Glen Canyon NRA) had generally negative trends, while the southern park units (Petrified Forest NP, Petroglyph NM, and Wupatki NM) had generally positive trends (Figures 14 and 15). The monsoon season had both fewer study areas and fewer days with "very or highly likely" NDVI trends: Three study areas each for negative and positive "very or highly likely" trends, all of these occurrences being for only a few rank-days.

More and Less Productive Study Area Pixels

Measuring NDVI trends for the more and less productive pixels of the study area provided trend information beyond that of the study area median values. In most cases, trends were of similar direction and magnitude for all three study area productivity levels; however, in a few cases they behaved differently: for the monsoon season in the Page area of the Glen Canyon NRA Desert Sand Shrubland, the more and less productive pixels had negative (though "uncertain") monsoon peak-day trends, while the study area median trend values for the monsoon peaks were positive (Figure 14). Similarly, for the Petrified Forest NP Sandy Loam Upland expansion lands, towards the minimum

days of the spring season, the more productive pixels had “highly likely” positive trends whereas the less productive pixels had “very likely” negative trends (Figure 13).

Several study areas had “very or highly likely” trends for the more and less productive pixel values but not for the median study area values: In spring, there were six study areas with “very or highly likely” trends in the study area median values, but this number rose to nine study areas when including the more and less productive pixels (Figures 12 and 13). During the monsoon season, there were five study areas with “very or highly likely” trends in study area median values, but this number rose to ten study areas when including the more and less productive pixels (Figures 14 and 15).

Further Topics of Investigation

The results of these analysis provide immediate information about phenological patterns over the last two decades. However, many opportunities remain for additional uses of these data and of ongoing phenological monitoring data. Fruitful areas of inquiry include quantifying the dependence of phenological patterns on climate variables, identifying which plant species responses are best correlated to the satellite record, and linking wildlife responses to phenological status. Two examples of how this phenological data could be used in the future to more explicitly link climate response to vegetation response include examination of the late-spring dip in greenness (Figures 1, 9, 10). The Tercek et al (2023) analysis of water deficit using climate projections suggests that this dip may become more extreme in the future in more areas of the southwest, and that species’ ranges may respond to this change because some plant species may be unable to tolerate the extreme moisture stress during this period. If this happens, resources like the maps created by the Seedlot Selection Tool (Figure 2, Appendix) may prove important for land managers and scientists to determine what species and genetic strains are likely to be successful as climate change progresses. Swan (2024) reported negative effects of spring moisture deficit on the cover of perennial grasses and shrubs, but also found positive impacts of July moisture deficit on perennial grasses. More detailed modelling of those results against the longer term phenological record may be helpful in disentangling and projecting the future effect size of these patterns. The spring and July moisture effects have potential to counteract one another, because climate models for the study areas reported by Swan (2024) project decreased moisture availability in spring and uncertain but often decreasing changes in July moisture availability (Andrews et al. 2019a, e, g, h, i)

Conclusions

Study Area Phenological Characteristics

Statistical summaries and annual patterns from the 12 study areas revealed high interannual variability in the timing and intensity of both spring and monsoon NDVI peaks (Figures 9 and 10). All the study areas had some years with larger spring peaks and some with larger monsoon peaks. Most study areas had more years with a dominant monsoon peak than spring peak (Figure 11). Only Glen Canyon NRA had more years with a dominant spring NDVI peak (65–75% of years had spring NDVI peaks), and Aztec Ruins NM had equal numbers of years dominated by spring peaks and monsoon peaks.

Trend Analyses

Exploratory trend analysis of the NDVI data found that there were many "likely" trends for ranked-day values, with a smaller number of "very or highly likely" trends. The spring season trends were spatially inconsistent among and within parks. The monsoon season trends were consistently negative or neutral for the more northerly parks (Aztec Ruins NM, Chaco Culture NHP, and Glen Canyon NRA), and consistently positive or neutral for the more southerly parks (Petrified Forest NP, Petroglyph NM, and Wupatki NM). Two parks had consistently negative or neutral trends for both seasons: Aztec Ruins NM and the three study areas at Glen Canyon NRA. Of the three study areas at Glen Canyon NRA, the Bullfrog area had the greatest number of days with negative trends in each season and likelihood category.

Management Implications and Future Research

There are three broad areas of management implications for this study: Study area phenology visualizations/covariates, disturbance event recording, and trend interpretation. Each has immediate implications as well as suggested lines of future research that could improve park resource management.

Study Area Phenology Visualizations and Covariates

Patterns of phenological data provide an intuitive way for resource managers to view seasonal and interannual variability in timing and intensity of green-up. The data provide covariates and explanatory information for interpreting changes in other resources of interest. Some examples of their potential utility include:

- They can be useful for considering early or preventative management responses for resources of special concern based on the most recent season's site conditions.
- They can provide vegetation condition and timing data that could explain patterns of wildlife response.
- They can help to understand what the immediate severity of trend impacts on the study area vegetation will be and to anticipate the location and severity of impacts on the study area vegetation if trends continue (e.g., leading to fire or die-off affecting vegetation).

- Changes in patterns of phenological timing can be used as a warning to look for other changes in the study area. For example, consistently earlier green-up could signal the expansion of an early-growing invasive annual species like cheat grass (Singh and Glenn 2009).

Several of these examples have potential for qualitative visual interpretation. They also provide a basis for future quantitative research that can link the phenological data with a variety of ecosystem outcomes, such as fluctuations in wildlife populations, success of individual plant species, or insect outbreaks and die-off events.

Disturbance and Multiyear Drought Event Recording

Drought-related disturbance events are an important ecosystem occurrence in the southwestern U.S. (Betancourt et al. 1993, Breshears et al. 2005, Clifford et al. 2011). Phenological monitoring has the potential to identify when and where these events have occurred or are occurring, and what contributing conditions led up to an event. In our study data, several parks show multiple consecutive seasons of low NDVI values, suggesting periods of vegetation stress or die-off that may be associated with drought. For example, multiple consecutive seasons of low NDVI values extending from spring 2017 to spring 2021 at the two Wupatki NM study areas (Figure 10) correspond with a widespread juniper die-off/die-back in adjacent pinyon-juniper woodlands that was observed by early spring of 2021 (Noel et al. 2023). Similar extended low-NDVI periods occur in other parks, including from 2008–2013 at the Petroglyph NM Malpais Grassland study area, and from 2020–2022 at the Aztec Ruins NM Limy Upland Shrubland study area.

Recording these multi-season events is important for two reasons:

1. The events provide quantitative information that can be used to parameterize models to link climate and vegetation response. Models that link climate and response form a foundation for providing accurate predictions of how ecosystems will respond to ongoing and future climate change.
2. If the events can be identified in near real-time, information about current conditions can be used to inform restoration or response efforts. For example, knowing whether current conditions are good or poor can suggest whether a restoration effort is likely to be successful given current conditions, or whether delaying the action or taking extra steps (such as supplemental watering or feeding) might increase the chances of restoration success.

Utility of Trend Information

We are only able to measure relatively short-term trends over the 20-year period. These should be considered within a larger, multidecadal-scale context. In particular, trend results may be confounded by the occurrence of a multiyear drought before and during the earliest years of the study period (Breshears et al. 2005), and by a second, longer megadrought whose timing thus far encompasses the study period (Williams et al. 2022). Future predictions depend on whether the conditions prevailing during this megadrought become the norm, or whether there will be decadal-scale variability in moisture conditions that could allow for relatively more mesic periods, and thus opportunities for

episodic establishment of long-lived species and more successful restoration efforts (Bradford et al. 2018). Trend results can be used to test whether current trends match climate model predictions of expected ongoing climate change. If they do, then the vegetation responses to these trends can help understand and inform predictions of continued future climate change.

Literature Cited

Andrews, C., J. Bradford, J. Norris, J. Gremer, M. Duniway, S. Munson, L. Thomas, and M. Swan. 2019a. Describing trends in past and future soil moisture in the clayey fan grassland ecosystem in Petrified Forest National Park. NPS/PEFO/NRR—2019/1993, National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2266266

Andrews, C., J. Bradford, J. Norris, J. Gremer, M. Duniway, S. Munson, L. Thomas, and M. Swan. 2019b. Describing trends in past and future soil moisture in the desert sand shrubland ecosystem in the Bullfrog Region of Glen Canyon National Recreation Area. NPS/GLCA/NRR—2019/1997, National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2266293

Andrews, C., J. Bradford, J. Norris, J. Gremer, M. Duniway, S. Munson, L. Thomas, and M. Swan. 2019c. Describing trends in past and future soil moisture in the desert sand shrubland ecosystem in the Escalante Region of Glen Canyon National Recreation Area. NPS/GLCA/NRR—2019/1995, National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2266273

Andrews, C., J. Bradford, J. Norris, J. Gremer, M. Duniway, S. Munson, L. Thomas, and M. Swan. 2019d. Describing trends in past and future soil moisture in the limy upland shrubland ecosystem in Aztec Ruins National Monument. NPS/AZRU/NRR—2019/1999, National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2266296

Andrews, C., J. Bradford, J. Norris, J. Gremer, M. Duniway, S. Munson, L. Thomas, and M. Swan. 2019e. Describing trends in past and future soil moisture in the loamy upland shrubland ecosystem in Wupatki National Monument. NPS/WUPA/NRR—2019/1990, National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2266218

Andrews, C., J. Bradford, J. Norris, J. Gremer, M. Duniway, S. Munson, L. Thomas, and M. Swan. 2019f. Describing trends in past and future soil moisture in the malpais grassland ecosystem in Petroglyph National Monument. NPS/PETR/NRR—2019/1996, National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2266280

Andrews, C., J. Bradford, J. Norris, J. Gremer, M. Duniway, S. Munson, L. Thomas, and M. Swan. 2019g. Describing trends in past and future soil moisture in the sandy loam upland grassland ecosystem in Chaco Culture National Historical Park. NPS/CHCU/NRR—2019/1998, National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2266295

Andrews, C., J. Bradford, J. Norris, J. Gremer, M. Duniway, S. Munson, L. Thomas, and M. Swan. 2019h. Describing trends in past and future soil moisture in the sandy loam upland grassland ecosystem in Petrified Forest National Park. NPS/PEFO/NRR—2019/1992, National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2266265

Andrews, C., J. Bradford, J. Norris, J. Gremer, M. Duniway, S. Munson, L. Thomas, and M. Swan. 2019i. Describing trends in past and future soil moisture in the volcanic upland grassland ecosystem in Wupatki National Monument. NPS/WUPA/NRR—2019/1994, National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2266271

Betancourt, J. L., E. A. Pierson, K. A. Rylander, J. A. Fairchild-Parks, and J. S. Dean. 1993. Influence of history and climate on New Mexico pinon-juniper woodlands. Pages 42–62 *in* E. F. Aldon and D. W. Shaw, editors. Managing pinyon-juniper ecosystems for sustainability and social needs. Rocky Mountain Forest and Range Experiment Station, U.S. Department of Agriculture.

Bothwell, H. M., L. M. Evans, E. I. Hersch-Green, S. A. Woolbright, G. J. Allan, and T. G. Whitham. 2021. Genetic data improves niche model discrimination and alters the direction and magnitude of climate change forecasts. Ecol Appl 31: e02254. DOI: 10.1002/eap.2254.

Bradford, J. B., J. L. Betancourt, B. J. Butterfield, S. M. Munson, and T. E. Wood. 2018. Anticipatory natural resource science and management for a changing future. Frontiers in Ecology and the Environment 16: 295–303. DOI: 10.1002/fee.1806.

Breshears, D. D., N. S. Cobb, P. M. Rich, K. P. Price, C. D. Allen, R. G. Balice, W. H. Romme, J. H. Kastens, M. L. Floyd, J. Belnap, J. J. Anderson, O. B. Myers, and C. W. Meyer. 2005. Regional vegetation die-off in response to global-change-type drought. Proc Natl Acad Sci U S A 102: 15144–15148. DOI: 10.1073/pnas.0505734102.

Bronaugh, D., and A. Schoeneberg. 2023. zyp: Zhang + Yue-Pilon Trends Package. R package version 0.11-1. https://CRAN.R-project.org/package=zyp

Choquette, A. F., R. M. Hirsch, J. C. Murphy, L. T. Johnson, and R. B. Confesor. 2019. Tracking changes in nutrient delivery to western Lake Erie: Approaches to compensate for variability and trends in streamflow. Journal of Great Lakes Research 45: 21–39. DOI: 10.1016/j.jglr.2018.11.012.

Clifford, M. J., N. S. Cobb, and M. Buenemann. 2011. Long-Term Tree Cover Dynamics in a Pinyon-Juniper Woodland: Climate-Change-Type Drought Resets Successional Clock. Ecosystems 14: 949–962. DOI: 10.1007/s10021-011-9458-2.

DeCoster, J. K., and M. C. Swan. 2009a. Integrated Upland Vegetation and Soils Monitoring for Aztec Ruins National Monument: 2008 Summary Report. NPS/SCPN/NRDS—2009/014, National Park Service Inventory and Monitoring Program, Fort Collins, Colorado.

DeCoster, J. K., Swan, M. C. 2009b. Integrated Upland Vegetation and Soils Monitoring for Petroglyph National Monument: 2008 Summary Report. NPS/SCPN/NRDS—2009/021, National Park Service Natural Resource Program Center, Fort Collins, Colorado.

DeCoster, J. K., C. L. Lauver, M. E. Miller, J. R. Norris, A. E. C. Snyder, M. C. Swan, L. P. Thomas, and D. L. Witwicki. 2012. Integrated upland monitoring protocol for the Southern Colorado Plateau Network. NPS/SCPN/NRR–2012/577, National Park Service, Fort Collins, CO. https://irma.nps.gov/DataStore/Reference/Profile/2189159

Garfin, G. M., J. K. Eischeid, M. T. Lenart, K. L. Cole, K. Ironside, and N. Cobb. 2010. Downscaling climate projections in topographically diverse landscapes of the Colorado Plateau in the arid southwestern United States. Pages 21–44 *in* v. R. I. C., B. F. Wakeling, and S. T.D., editors. The Colorado Plateau IV: shaping conservation through science and management. University of Arizona Press, Tucson, Arizona, USA.

Garfin, G., A. Jardine, R. Merideth, M. Black, and S. LeRoy. 2013. Assessment of climate change in the southwest United States: a report prepared for the National Climate Assessment.

Hereford, R., and R. H. Webb. 1992. Historic variation of warm-season rainfall, Southern Colorado Plateau, Southwestern U.S.A. Climatic Change 22: 239–256. DOI: 10.1007/bf00143030.

Hirsch, R. M. 2023. Daily Streamflow Trend Analysis: Using the R-package EGRET to investigate trends in daily streamflow. U.S. Geological Survey. https://waterdata.usgs.gov/blog/quantile-kendall/

Johnson, N. C., D. J. Amaya, Q. Ding, Y. Kosaka, H. Tokinaga, and S.-P. Xie. 2020. Multidecadal modulations of key metrics of global climate change. Global and Planetary Change 188. DOI: 10.1016/j.gloplacha.2020.103149.

Jolly, W. M., R. Nemani, and S. W. Running. 2005. A generalized, bioclimatic index to predict foliar phenology in response to climate. Global Change Biology 11: 619–632. DOI: 10.1111/j.1365-2486.2005.00930.x.

Koehler, R. 2004. Raster-based analysis and visualization of hydrologic time-series. doctoral dissertation. The University of Arizona., The University of Arizona.

Leung, L. R., A. Terando, R. Joseph, G. Tselioudis, L. M. Bruhwiler, B. Cook, C. Deser, A. Hall, B. D. Hamlington, A. Hoell, F. M. Hoffman, S. Klein, V. Naik, A. G. Pendergrass, C. Tebaldi, P. A. Ullrich, and W. M.F. 2023. Ch. 3. Earth systems processes. Page 70 *in* A. R. Crimmins, C. W. Avery, D. R. Easterling, K. E. Kunkel, B. C. Stewart, and T. K. Maycock, editors. Fifth National Climate Assessment. U.S. Global Change Research Program, Washington, DC, USA.

Mastrandrea, M. D., C. B. Field, T. F. Stocker, O. Edenhofer, K. L. Ebi, D. J. Frame, H. Held, E. Kriegler, K. J. Mach, P. R. Matschoss, G.-K. Plattner, G. W. Yohe, and F. W. Zwiers. 2010. Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland. https://www.ipcc.ch/site/assets/uploads/2018/05/uncertainty-guidance-note.pdf

Miller, M. E. 2005. The structure and functioning of dryland ecosystems - conceptual models to inform long-term ecological monitoring. Scientific Investigations Report. U.S. Geological Survey 2005-5197. DOI: 10.3133/sir20055197.

Noel, A. R., R. K. Shriver, S. D. Crausbay, and J. B. Bradford. 2023. Where can managers effectively resist climate-driven ecological transformation in pinyon-juniper woodlands of the US Southwest? Glob Chang Biol 29: 4327–4341. DOI: 10.1111/gcb.16756.

Neale, D. B., and N. C. Wheeler. 2019. Phenotypic Variation in Natural Populations. In: The Conifers: Genomes, Variation and Evolution. Springer, Cham. https://doi.org/10.1007/978-3-319-46807-5_8

Norris, J. R. 2020. Standard operating procedure 1: Land surface phenology data processing overview for the Southern Colorado Plateau Network. National Park Service, Southern Colorado Plateau Network, Flagstaff, AZ. https://irma.nps.gov/DataStore/Reference/Profile/2268201

Norris, J. R., and L. W. Ploughe. 2025. Data release associated with the report "Trends in satellite-derived phenology in grasslands and shrublands of Southern Colorado Plateau Network parks" (2003–2022). National Park Service. Fort Collins, CO. https://doi.org/10.57830/2302939

Parker, D., C. Folland, A. Scaife, J. Knight, A. Colman, P. Baines, and B. Dong. 2007. Decadal to multidecadal variability and the climate change background. Journal of Geophysical Research: Atmospheres 112. DOI: 10.1029/2007jd008411.

PRISM Climate Group at Oregon State University. 2022. United States Average Monthly Total Precipitation, 1991–2020 (800m; BIL) Corvallis, OR, USA.

Rehfeldt, G. E., N. L. Crookston, M. V. Warwell, and J. S. Evans. 2006. Empirical Analyses of Plant-Climate Relationships for the Western United States. International Journal of Plant Sciences 167: 1123–1150. DOI: 10.1086/507711.

Richardson, B. A., S. G. Kitchen, R. L. Pendleton, B. K. Pendleton, M. J. Germino, G. E. Rehfeldt, and S. E. Meyer. 2014. Adaptive responses reveal contemporary and future ecotypes in a desert shrub. Ecol Appl 24: 413–427. DOI: 10.1890/13-0587.1.

Salley, S. W., C. J. Talbot, and J. R. Brown. 2016. The Natural Resources Conservation Service Land Resource Hierarchy and Ecological Sites. Soil Science Society of America Journal 80:1–9. DOI: 10.2136/sssaj2015.05.0305.

Singh, N., and N. F. Glenn. 2009. Multitemporal spectral analysis for cheatgrass (Bromus tectorum) classification. International Journal of Remote Sensing 30: 3441–3462. DOI: 10.1080/01431160802562222.

St. Clair, J. B., B. A. Richardson, N. Stevenson-Molnar, G. T. Howe, A. D. Bower, V. J. Erickson, B. Ward, D. Bachelet, F. F. Kilkenny, and T. Wang. 2022. Seedlot Selection Tool and Climate-Smart Restoration Tool: Web-based tools for sourcing seed adapted to future climates. Ecosphere 13. DOI: 10.1002/ecs2.4089.

Swan, M. C. 2024. Site characterization and change over time in semi-arid grassland and shrublands at three parks—Chaco Culture National Historic Park, Petrified Forest National Park, and Wupatki National Monument: Upland vegetation and soils monitoring 2007–2021. NPS/SCPN/NRR—2024/2616, National Park Service Inventory and Monitoring Program, Fort Collins, Colorado. DOI: 10.36967/2301582.

Swan, M. C., and L. W. Ploughe. 2022. SCPN Upland Vegetation herbaceous and shrub vegetation and soils 2007–2022 Data Package. Fort Collins CO. DOI: doi.org/10.57830/2300890.

Tercek, M. T., J. E. Gross, and D. P. Thoma. 2023. Robust projections and consequences of an expanding bimodal growing season in the western United States. Ecosphere 14. DOI: 10.1002/ecs2.4530.

Thoma, D., J. Norris, and P. Lauck. 2017. Satellite-based vegetation condition and phenology, and snow cover extent monitoring protocol for the Northern and Southern Colorado Plateau Networks. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2246068

Thomas, L. P., M. N. Hendrie, C. L. Lauver, S. A. Monroe, N. J. Tancreto, S. L. Garman, and M. E. Miller. 2006. Vital signs monitoring plan for the Southern Colorado Plateau Network. Natural Resource Report. NPS/SCPN/NRR—2006/002, Fort Collins, Colorado.

Tucker, C. J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment 8:127–150. DOI: 10.1016/0034-4257(79)90013-0.

Vermote, E. 2020. MODIS surface reflectance User's Guide. DOI: 10.5067/MODIS/MOD09GQ.006.

Vose, R. S., S. Applequist, M. Squires, I. Durre, M. J. Menne, C. N. Williams Jr., C. Fenimore, K. Gleason, and D. Arndt. 2014. NOAA Monthly U.S. Climate Gridded Dataset (NClimGrid), Version 1. NOAA National Centers for Environmental Information. DOI:10.7289/V5SX6B56 (accessed 12-10-2023).

White, M. A., F. Hoffman, W. W. Hargrove, and R. R. Nemani. 2005. A global framework for monitoring phenological responses to climate change. Geophysical Research Letters 32. DOI: 10.1029/2004gl021961.

White, M. A., K. M. De Beurs, K. Didan, D. W. Inouye, A. D. Richardson, O. P. Jensen, J. O'Keefe, G. Zhang, R. R. Nemani, W. J. D. Van Leeuwen, J. F. Brown, A. De Wit, M. Schaepman, X. Lin, M. Dettinger, A. S. Bailey, J. Kimball, M. D. Schwartz, D. D. Baldocchi, J. T. Lee, and W. K. Lauenroth. 2009. Intercomparison, interpretation, and assessment of spring phenology in North America estimated from remote sensing for 1982–2006. Global Change Biology 15: 2335–2359. DOI: 10.1111/j.1365-2486.2009.01910.x.

Williams, A. P., B. I. Cook, and J. E. Smerdon. 2022. Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. Nature Climate Change 12: 232–234. DOI: 10.1038/s41558-022-01290-z.

Yanai, I., and M. Lercher. 2021. The data-hypothesis conversation. Genome Biol 22: 58. DOI: 10.1186/s13059-021-02277-3.

Zhang, X., L. A. Vincent, W. D. Hogg, and A. Niitsoo. 2000. Temperature and precipitation trends in Canada during the 20th century. Atmosphere-Ocean 38: 395–429. DOI: 10.1080/07055900.2000.9649654.

Zhu, Z., A. Wasti, T. Schade, and P. A. Ray. 2021. Techniques to evaluate the modifier process of National Weather Service flood forecasts. Journal of Hydrology X 11. DOI: 10.1016/j.hydroa.2020.100073.

Appendix

Overview of Contents

This appendix includes high-resolution park-specific maps and graphs for each study area (Figures 16–68). Multi-park panel graph examples of these graphs are included in the main report. Methods used to create figures are described in the main report, except for the Seedlot Selection Tool maps, which are described here. A conceptual example of the ranked-day trend estimates (Figure 16) can be helpful in interpreting each study areas ranked-day trend estimate graphs.

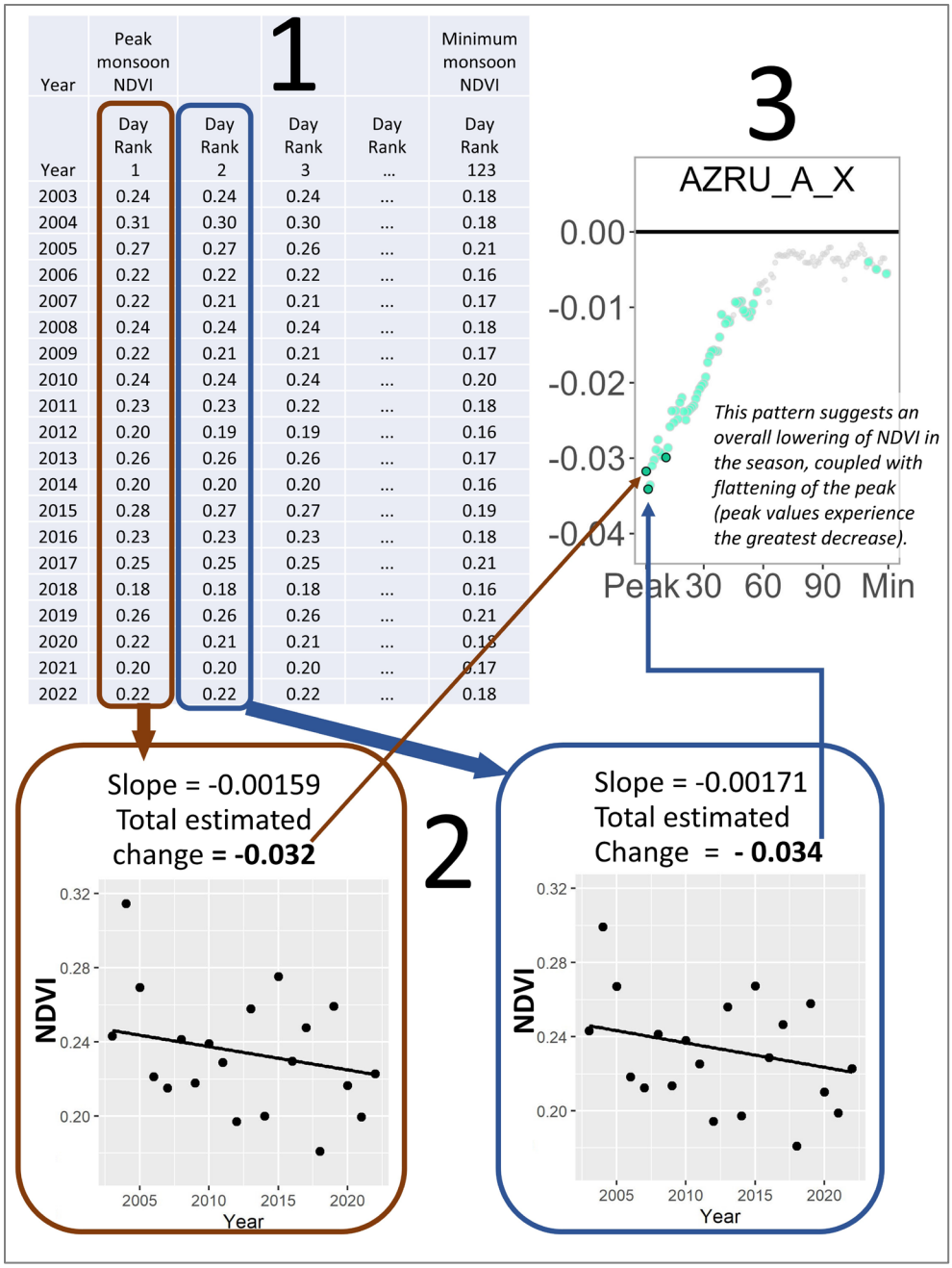


Figure 16. Conceptual diagram of the steps used in ranked-day trend analysis. Step 1 shows individual day ranks as columns, where Day Rank 1 is the seasonal peak NDVI value for the year; Day Rank 2 is the second-highest NDVI value, etc. proceeding down to the seasonal minimum NDVI value for the year. Step 2 shows a graphical example of the regression analysis of NDVI against year, the calculation of the slope of the regression, and conversion of slope to the total estimated NDVI change through time. Step 3 shows how the total estimated change through time is represented as a value on a graph, which shows corresponding trend values for each ranked day of the season. A lowering and flattening of the overall phenological curve in the monsoon season is suggested by the large decreases around the peak dates and smaller decreases on the higher-rank days. Color coding used on the plot in Step 3 is described further in Figure 12.

NPS / JODI NORRIS

Seedlot Selection Tool Map Methods

Seedlot selection tool maps (St. Clair et al. 2022) were created with these settings: Current climate was based on 1981–2010 normals. Projected climate was based on the years 2071–2100 using the RCP 8.5 scenario. Settings used allowed liberal definitions of matches, requiring similarity in only three variables: Mean Coldest Month Temperature (using the default transfer limit of ± 2.00 °C), Summer Heat Moisture Index (using the default transfer limit of ± 190.2), and Frost Free Period (using a user-set transfer limit of ± 30 days). More conservative matches (using additional climate variables) resulted in little or no area with similar projected climate for most study areas.

Aztec Ruins NM

MODIS Sensor Pixels Used in Ranked-Day Analysis

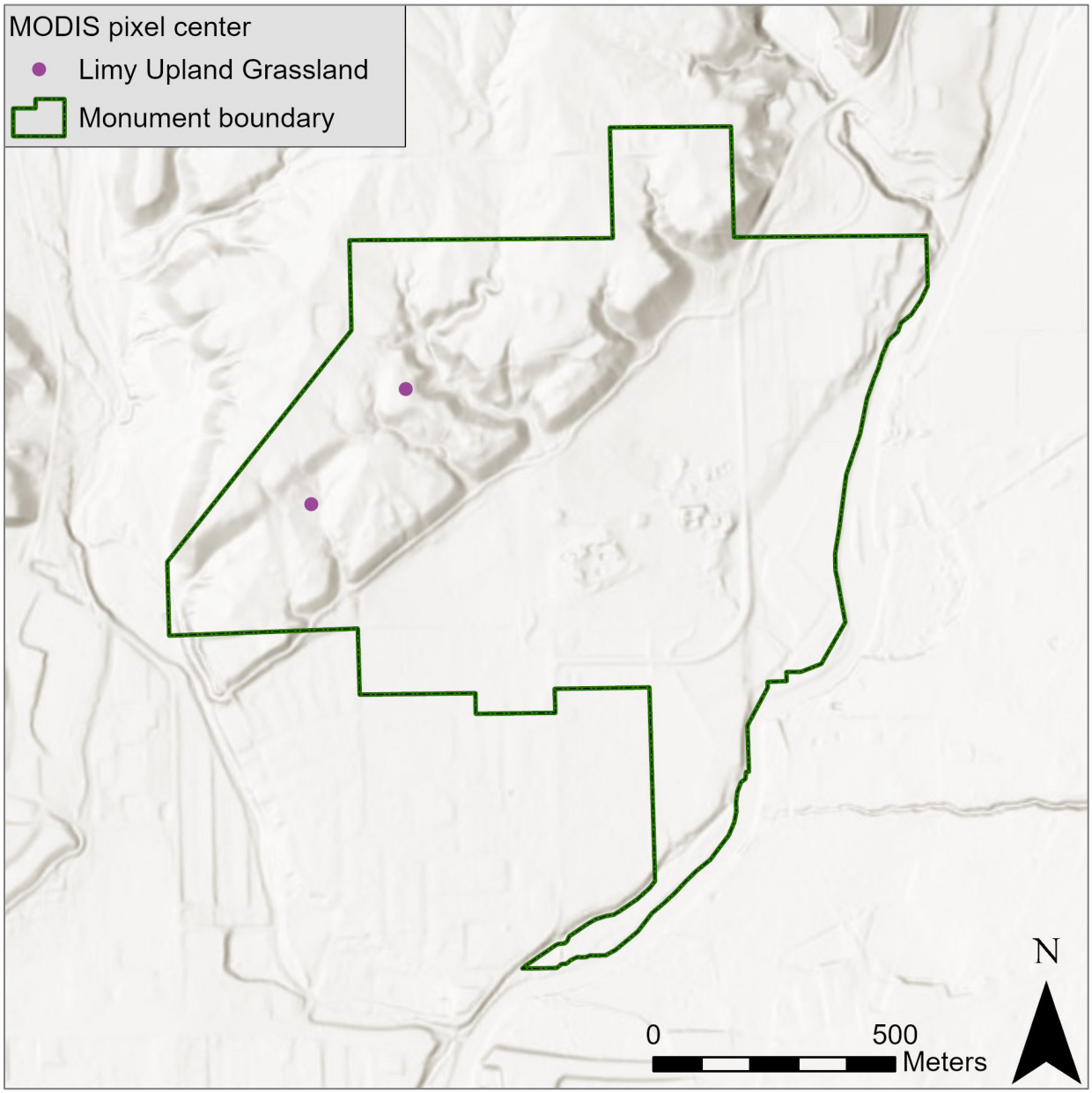


Figure 17. Map of MODIS pixel centers used for analysis at Aztec Ruins NM. Pixels analyzed as 20th and 80th percentile are not present for this study area because it had too few pixels to separate into productivity categories.

NPS / KRISTIN STRAKA

Daily NDVI Data, Raster Graph

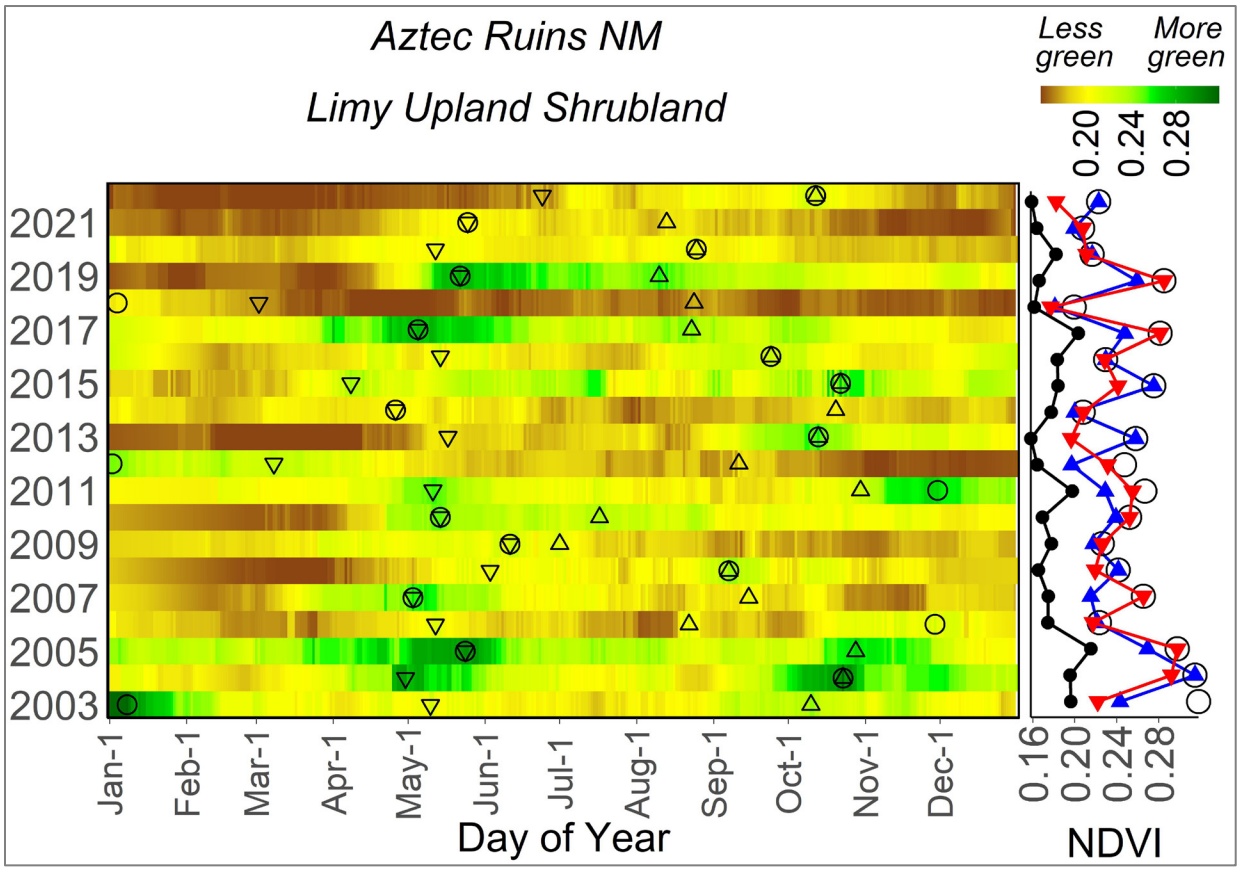


Figure 18. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Aztec Ruins NM Limy Upland Shrubland study area. The graphs show that the study area usually has low greenness during the winter, though a few years, including the first three years, have episodes of greenness in the winter. Many years have separate peaks of greenness occurring during the springtime and monsoon season. Some years, such as 2014 and 2020–2022 have little or no greenup evident throughout the growing season, suggesting vegetation stress during those years. Circular and triangular symbols mark the timing and intensity of the peak-of-season dates for each year: downward and upward pointing triangles mark the spring (March–June) and monsoon peak (July–October) timing. Intensity of the spring peak and monsoon peak is similarly marked by a downward or upward pointing triangle on the marginal plot. Open circles mark the timing and intensity of the annual peak. Closed circles on the marginal plots mark the approximate annual minimum NDVI value, which is approximate and has no associated calendar date because of uncertainty introduced by snow cover.

NPS / JODI NORRIS

Ranked Daily Quantile Trends

Spring Trends

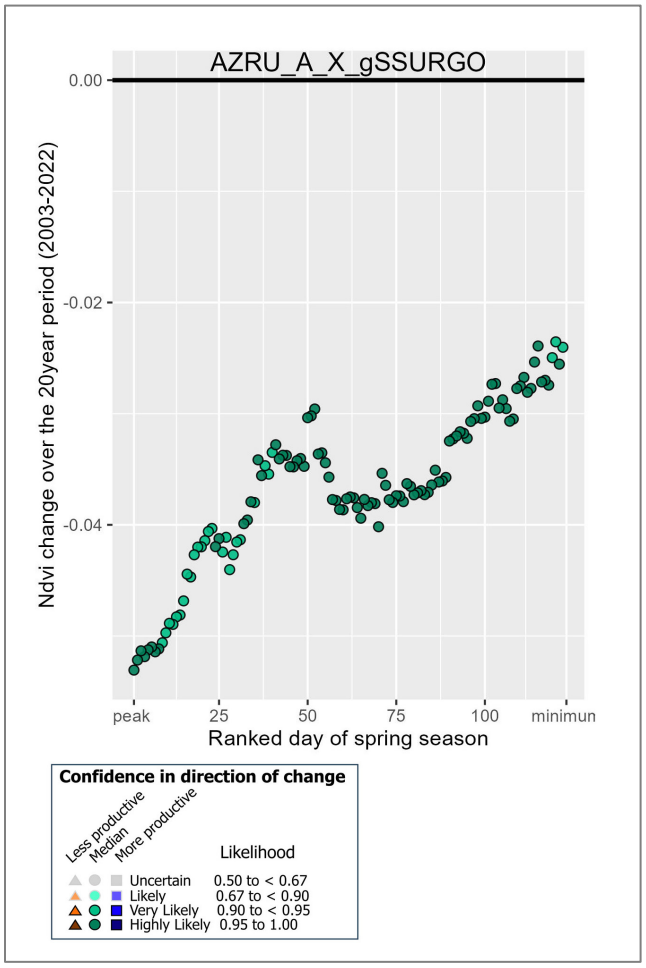


Figure 19. Ranked-day NDVI trend estimates for the spring season for the Aztec Ruins Limy Upland Shrubland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the spring season (March–June), with the "Peak" being the annual peak values for the season and the "Min" being the annual minimum value for the season. The points between the "Peak" and "Min" represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the spring season is rank 122 (number of days in the spring season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the "Less productive" and "More productive" parts of the study area. In this graph, only the median productivity category is shown because the Aztec Ruins Limy Upland Shrubland study area had too few pixels to separate into productivity categories. Decreasing NDVI trends are seen for all days of the spring season. The largest trends seen for declines in the peak and near-peak values. Confidence in direction of trend for all days ranges from very likely to highly likely. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

Monsoon Trends

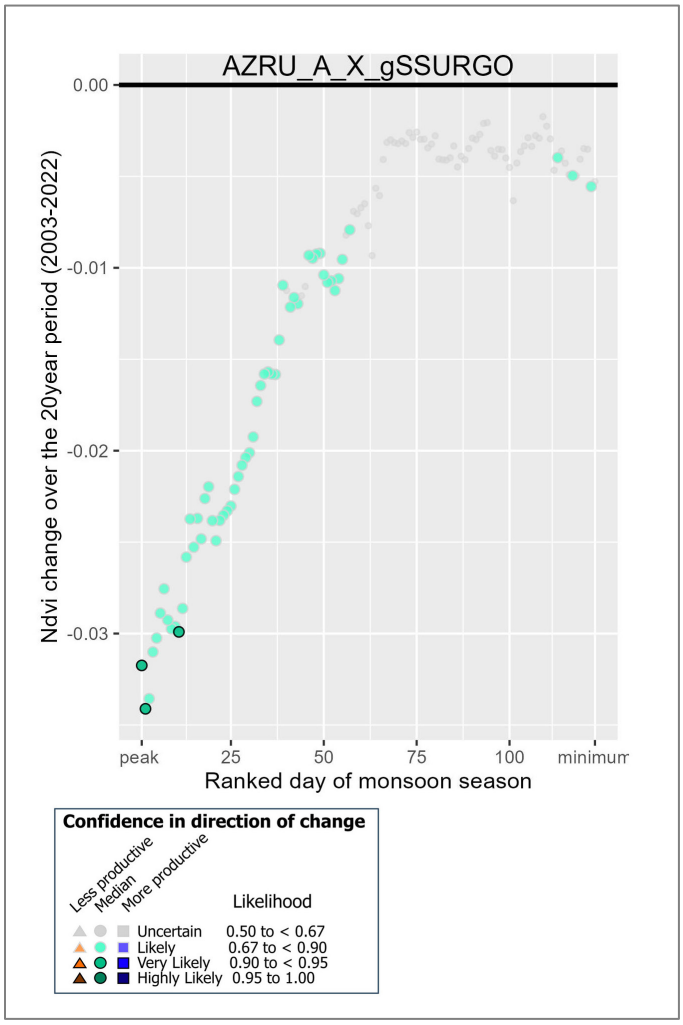


Figure 20. Ranked-day NDVI trend estimates for the monsoon season for the Aztec Ruins NM Limy Upland Shrubland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the monsoon season (July–October), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the monsoon season is rank 123 (number of days in the monsoon season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. In this graph, only the median productivity category is shown because the Aztec Ruins Limy Upland Shrubland study area had too few pixels to separate into productivity categories. Decreasing NDVI trends are seen for all days of the monsoon season. The largest trends seen for declines in the peak and near-peak values. More than half the days have a confidence in the direction of trend of likely or very likely. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

Seedlot Selection Tool Maps

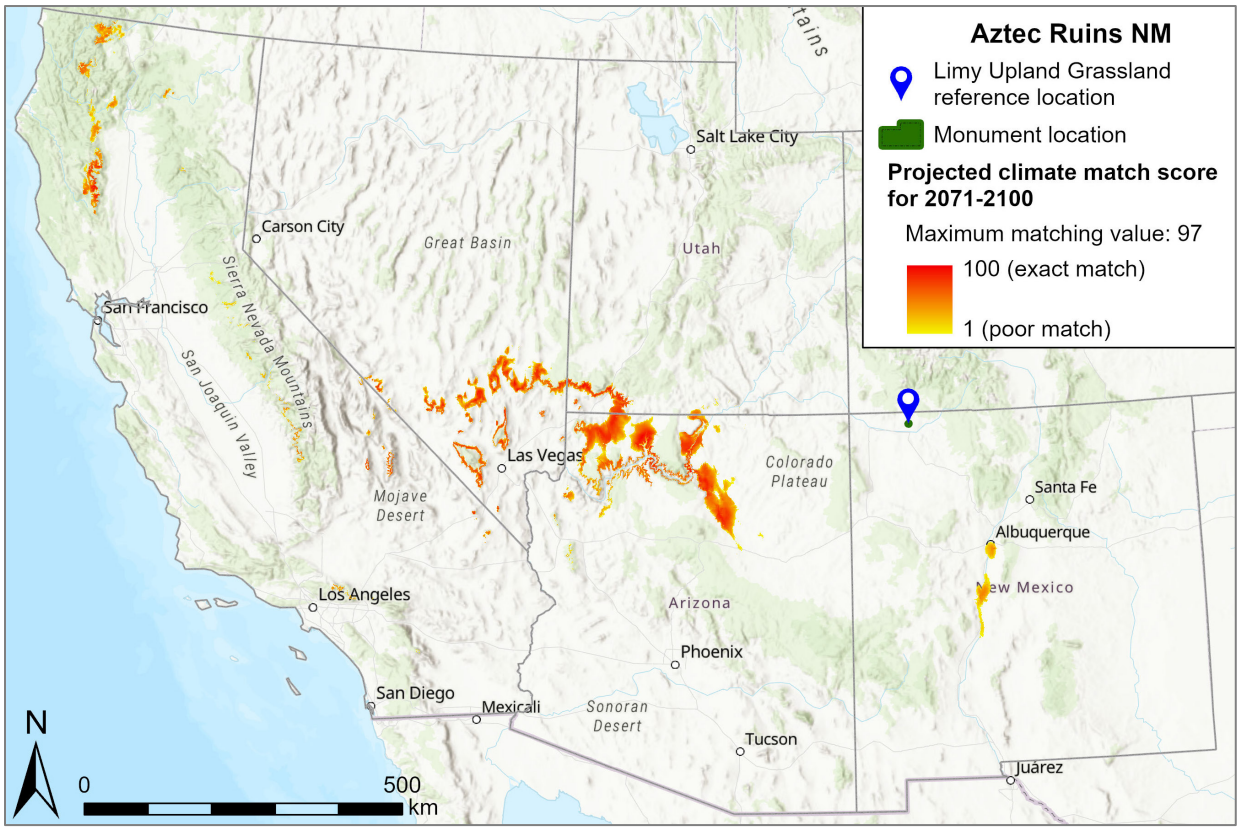


Figure 21. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in Aztec Ruins NM. Data derived from Seedlot Selection Tool scores (St. Clair et al. 2022). Current climate was based on 1981–2010 normals. Projected climate was based on the years 2071–2100 using the RCP 8.5 scenario. Settings used allowed liberal definitions of matches, requiring similarity in only three variables: Mean Coldest Month Temperature, Summer Heat Moisture Index, and Frost-Free Period. Map shows possible future directions of natural or assisted migrations of species or of genetic strains within species. Data used to create this map are available in the associated data release. *NPS / KRISTIN STRAKA*

Chaco Culture NHP

MODIS Sensor Pixels Used in Ranked-Day Analysis

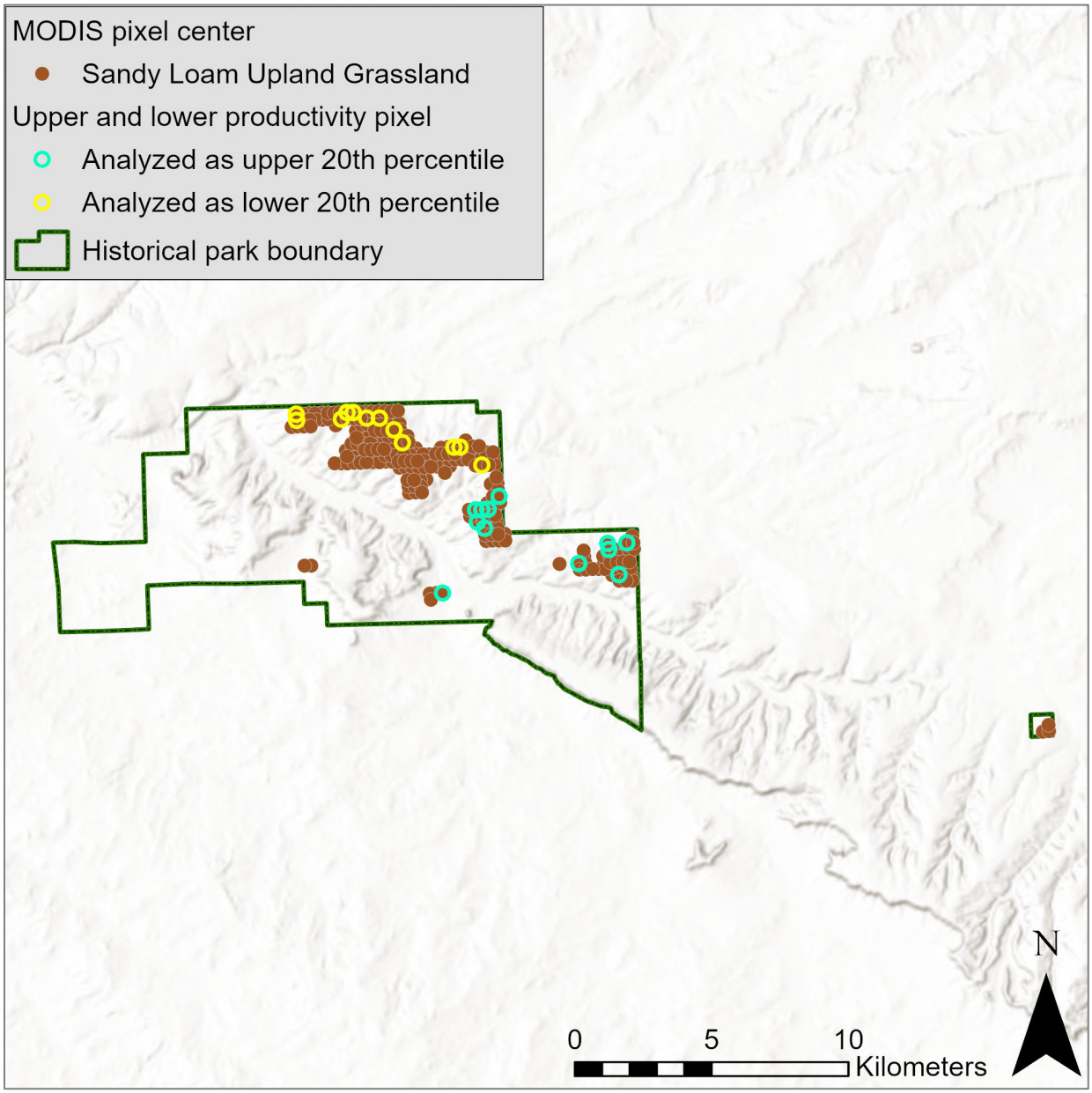


Figure 22. Map of MODIS pixel centers used for analysis at Chaco Culture NHP. Pixels analyzed as 20th and 80th percentile are limited to the 5% of pixels centered around the 20th and 80th percentiles of average greenness across the period of record (i.e., those pixels within the percentile ranges of 17.5%–22.5% and 77.5%–82.5%). This restriction was made to avoid possible outliers that might be incorrectly mapped as the target ecosystem and therefore which might fall at the extreme ends of the productivity distribution.
NPS / KRISTIN STRAKA

Daily NDVI Data, Raster Graph

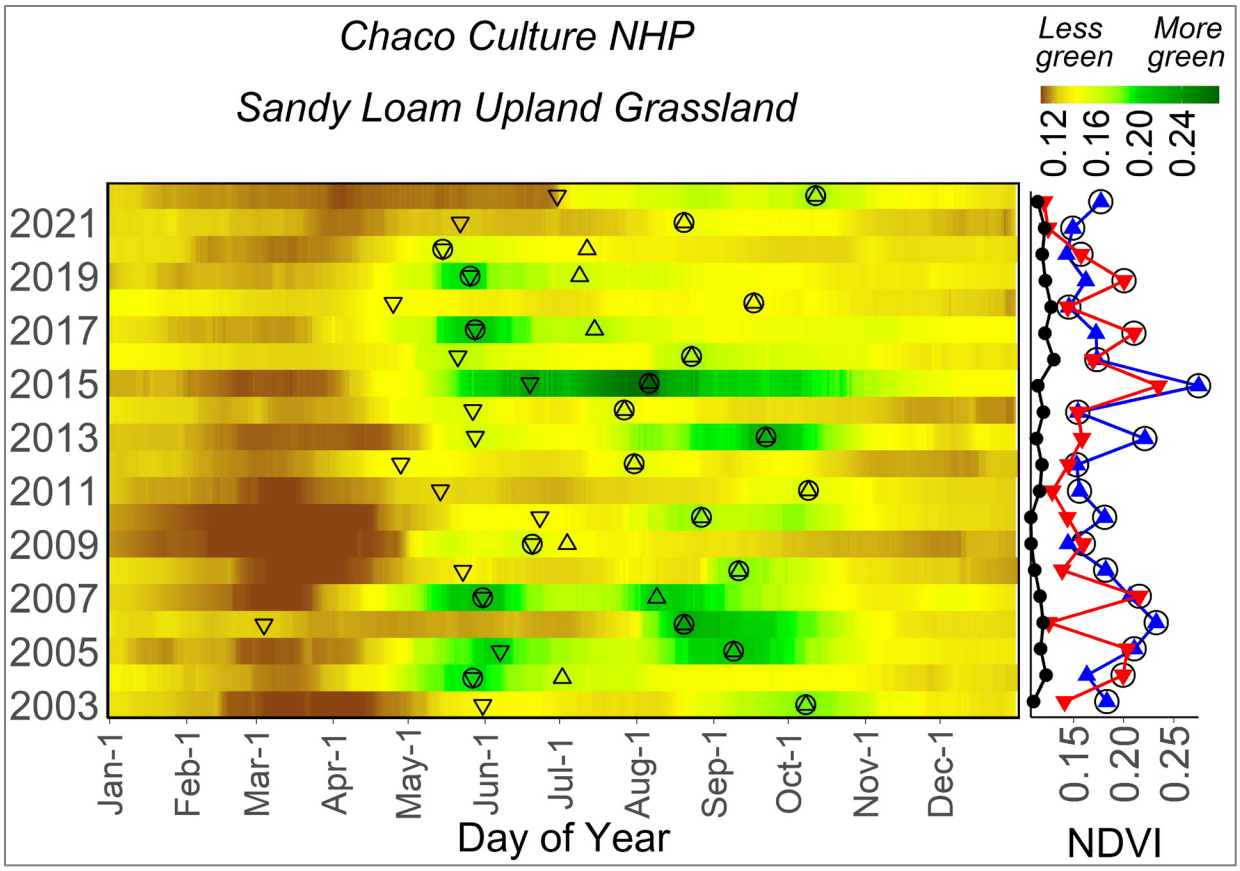


Figure 23. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Chaco Culture NHP Sandy Loam Upland Grassland study area. The graphs show that the study area has low greenness during the winter. Many years have separate peaks of greenness occurring during the springtime and monsoon season. Some years, such as 2011, 2012, 2018, and 2021 have little greenup evident throughout the growing season, suggesting vegetation stress during those years. Circular and triangular symbols mark the timing and intensity of the peak-of-season dates for each year: downward and upward pointing triangles mark the spring (March–June) and monsoon peak (July–October) timing. Intensity of the spring peak and monsoon peak is similarly marked by a downward or upward pointing triangle on the marginal plot. Open circles mark the timing and intensity of the annual peak. Closed circles on the marginal plots mark the approximate annual minimum NDVI value, which is approximate and has no associated calendar date because of uncertainty introduced by snow cover.

NPS / JODI NORRIS

Ranked Daily Quantile Trends

Spring Trends

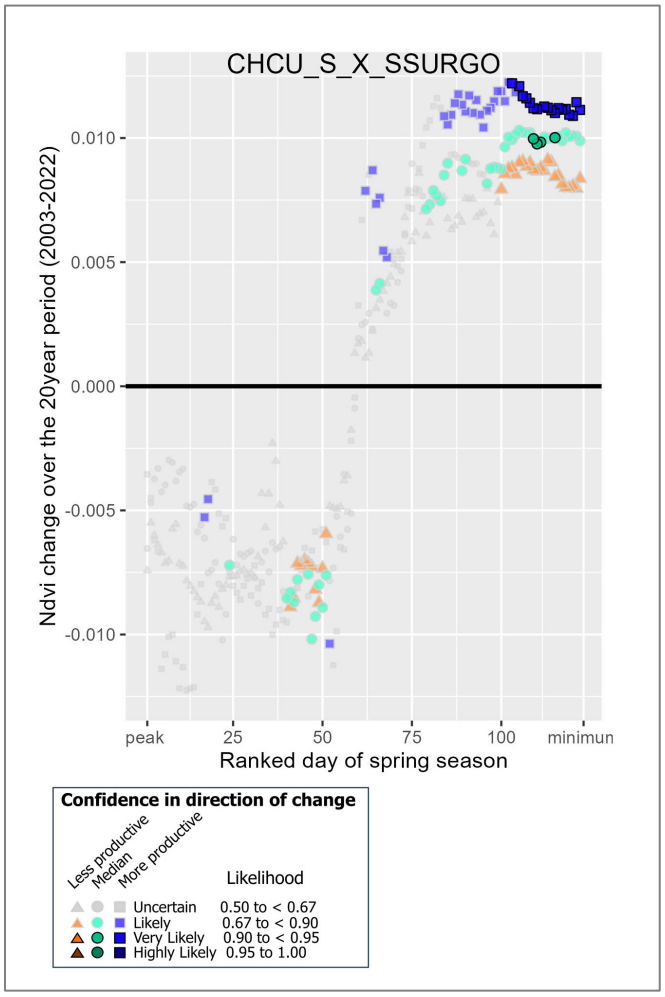


Figure 24. Ranked-day NDVI trend estimates for the spring season for the Chaco Culture NHP Sandy Loam Upland Grassland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the spring season (March–June), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the spring season is rank 122 (number of days in the spring season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Plot shows an overall flattening of the spring phenology pattern for all three productivity levels, with a lowering of the seasonal peak and an increase in the seasonal minimum values. The greatest confidence in the directions of this is for the positive trend in values near the minimum day of the season. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

Monsoon Trends

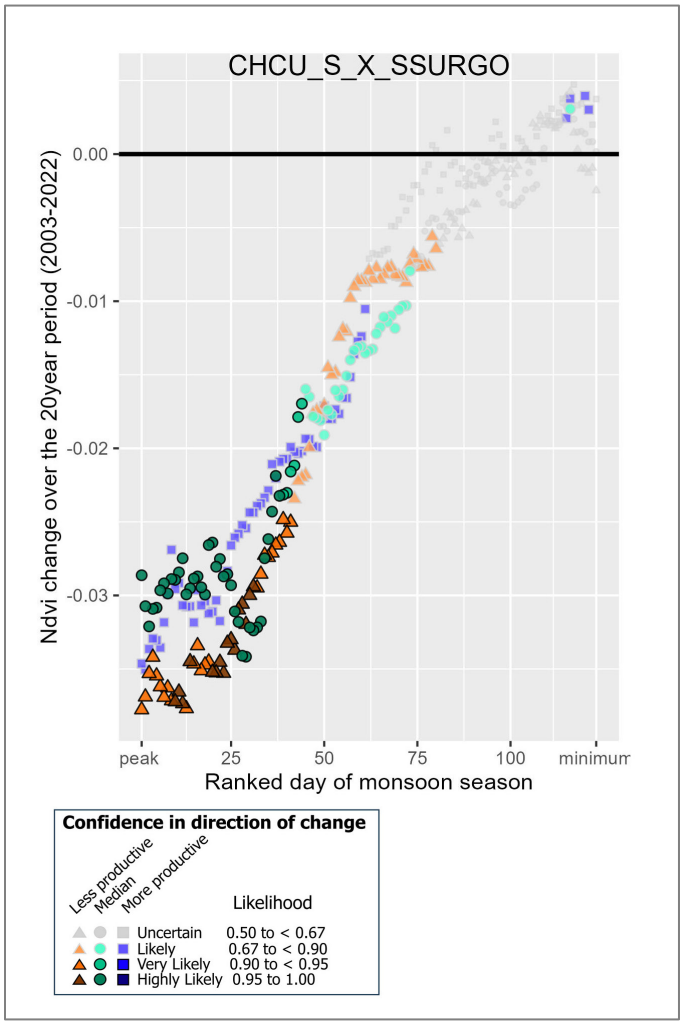


Figure 25. Ranked-day NDVI trend estimates for the monsoon season for the Chaco Culture NHP Sandy Loam Upland Grassland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the monsoon season (July–October), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the monsoon season is rank 123 (number of days in the monsoon season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Decreasing NDVI trends are seen for almost all days of the monsoon season, except for a small increasing trend seen in the near-minimum days. The largest trends and highest confidence levels are seen for declines in the peak and near-peak values. This pattern is consistent across all three productivity levels, with the greatest confidence in negative direction of trend for the median and less productive study area categories. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

Seedlot Selection Tool Maps

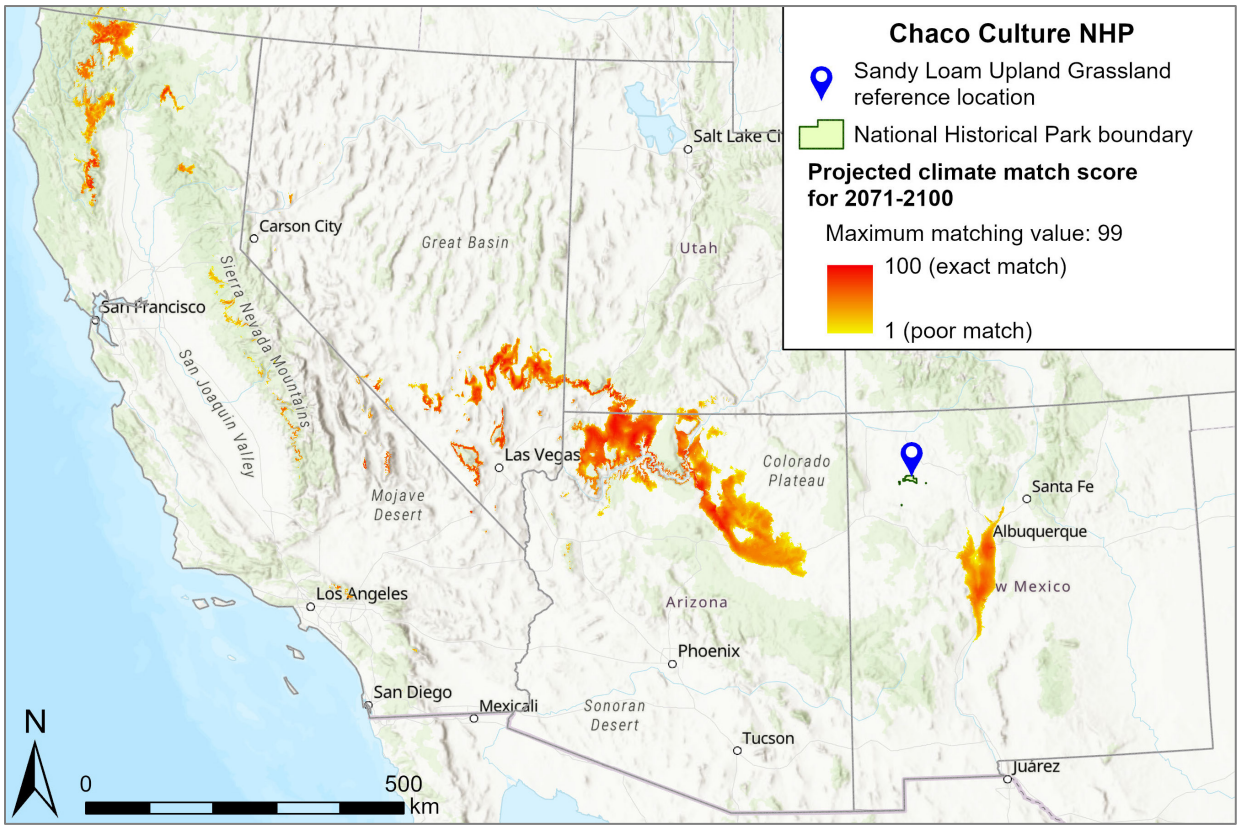


Figure 26. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in Chaco Culture NHP. Data derived from Seedlot Selection Tool scores (St. Clair et al. 2022). Current climate was based on 1981–2010 normals. Projected climate was based on the years 2071–2100 using the RCP 8.5 scenario. Settings used allowed liberal definitions of matches, requiring similarity in only three variables: Mean Coldest Month Temperature, Summer Heat Moisture Index, and Frost-Free Period. Map shows possible future directions of natural or assisted migrations of species or of genetic strains within species. Data used to create this map are available in the associated data release. *NPS / KRISTIN STRAKA*

Glen Canyon NRA

MODIS Sensor Pixels Used in Ranked-Day Analysis

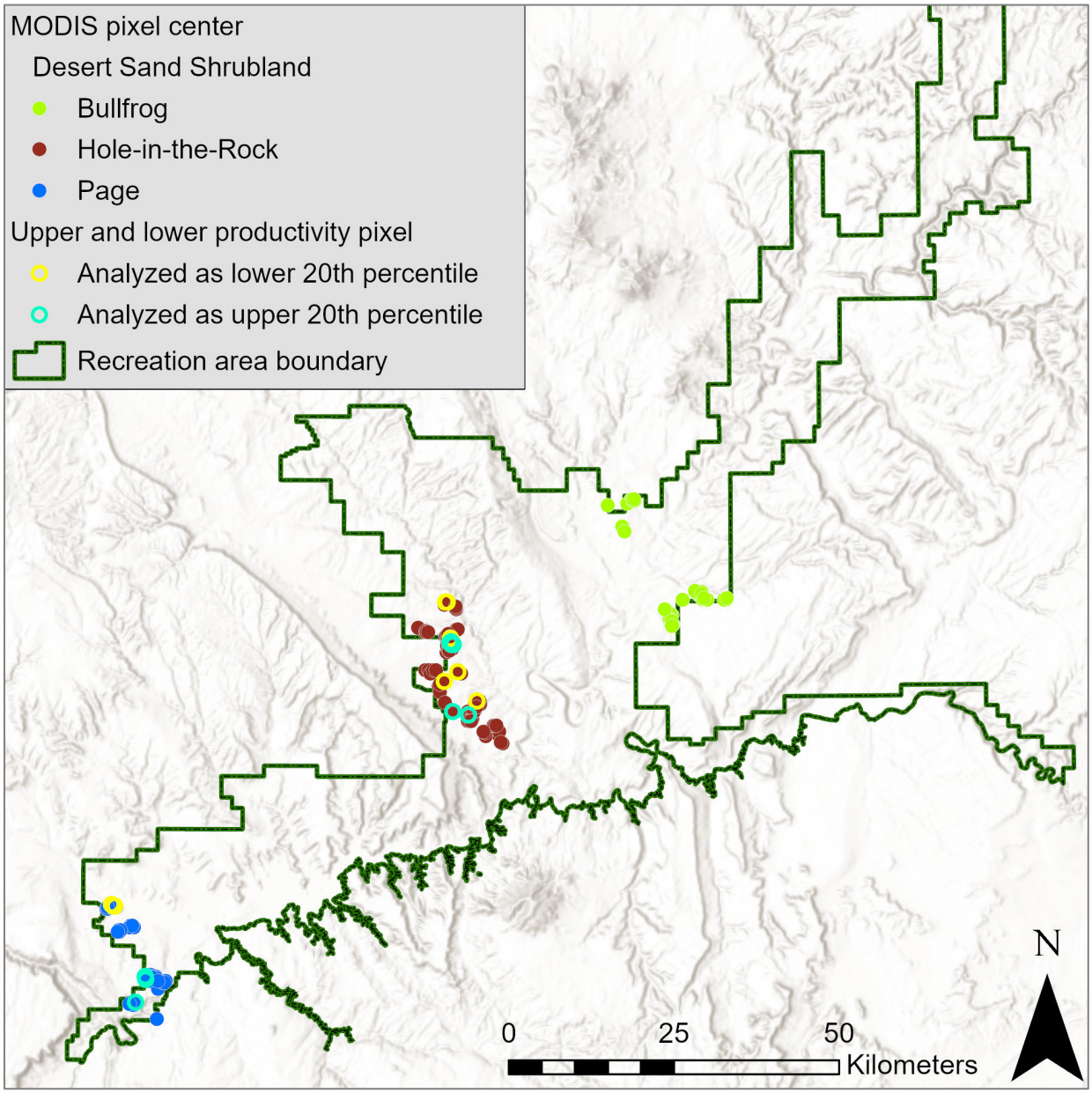


Figure 27. Map of MODIS pixel centers used for analysis at Glen Canyon NRA. Pixels analyzed as 20th and 80th percentile are limited to the 5% of pixels centered around the 20th and 80th percentiles of average greenness across the period of record (i.e., those pixels within the percentile ranges of 17.5%–22.5% and 77.5%–82.5%). This restriction was made to avoid possible outliers that might be incorrectly mapped as the target ecosystem and therefore which might fall at the extreme ends of the productivity distribution. These 20th and 80th percentile pixels are not present among the Bullfrog study area markers because there were too few total pixels available in the Bullfrog study area to divide into those percentile groups. *NPS / KRISTIN STRAKA*

Daily NDVI Data, Raster Graphs

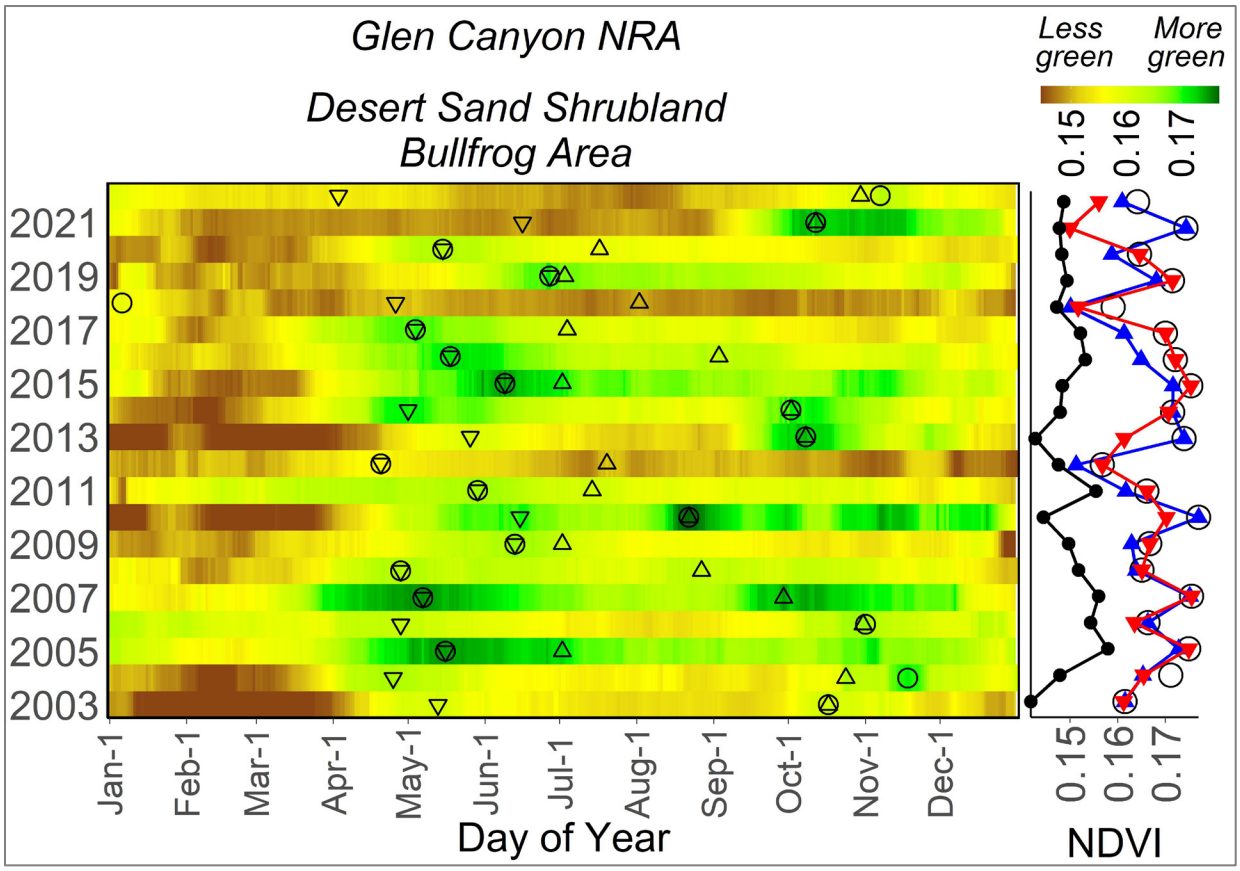


Figure 28. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Bullfrog Area of the Glen Canyon NRA Desert Sand Shrubland study area. The graphs show that the study area typically has low greenness during the winter, though a few years have episodes of greenness in the winter. Many years have separate peaks of greenness occurring during the springtime and monsoon season. Some years, such as 2012, 2018, and 2022 have little or no greenup evident throughout the growing season, suggesting vegetation stress during those years. Circular and triangular symbols mark the timing and intensity of the peak-of-season dates for each year: downward and upward pointing triangles mark the spring (March–June) and monsoon peak (July–October) timing. Intensity of the spring peak and monsoon peak is similarly marked by a downward or upward pointing triangle on the marginal plot. Open circles mark the timing and intensity of the annual peak. Closed circles on the marginal plots mark the approximate annual minimum NDVI value, which is approximate and has no associated calendar date because of uncertainty introduced by snow cover.

NPS / JODI NORRIS

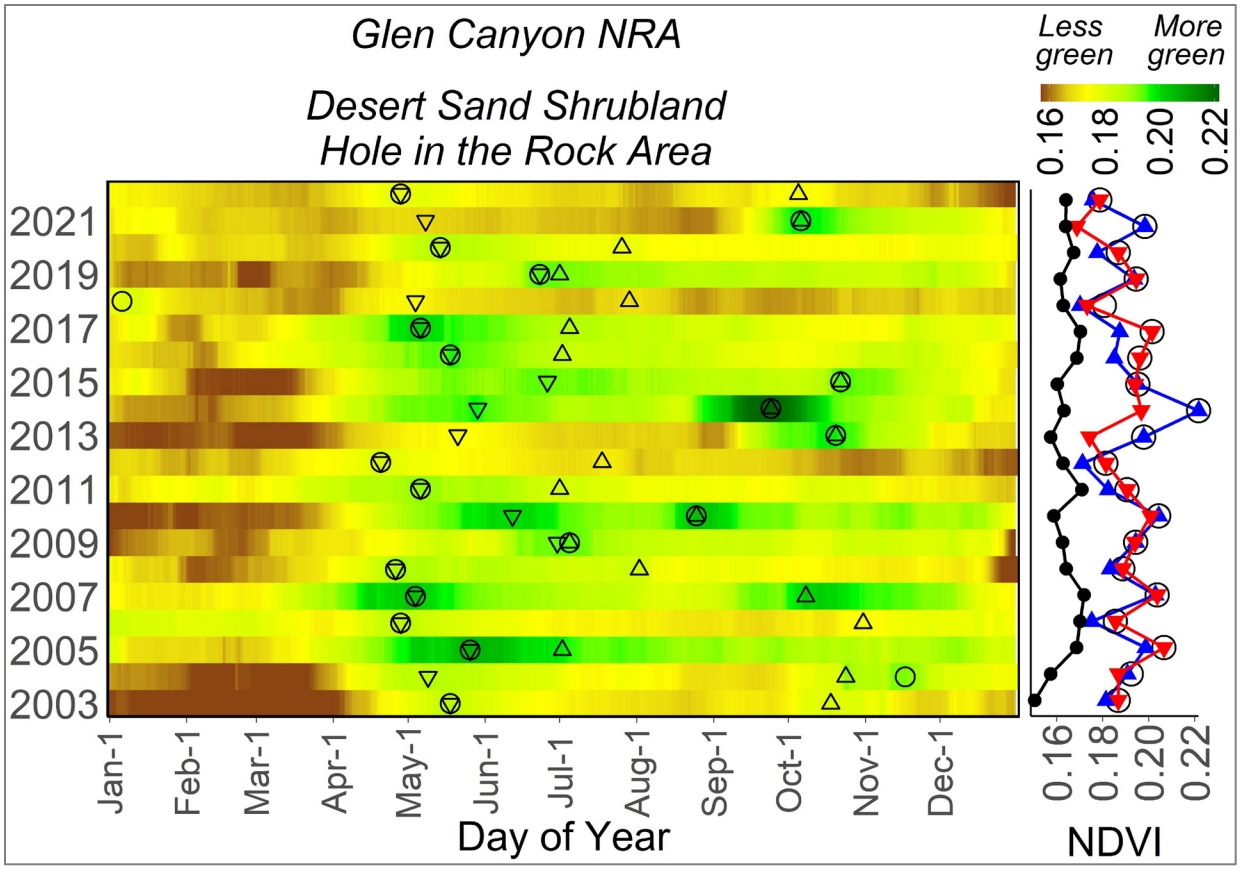


Figure 29. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Hole in the Rock Area of the Glen Canyon NRA Desert Sand Shrubland study area. The graphs show that the study area typically has low greenness during the winter, though a few years have minor episodes of greenness in the winter. Many years have separate peaks of greenness occurring during the springtime and monsoon season. Some years, such as 2018, and 2022 have little or no greenup evident throughout the growing season, suggesting vegetation stress during those years. Circular and triangular symbols mark the timing and intensity of the peak-of-season dates for each year: downward and upward pointing triangles mark the spring (March–June) and monsoon peak (July–October) timing. Intensity of the spring peak and monsoon peak is similarly marked by a downward or upward pointing triangle on the marginal plot. Open circles mark the timing and intensity of the annual peak. Closed circles on the marginal plots mark the approximate annual minimum NDVI value, which is approximate and has no associated calendar date because of uncertainty introduced by snow cover.

NPS / JODI NORRIS

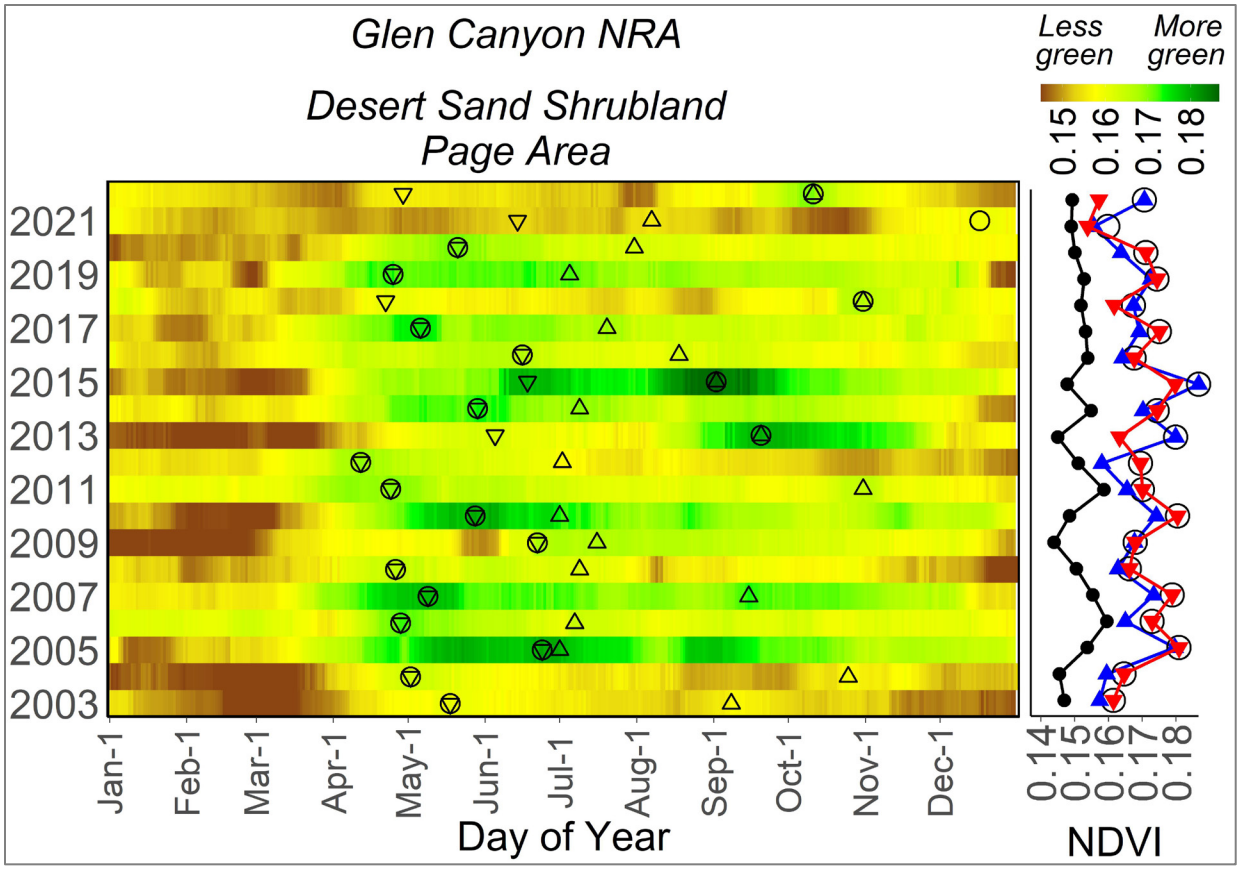


Figure 30. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Page Area of the Glen Canyon NRA Desert Sand Shrubland study area. The graphs show that the study area has low greenness during the winter. Most years have separate peaks of greenness occurring during the springtime and monsoon season. Some years, such as 2003, 2004, 2018, and 2021 have little or no greenup evident throughout the growing season, suggesting vegetation stress during those years. Circular and triangular symbols mark the timing and intensity of the peak-of-season dates for each year: downward and upward pointing triangles mark the spring (March–June) and monsoon peak (July–October) timing. Intensity of the spring peak and monsoon peak is similarly marked by a downward or upward pointing triangle on the marginal plot. Open circles mark the timing and intensity of the annual peak. Closed circles on the marginal plots mark the approximate annual minimum NDVI value, which is approximate and has no associated calendar date because of uncertainty introduced by snow cover.

NPS / JODI NORRIS

Ranked Daily Quantile Trends

Spring Trends

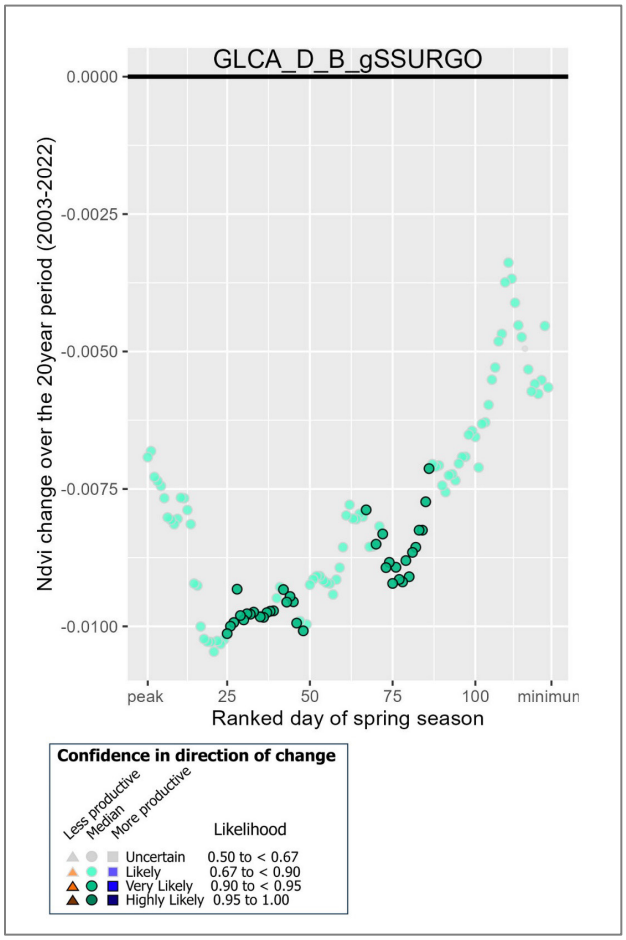


Figure 31. Ranked-day NDVI trend estimates for the spring season for the Bullfrog Area of the Glen Canyon NRA Desert Sand Shrubland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the spring season (March–June), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the spring season is rank 122 (number of days in the spring season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. In this graph, only the median productivity category is shown because the Bullfrog area of the Glen Canyon NRA Desert Sand Shrubland study area had too few pixels to separate into productivity categories. Plot shows decreasing NDVI trends for all days of the spring season. The middle-ranked days of the season have the largest trend decreases. This suggests that in addition to an overall downward shift throughout the spring season, the trend is towards narrower, shorter-lived peaks during the spring season. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

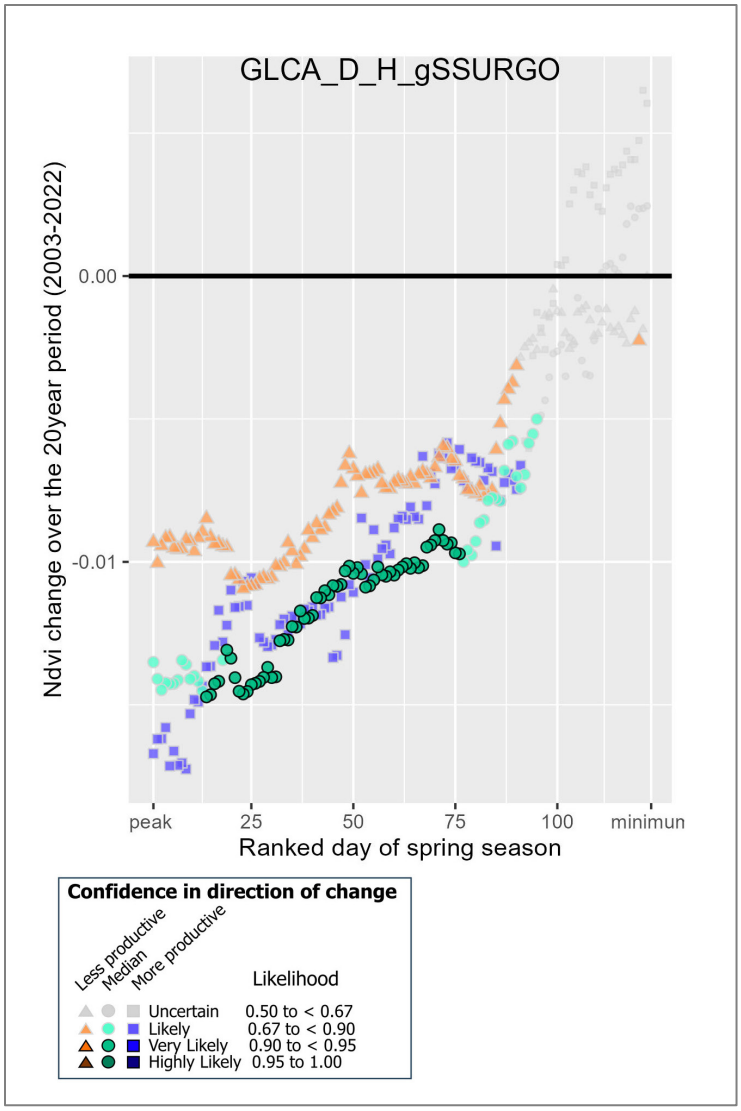


Figure 32. Ranked-day NDVI trend estimates for the spring season for the Hole in the Rock area of the Glen Canyon NRA Desert Sand Shrubland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the spring season (March–June), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the spring season is rank 122 (number of days in the spring season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Plot shows a pattern of decreasing NDVI trends for almost all days of the spring season, except for a small, uncertain increasing trend seen in the near-minimum days. The largest trends are seen for declines in the peak and near-peak values. This pattern is consistent across all three productivity levels, with the greatest confidence in negative direction of trend for the median productivity category. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

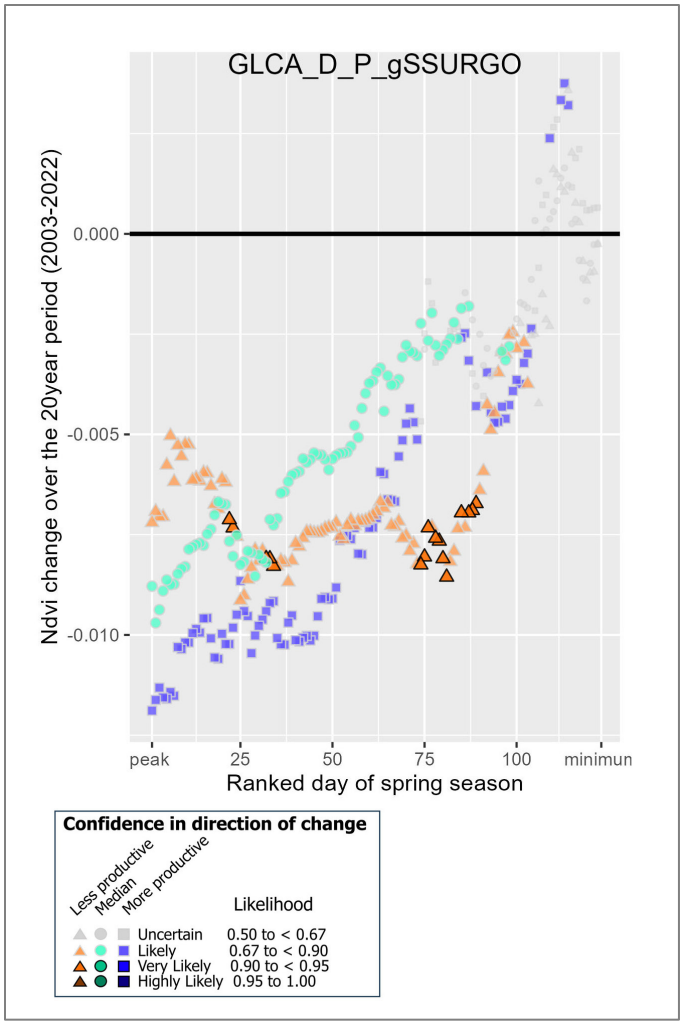


Figure 33. Ranked-day NDVI trend estimates for the spring season for the Page Area of the Glen Canyon NRA Desert Sand Shrubland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the spring season (March–June), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the spring season is rank 122 (number of days in the spring season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Plot shows a pattern of decreasing NDVI trends seen for almost all days of the spring season, except for a small increasing trend seen in the near-minimum days. The largest trends are generally seen for declines in the peak and near-peak values. This pattern is consistent for the median and more productive levels, while the less productive pixels have the largest negative trends in the middle set of days, suggesting an overall narrower (shorter time) peak of greenness for the lower productivity areas. The confidence for most of the change direction is likely, with a few “very likely” confidence levels for the less productive pixel values. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

Monsoon Trends

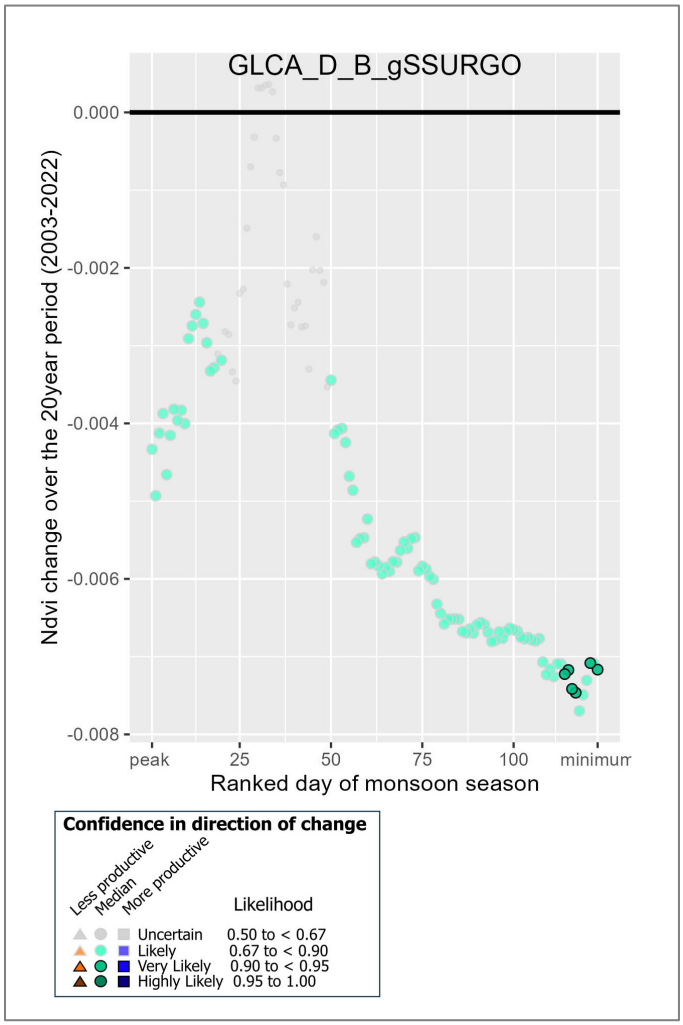


Figure 34. Ranked-day NDVI trend estimates for the monsoon season for the Bullfrog Area of the Glen Canyon NRA Desert Sand Shrubland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the monsoon season (July–October), with the "Peak" being the annual peak values for the season and the "Min" being the annual minimum value for the season. The points between the "Peak" and "Min" represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the monsoon season is rank 123 (number of days in the monsoon season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the "Less productive" and "More productive" parts of the study area. In this graph, only the median productivity category is shown because the Bullfrog area of the Glen Canyon NRA Desert Sand Shrubland study area had too few pixels to separate into productivity categories. Plot shows a pattern of decreasing NDVI trends seen for almost all days of the monsoon season. The largest trends and greatest confidence in direction of trend are seen for declines in the minimum NDVI values. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

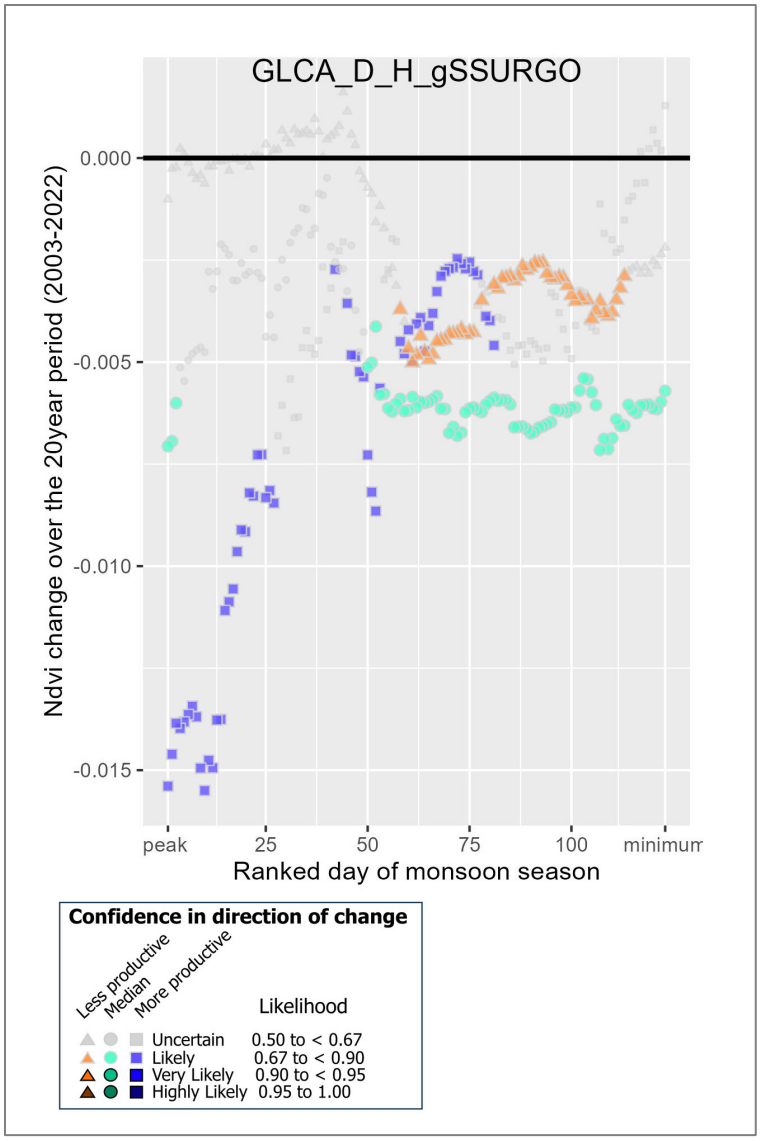


Figure 35. Ranked-day NDVI trend estimates for the monsoon season for the Hole in the Rock Area of the Glen Canyon NRA Desert Sand Shrubland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the monsoon season (July–October), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the monsoon season is rank 123 (number of days in the monsoon season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Decreasing NDVI values are seen for most days of the monsoon season. The largest declines are in the peak and near-peak values of the more productive pixels. The highest confidence level seen in these trends is “likely”, with most of the rank-days have a “likely” level of confidence in a negative trend for at least one of the productivity levels. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

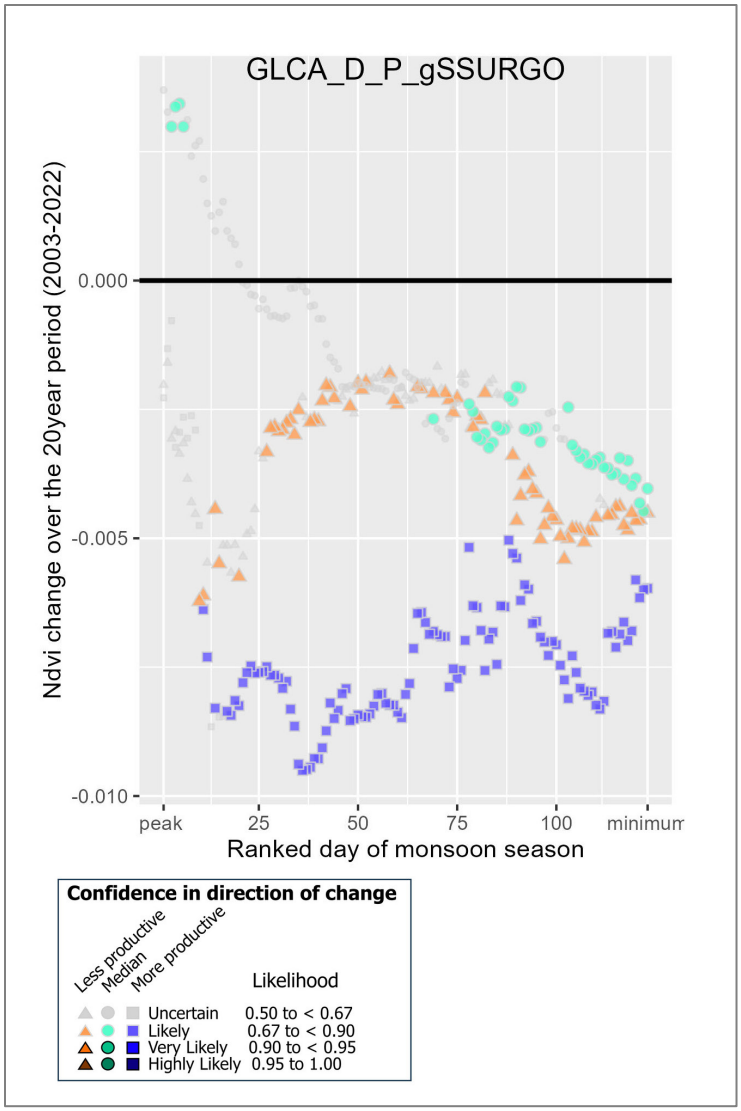


Figure 36. Ranked-day NDVI trend estimates for the monsoon season for the Page Area of the Glen Canyon NRA Desert Sand Shrubland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the monsoon season (July–October), with the "Peak" being the annual peak values for the season and the "Min" being the annual minimum value for the season. The points between the "Peak" and "Min" represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the monsoon season is rank 123 (number of days in the monsoon season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the "Less productive" and "More productive" parts of the study area. Plot shows trends of decreasing NDVI values for most days of the monsoon season. The largest declines are in the more productive pixels. The median pixels trend directions range from negative at the season minimum to positive trends at the season peak. The highest confidence level seen in these trends is "likely", with most of the rank-days have a "likely" level of confidence in a negative trend for at least one of the productivity levels. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

Seedlot Selection Tool Maps

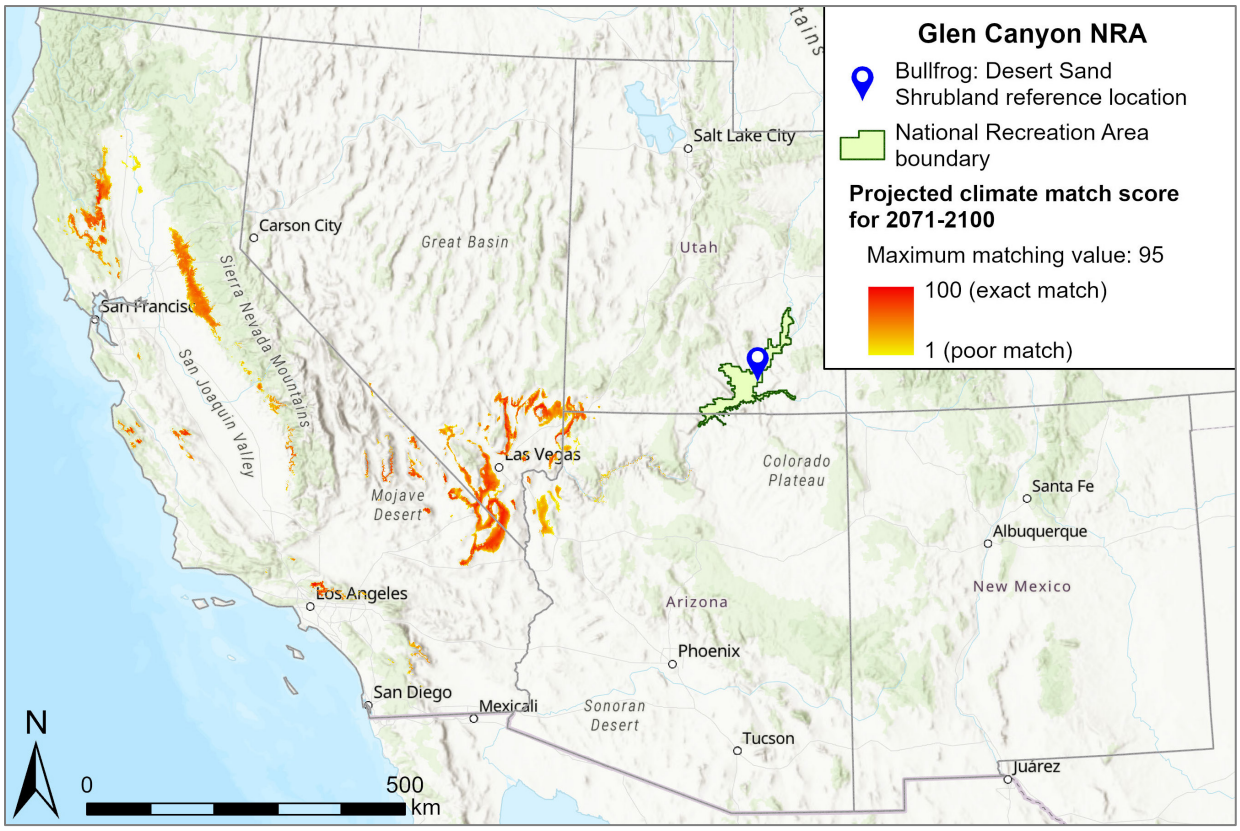


Figure 37. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Bullfrog Area of the Glen Canyon NRA Desert Sand Shrubland study area. Data derived from Seedlot Selection Tool scores (St. Clair et al. 2022). Current climate was based on 1981–2010 normals. Projected climate was based on the years 2071–2100 using the RCP 8.5 scenario. Settings used allowed liberal definitions of matches, requiring similarity in only three variables: Mean Coldest Month Temperature, Summer Heat Moisture Index, and Frost-Free Period. Map shows possible future directions of natural or assisted migrations of species or of genetic strains within species. Data used to create this map are available in the associated data release.

NPS / KRISTIN STRAKA

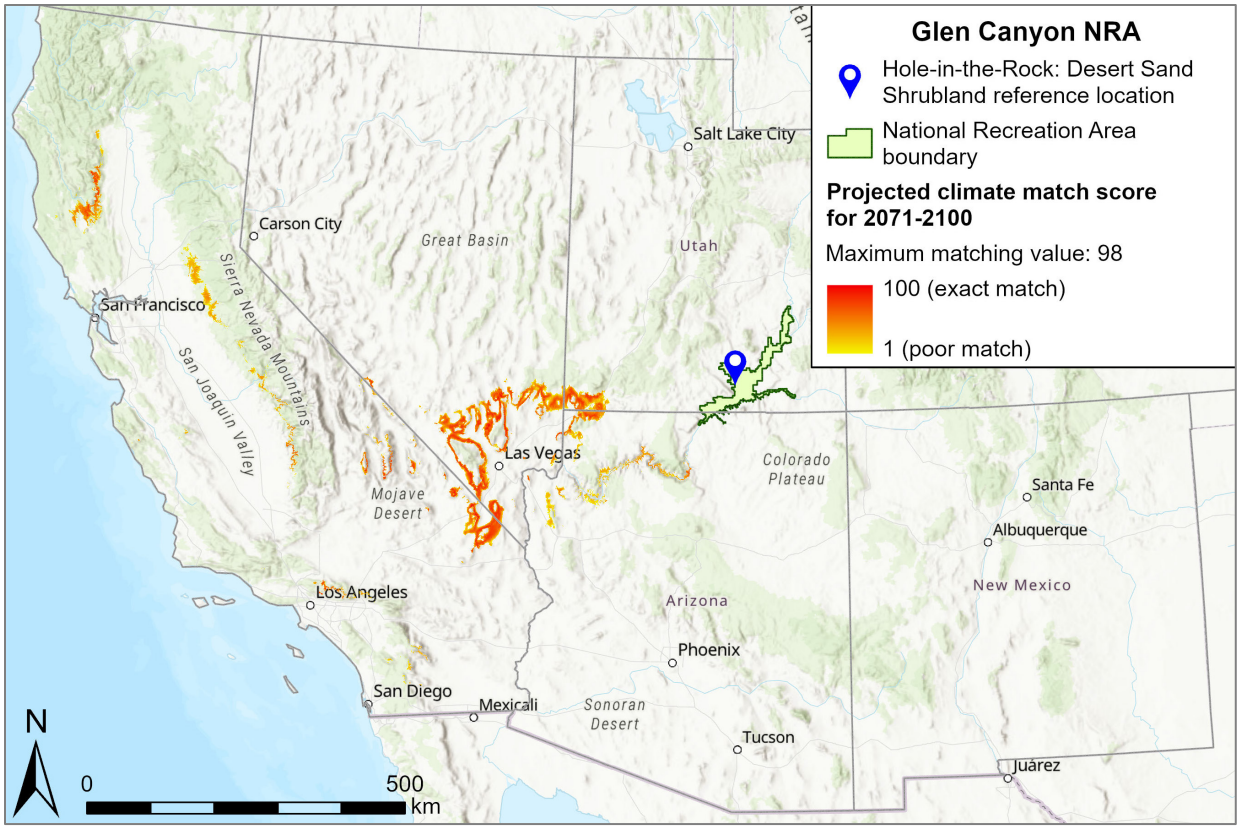


Figure 38. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Hole in the Rock Area of the Glen Canyon NRA Desert Sand Shrubland study area. Data derived from Seedlot Selection Tool scores (St. Clair et al. 2022). Current climate was based on 1981–2010 normals. Projected climate was based on the years 2071–2100 using the RCP 8.5 scenario. Settings used allowed liberal definitions of matches, requiring similarity in only three variables: Mean Coldest Month Temperature, Summer Heat Moisture Index, and Frost-Free Period. Map shows possible future directions of natural or assisted migrations of species or of genetic strains within species. Data used to create this map are available in the associated data release.

NPS / KRISTIN STRAKA

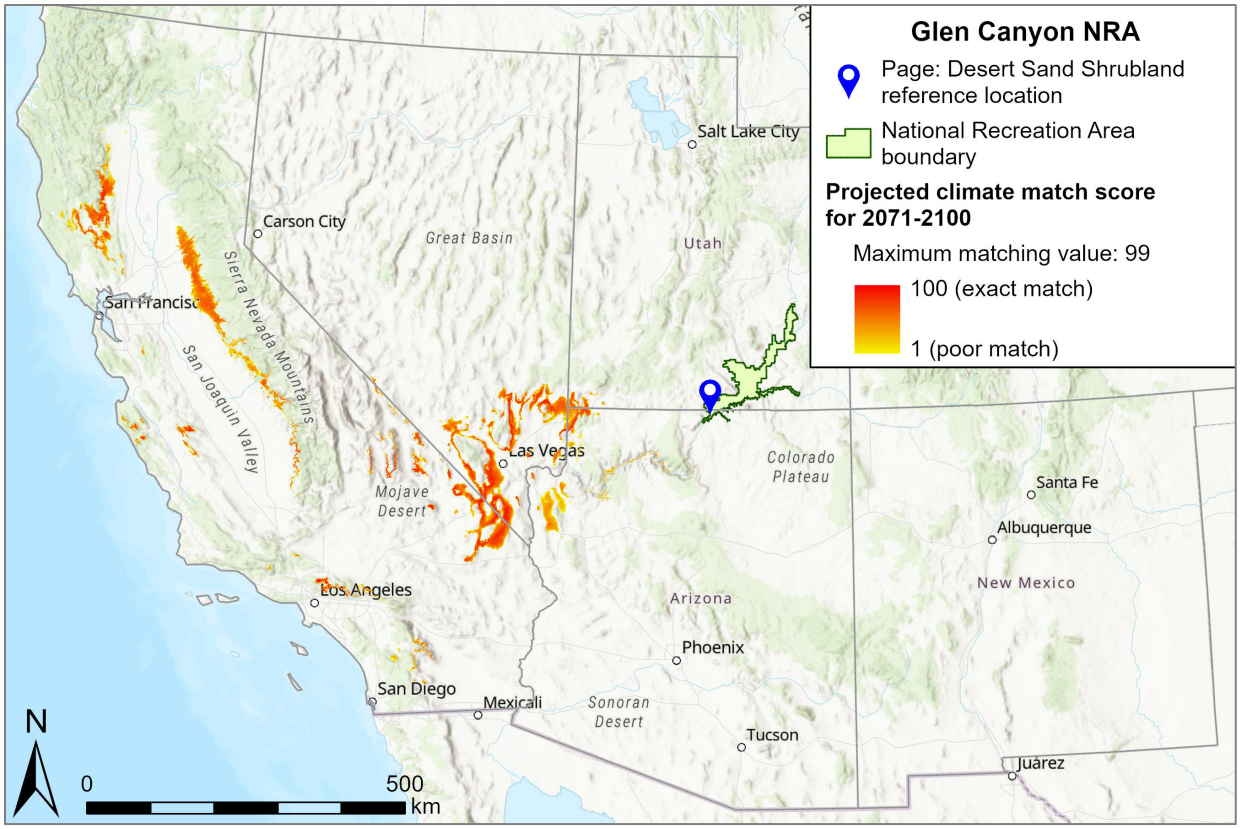


Figure 39. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Page Area of the Glen Canyon NRA Desert Sand Shrubland study area. Data derived from Seedlot Selection Tool scores (St. Clair et al. 2022). Current climate was based on 1981–2010 normals. Projected climate was based on the years 2071–2100 using the RCP 8.5 scenario. Settings used allowed liberal definitions of matches, requiring similarity in only three variables: Mean Coldest Month Temperature, Summer Heat Moisture Index, and Frost-Free Period. Map shows possible future directions of natural or assisted migrations of species or of genetic strains within species. Data used to create this map are available in the associated data release.

NPS / KRISTIN STRAKA

Petrified Forest NP

MODIS Sensor Pixels Used in Ranked-Day Analysis

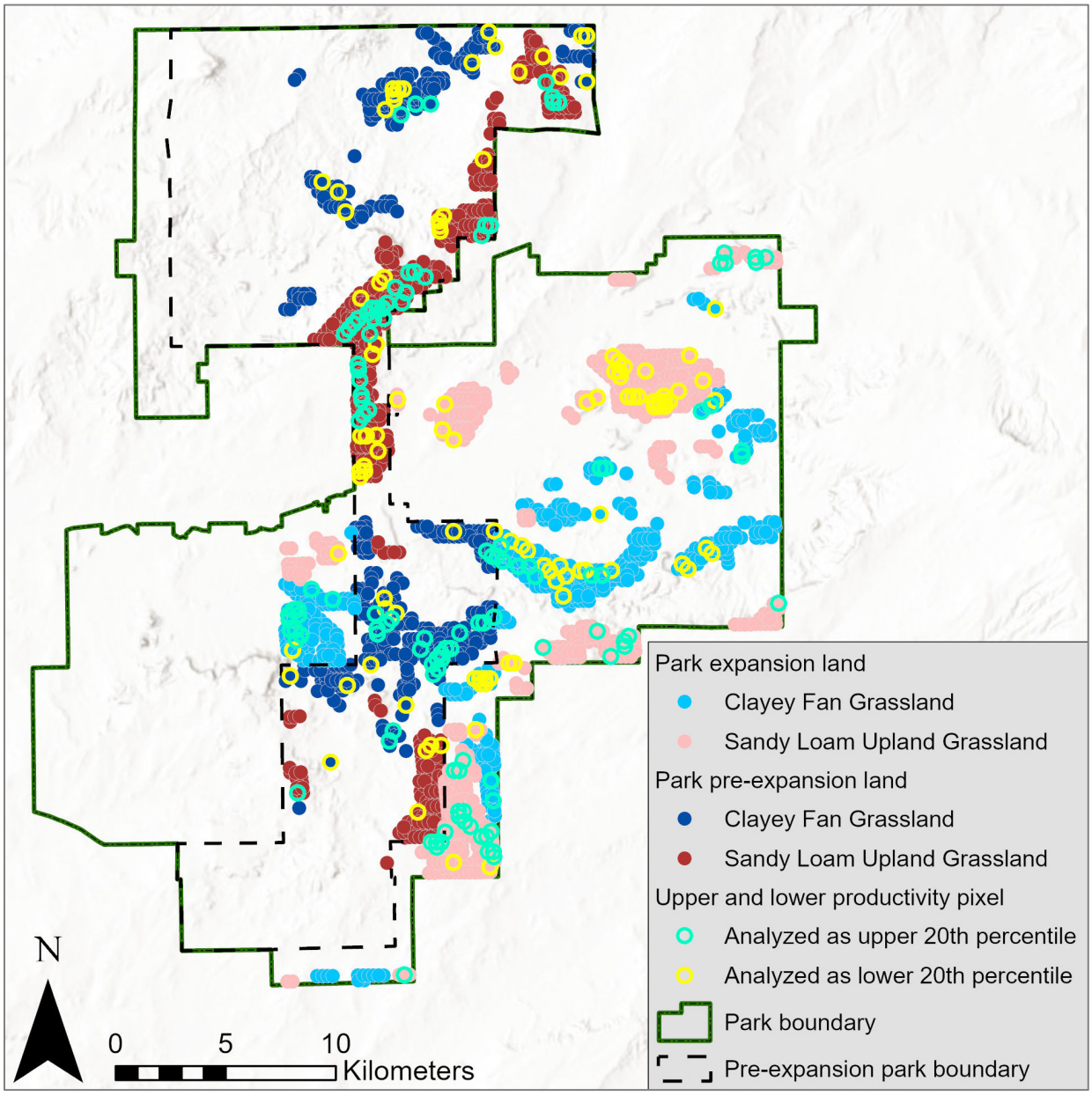


Figure 40. Map of MODIS pixel centers used for analysis at Petrified Forest NP. Pixels analyzed as 20th and 80th percentile are limited to the 5% of pixels centered around the 20th and 80th percentiles of average greenness across the period of record (i.e., those pixels within the percentile ranges of 17.5%–22.5% and 77.5%–82.5%). This restriction was made to avoid possible outliers that might be incorrectly mapped as the target ecosystem and therefore which might fall at the extreme ends of the productivity distribution.
NPS / KRISTIN STRAKA

Daily NDVI Data, Raster Graphs

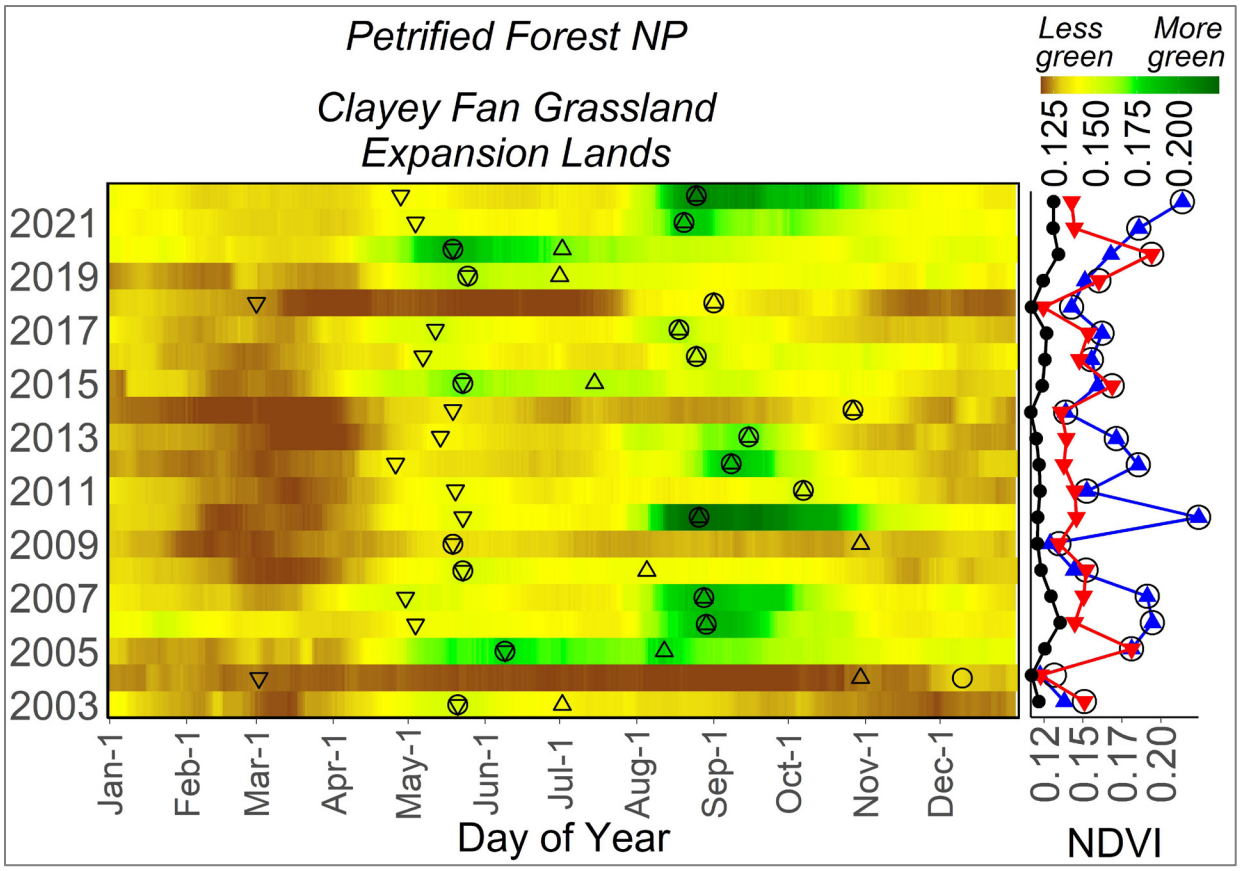


Figure 41. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Petrified Forest NP Clayey Fan Grassland, Expansion Lands study area. The graphs show that the study area has low greenness during the winter. About half of the years have prominent monsoon peaks, and very few years have prominent spring peaks. Some years, such as 2004, 2009, 2014, and 2018 have little or no greenup evident throughout the growing season, suggesting vegetation stress during those years. Circular and triangular symbols mark the timing and intensity of the peak-of-season dates for each year: downward and upward pointing triangles mark the spring (March–June) and monsoon peak (July–October) timing. Intensity of the spring peak and monsoon peak is similarly marked by a downward or upward pointing triangle on the marginal plot. Open circles mark the timing and intensity of the annual peak. Closed circles on the marginal plots mark the approximate annual minimum NDVI value, which is approximate and has no associated calendar date because of uncertainty introduced by snow cover.

NPS / JODI NORRIS

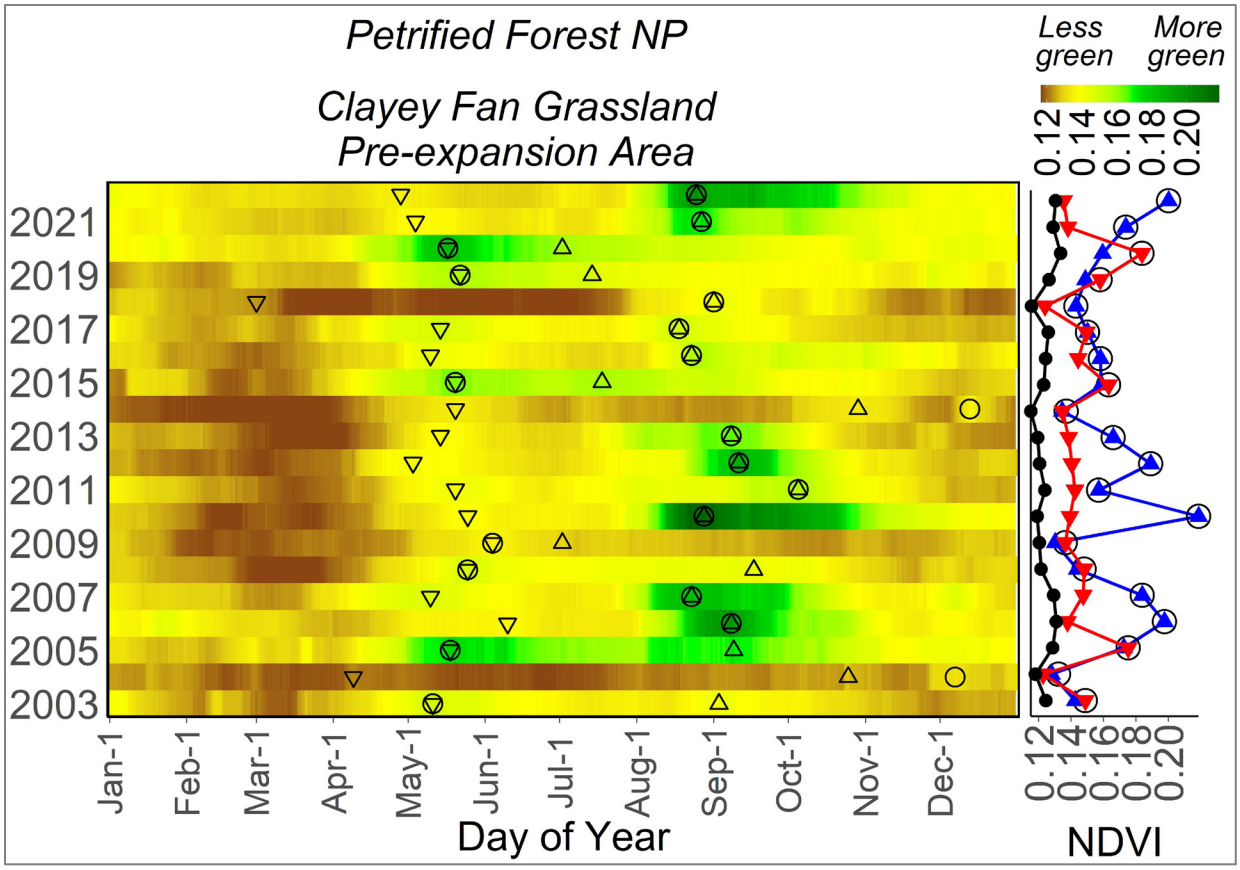


Figure 42. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Petrified Forest NP Clayey Fan Grassland, Pre-expansion Area study area. The graphs show that the study area has low greenness during the winter. About half of the years have prominent monsoon peaks, and very few years have prominent spring peaks. Some years, such as 2004, 2009, 2014, and 2018 have little or no greenup evident throughout the growing season, suggesting vegetation stress during those years. Circular and triangular symbols mark the timing and intensity of the peak-of-season dates for each year: downward and upward pointing triangles mark the spring (March–June) and monsoon peak (July–October) timing. Intensity of the spring peak and monsoon peak is similarly marked by a downward or upward pointing triangle on the marginal plot. Open circles mark the timing and intensity of the annual peak. Closed circles on the marginal plots mark the approximate annual minimum NDVI value, which is approximate and has no associated calendar date because of uncertainty introduced by snow cover.

NPS / JODI NORRIS

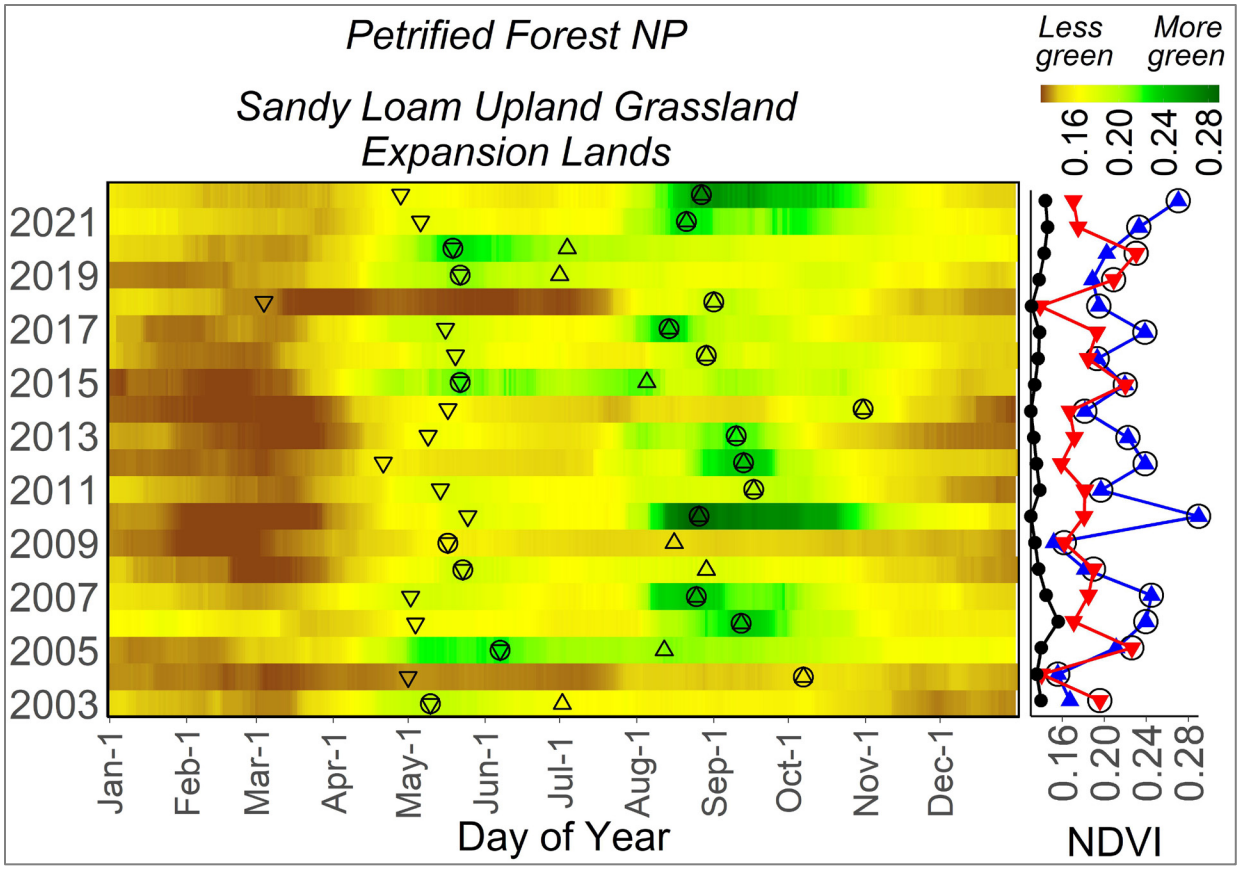


Figure 43. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Petrified Forest NP Sandy Loam Upland Grassland, Expansion Lands study area. The graphs show that the study area has low greenness during the winter. About half of the years have prominent monsoon peaks, and several years have prominent spring peaks. Two years (2004 and 2009) have little or no greenup evident throughout the growing season, suggesting vegetation stress during those years. Circular and triangular symbols mark the timing and intensity of the peak-of-season dates for each year: downward and upward pointing triangles mark the spring (March–June) and monsoon peak (July–October) timing. Intensity of the spring peak and monsoon peak is similarly marked by a downward or upward pointing triangle on the marginal plot. Open circles mark the timing and intensity of the annual peak. Closed circles on the marginal plots mark the approximate annual minimum NDVI value, which is approximate and has no associated calendar date because of uncertainty introduced by snow cover.

NPS / JODI NORRIS

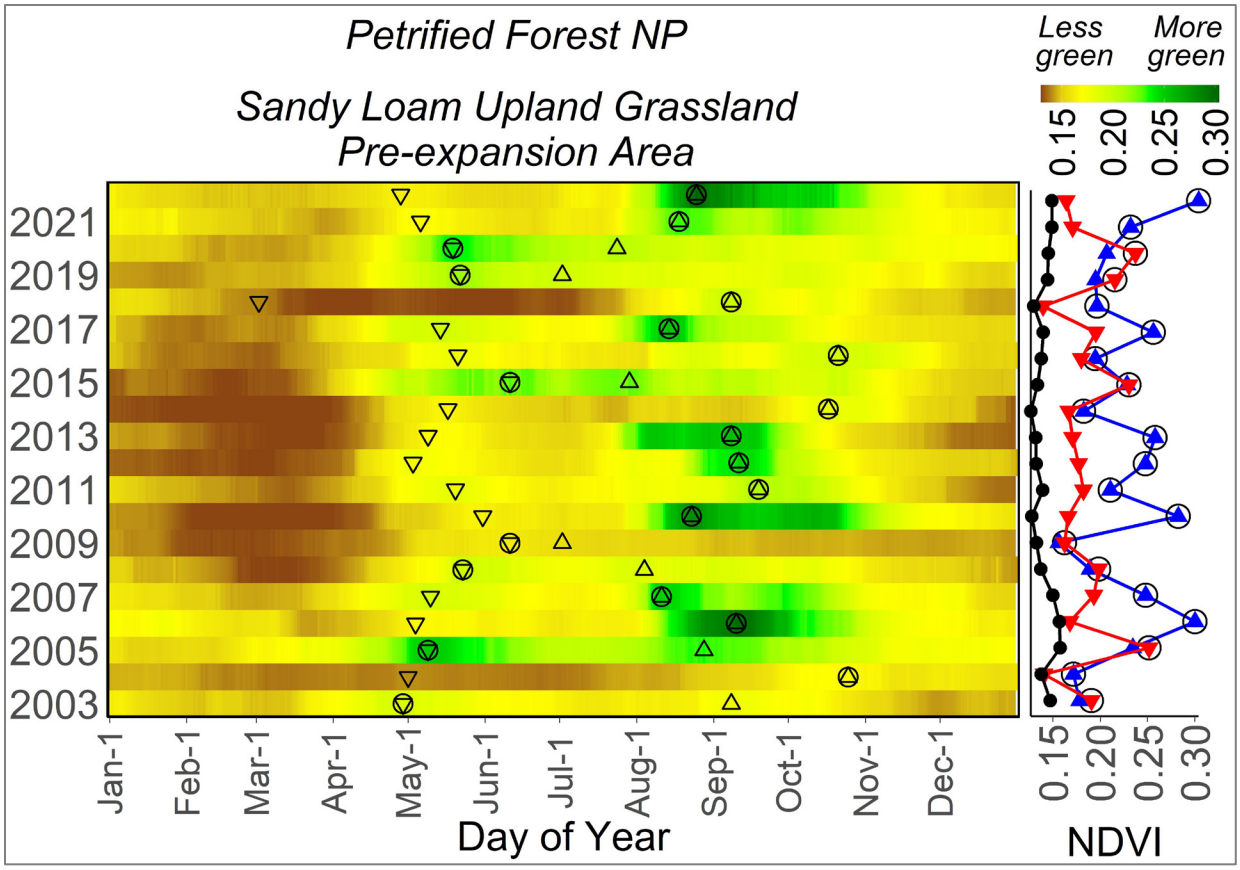


Figure 44. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Petrified Forest NP Sandy Loam Upland Grassland, Pre-expansion Area study area. The graphs show that the study area has low greenness during the winter. About half of the years have prominent monsoon peaks, and several years have prominent spring peaks. Two years (2004 and 2009) have little or no greenup evident throughout the growing season, suggesting vegetation stress during those years. Circular and triangular symbols mark the timing and intensity of the peak-of-season dates for each year: downward and upward pointing triangles mark the spring (March–June) and monsoon peak (July–October) timing. Intensity of the spring peak and monsoon peak is similarly marked by a downward or upward pointing triangle on the marginal plot. Open circles mark the timing and intensity of the annual peak. Closed circles on the marginal plots mark the approximate annual minimum NDVI value, which is approximate and has no associated calendar date because of uncertainty introduced by snow cover.

NPS / JODI NORRIS

Ranked Daily Quantile Trends

Spring Trends

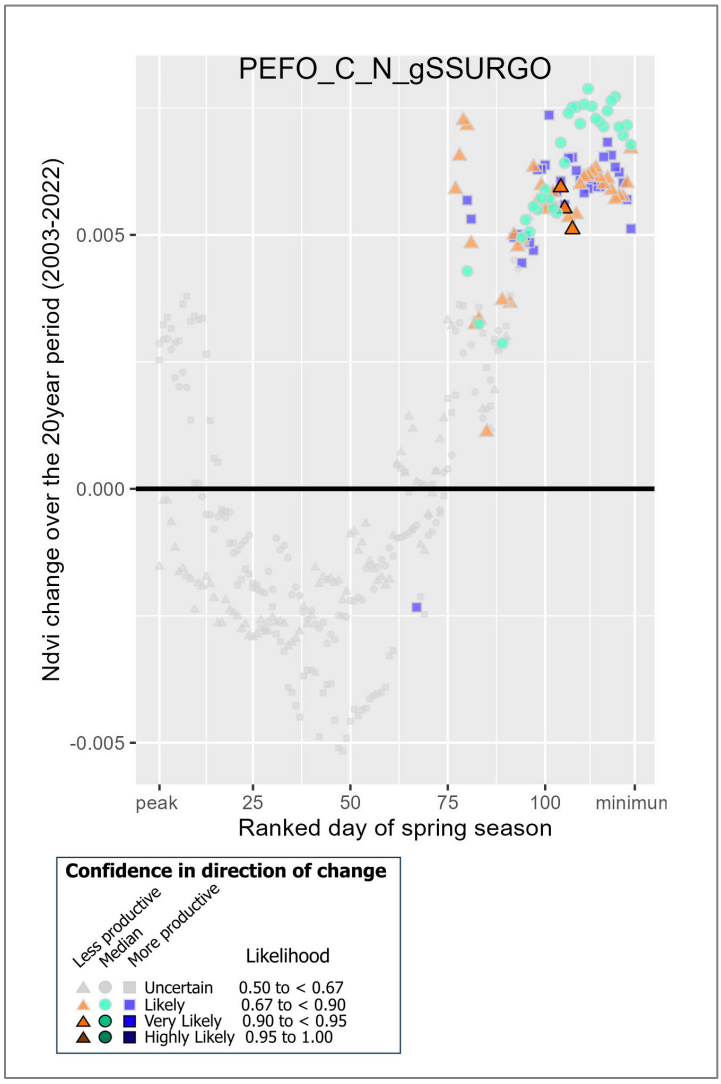


Figure 45. Ranked-day NDVI trend estimates for the spring season for the Petrified Forest NP Clayey Fan Grassland, Expansion Lands study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the spring season (March–June), with the "Peak" being the annual peak values for the season and the "Min" being the annual minimum value for the season. The points between the "Peak" and "Min" represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the spring season is rank 122 (number of days in the spring season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the "Less productive" and "More productive" parts of the study area. Plot shows uncertain changes for most of the spring season, with consistently increasing trends for the days near the season's minimum for all three productivity levels. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

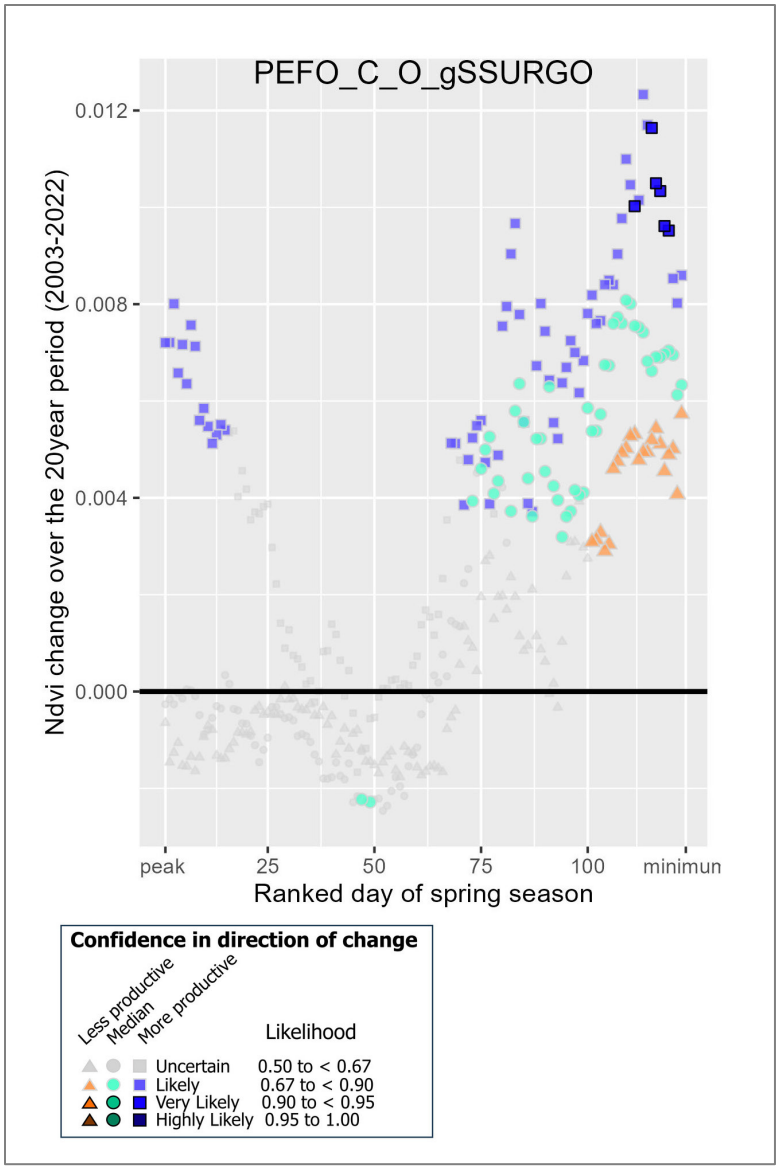


Figure 46. Ranked-day NDVI trend estimates for the spring season for the Petrified Forest NP Clayey Fan Grassland, Pre-expansion Area study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the spring season (March–June), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the spring season is rank 122 (number of days in the spring season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Plot shows trends of increasing NDVI for all three productivity levels for days at and near the season minimum, as well as trends of increasing NDVI for the peak days of the spring season for the pixels in the highest productivity group. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

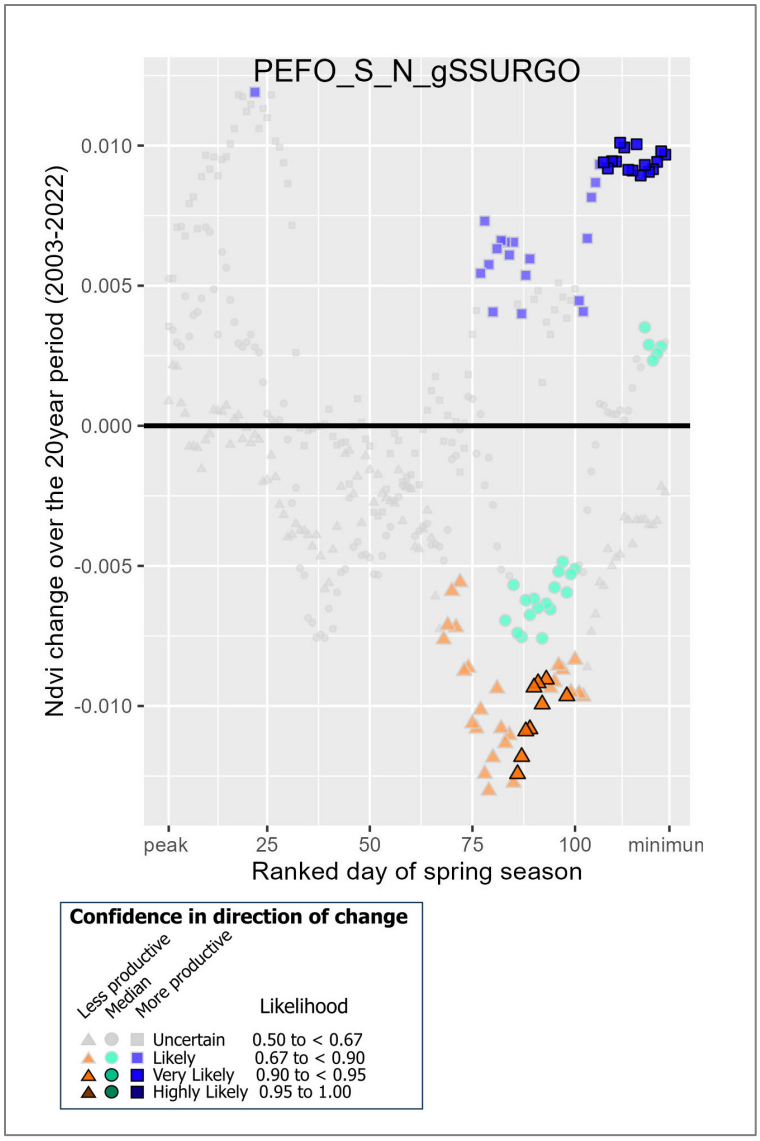


Figure 47. Ranked-day NDVI trend estimates for the spring season for the Petrified Forest NP Sandy Loam Upland Grassland, Expansion Lands study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the spring season (March–June), with the "Peak" being the annual peak values for the season and the "Min" being the annual minimum value for the season. The points between the "Peak" and "Min" represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the spring season is rank 122 (number of days in the spring season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the "Less productive" and "More productive" parts of the study area. Plot shows trends of increasing NDVI for the most productive and median productivity levels for days at and near the spring season minimum; however, there are decreasing trends during the lower (but not minimum) days of the season for the less productive and median productivity levels, while the trends are positive for those same days for the more productive pixels. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.
NPS / JODI NORRIS

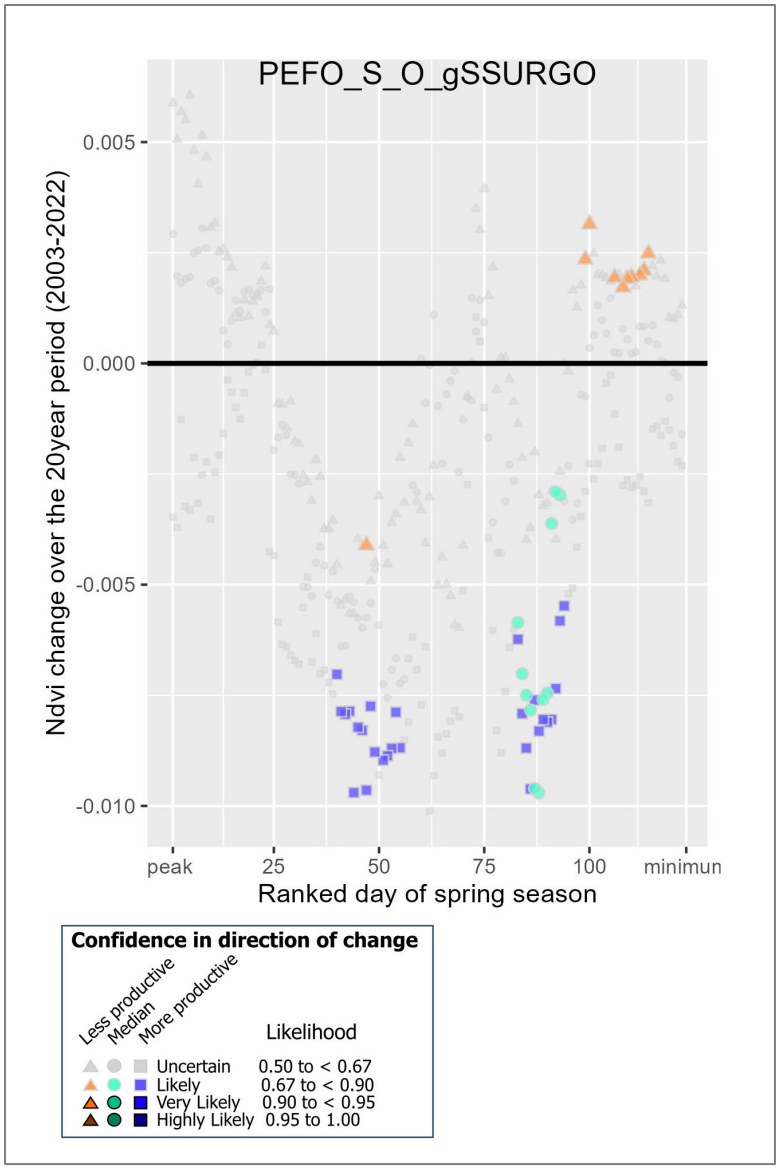


Figure 48. Ranked-day NDVI trend estimates for the spring season for the Petrified Forest NP Sandy Loam Upland Grassland, Pre-expansion Area study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the spring season (March–June), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the spring season is rank 122 (number of days in the spring season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Plot shows trends of increasing NDVI for the least productive pixels for days near the spring season minimum; however, there are decreasing trends intermittently during other days of the season for both the more productive pixels and median values. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

Monsoon Trends

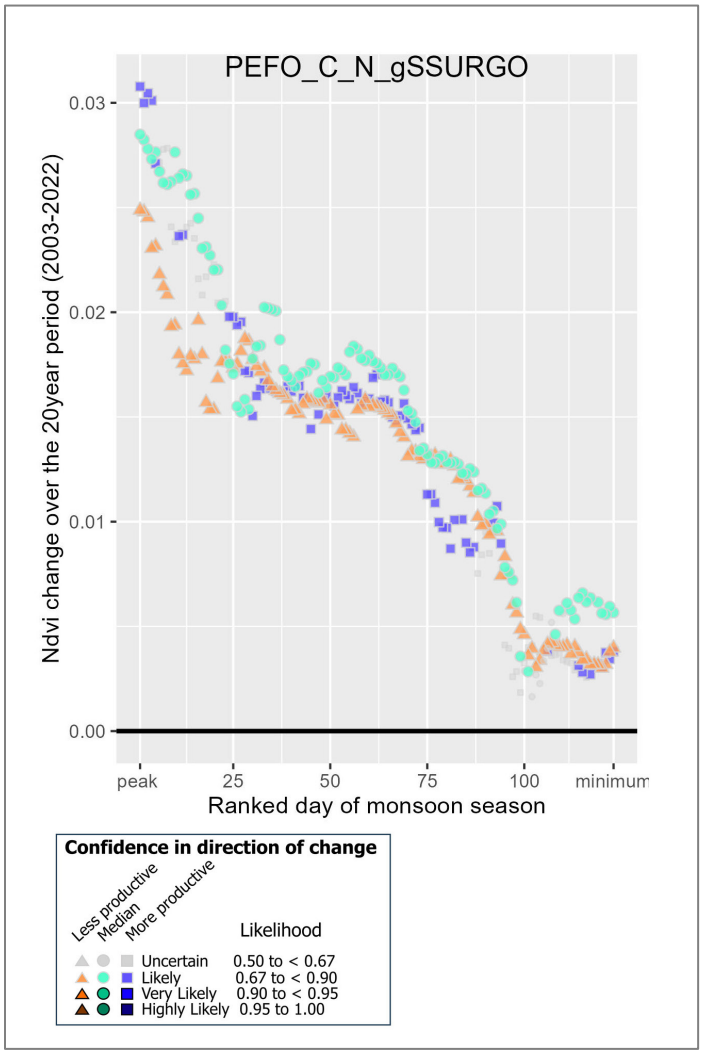


Figure 49. Ranked-day NDVI trend estimates for the monsoon season for the Petrified Forest NP Clayey Fan Grassland, Expansion Lands study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the monsoon season (July–October), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the monsoon season is rank 123 (number of days in the monsoon season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Plot shows a pattern of increasing NDVI trends for all days of the monsoon season. The largest trends are seen for increases in the peak and near-peak values. This pattern is consistent across all three productivity levels, with confidence levels of likely for most days and across all three productivity levels. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

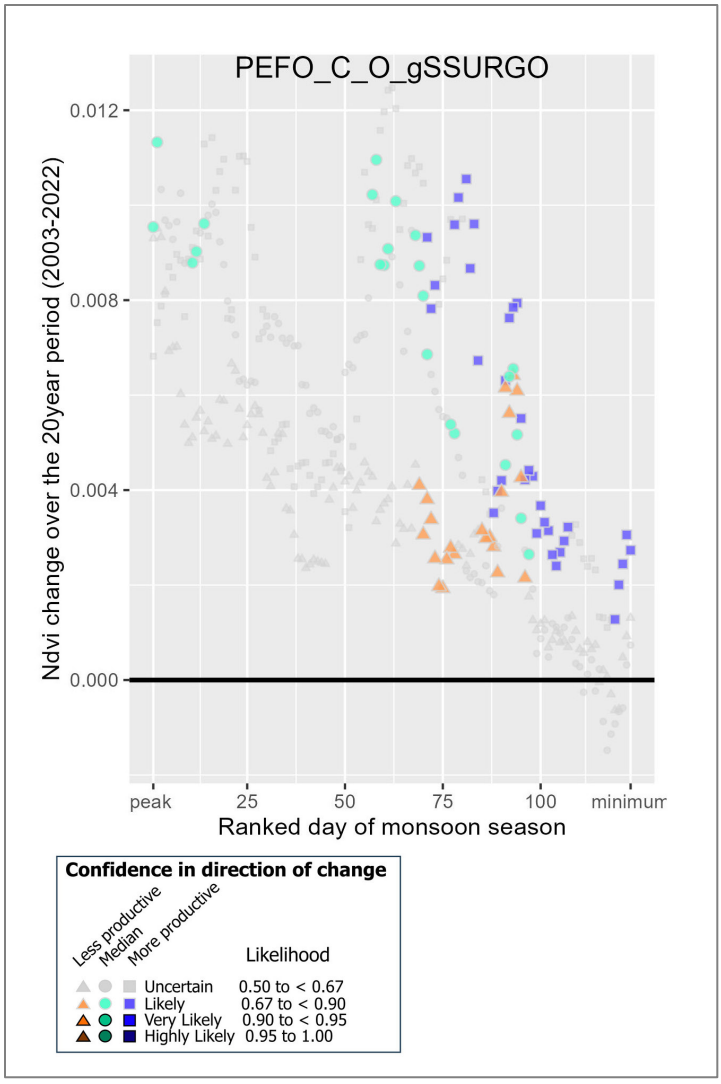


Figure 50. Ranked-day NDVI trend estimates for the monsoon season for the Petrified Forest NP Clayey Fan Grassland, Pre-expansion Area study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the monsoon season (July–October), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the monsoon season is rank 123 (number of days in the monsoon season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Plot shows trends of increasing NDVI values for all days of the monsoon season. The highest confidence level seen in these trends is “likely”, with approximately half of the rank-days have a “likely” level of confidence in a positive trend for at least one of the productivity levels. All productivity levels have some days with increasing trends at the likely confidence level, although no productivity level has more than half of the rank-days showing increasing trends at the likely confidence level. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

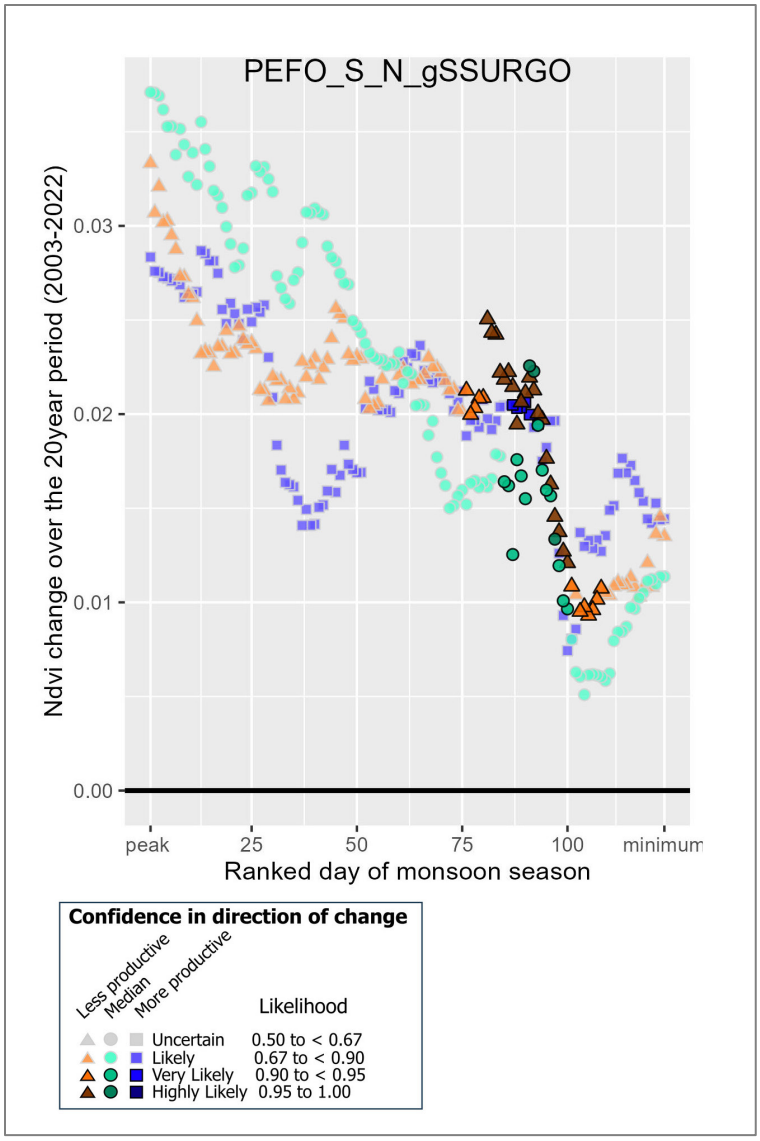


Figure 51. Ranked-day NDVI trend estimates for the monsoon season for the Petrified Forest NP Sandy Loam Upland Grassland, Expansion Lands study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the monsoon season (July–October), with the "Peak" being the annual peak values for the season and the "Min" being the annual minimum value for the season. The points between the "Peak" and "Min" represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the monsoon season is rank 123 (number of days in the monsoon season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the "Less productive" and "More productive" parts of the study area. Plot shows trends of increasing NDVI values for all days of the monsoon season. The highest confidence level seen in these trends is "highly likely". All the rank-days at all productivity levels have at least a "likely" level of confidence in a positive trend for all of the productivity levels. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

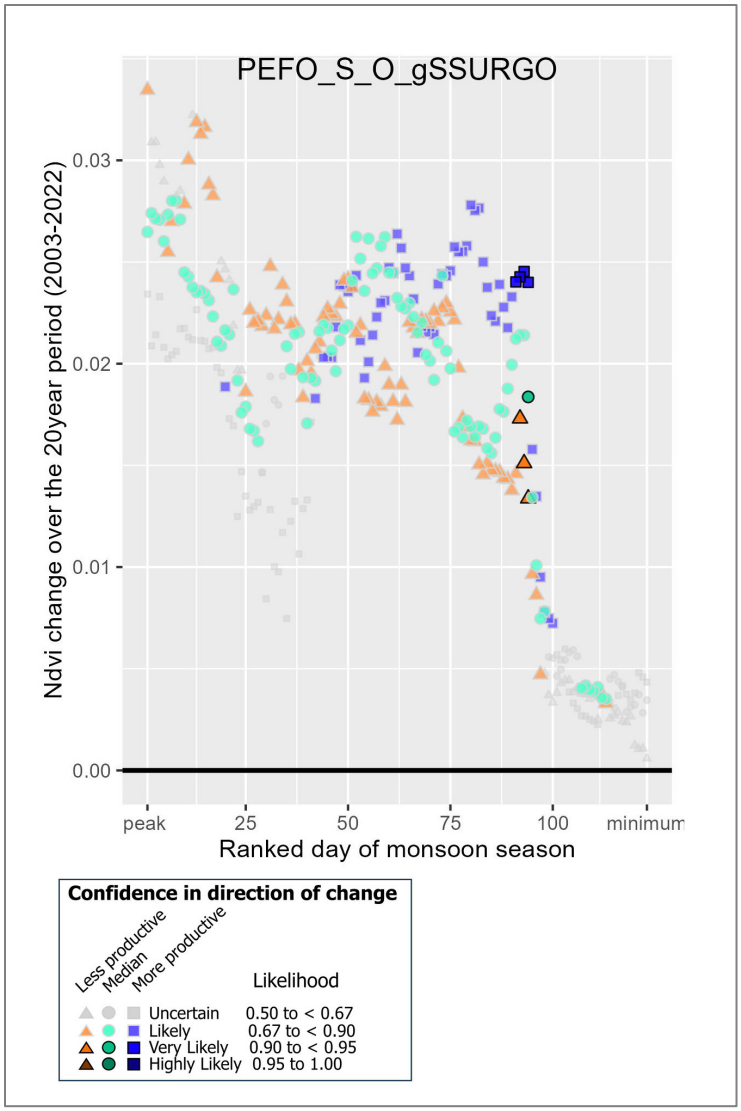


Figure 52. Ranked-day NDVI trend estimates for the monsoon season for the Petrified Forest NP Sandy Loam Upland Grassland, Pre-expansion Area study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the monsoon season (July–October), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the monsoon season is rank 123 (number of days in the monsoon season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Plot shows trends of increasing NDVI values for all days of the monsoon season. The highest confidence level seen in these trends is “very likely”. More than three-quarters of the rank-days have a “likely” or higher level of confidence in a positive trend for at least one of the productivity levels. All productivity levels have most days of the season with positive trends with a confidence level of at least likely. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

Seedlot Selection Tool Maps

Mapped estimates of locations that today have similar climate conditions to those expected in Petrified Forest NP Study Areas by the end of this century, suggesting what vegetation communities may shift towards and possible seed sources for genetic strains of species that may be more suited to future climate. Brighter red colors indicate a closer match.

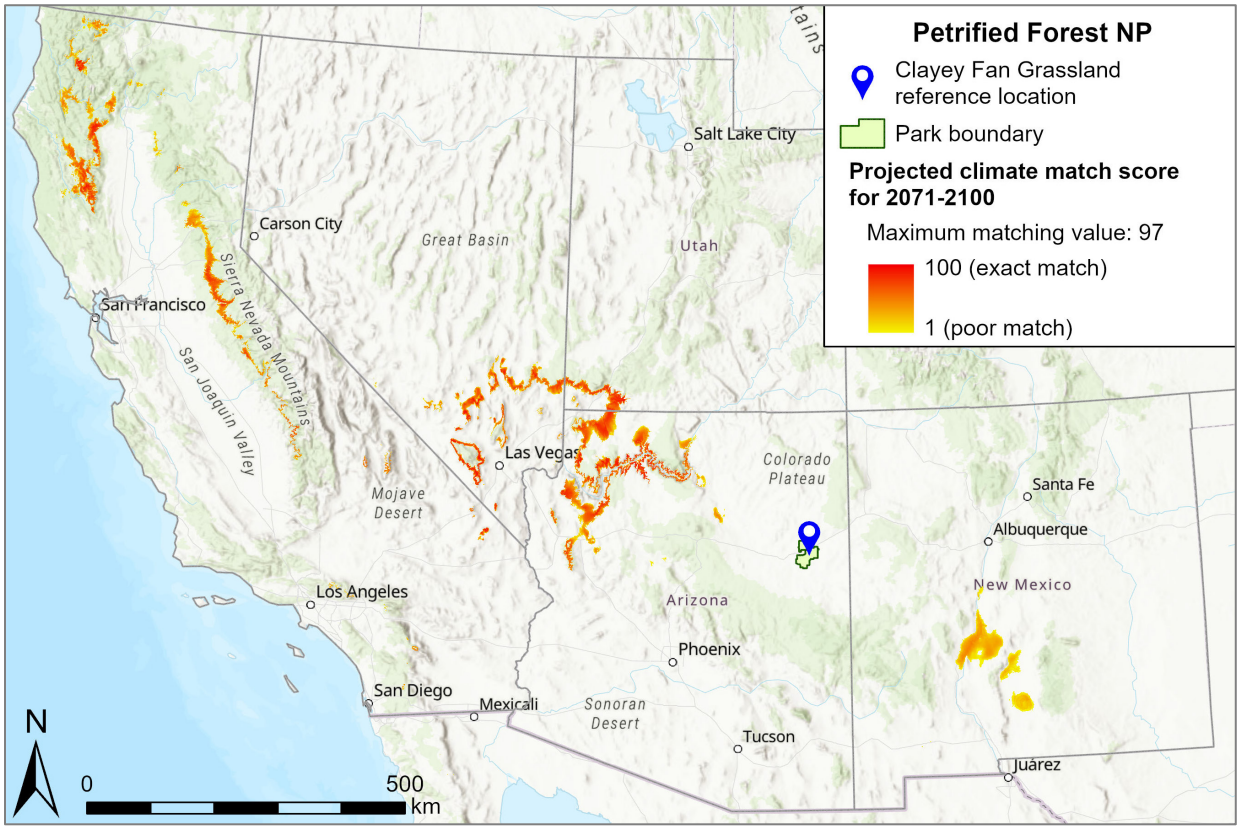


Figure 53. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Petrified Forest NP Clayey Fan Grassland study area. Data derived from Seedlot Selection Tool scores (St. Clair et al. 2022). Current climate was based on 1981–2010 normals. Projected climate was based on the years 2071–2100 using the RCP 8.5 scenario. Settings used allowed liberal definitions of matches, requiring similarity in only three variables: Mean Coldest Month Temperature, Summer Heat Moisture Index, and Frost-Free Period. Map shows possible future directions of natural or assisted migrations of species or of genetic strains within species. Data used to create this map are available in the associated data release.

NPS / KRISTIN STRAKA

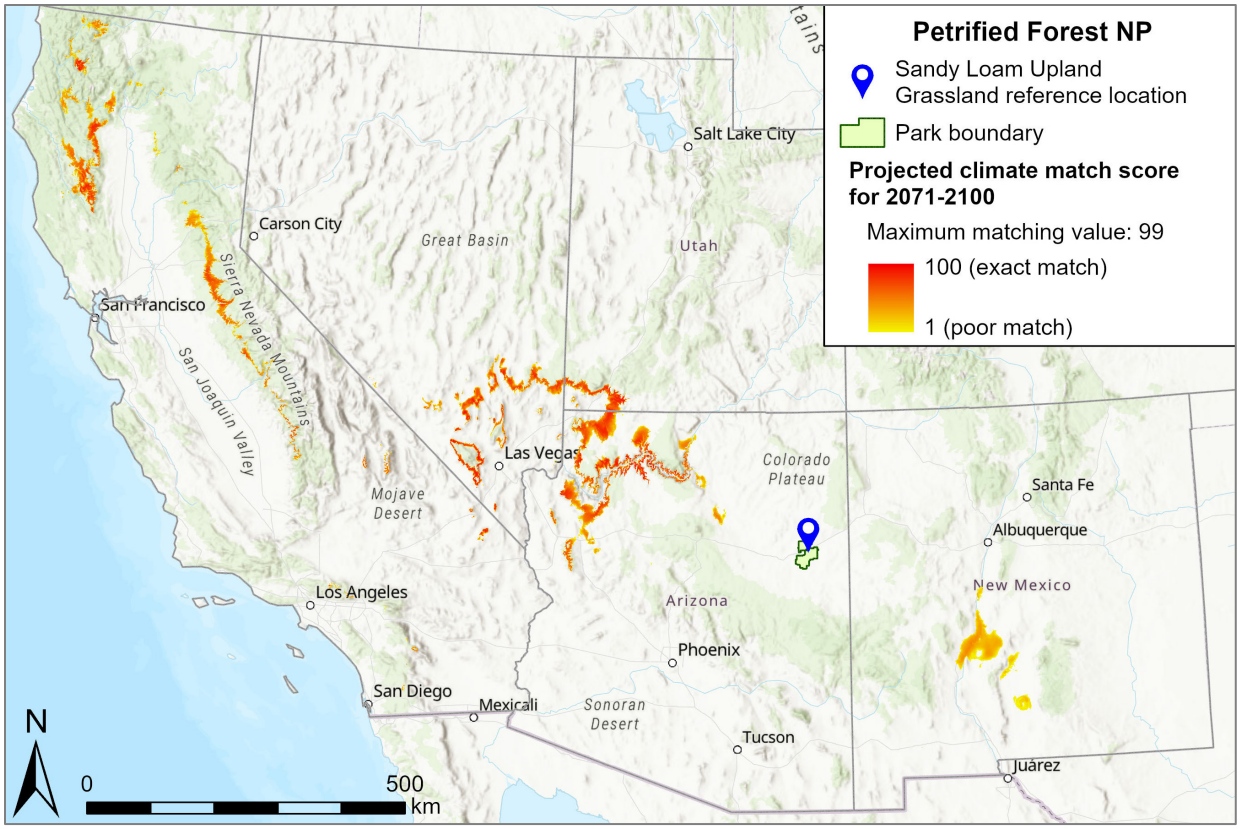


Figure 54. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Petrified Forest NP Sandy Loam Upland Grassland study area. Data derived from Seedlot Selection Tool scores (St. Clair et al. 2022). Current climate was based on 1981–2010 normals. Projected climate was based on the years 2071–2100 using the RCP 8.5 scenario. Settings used allowed liberal definitions of matches, requiring similarity in only three variables: Mean Coldest Month Temperature, Summer Heat Moisture Index, and Frost-Free Period. Map shows possible future directions of natural or assisted migrations of species or of genetic strains within species. Data used to create this map are available in the associated data release.

NPS / KRISTIN STRAKA

Petroglyph NM

MODIS Sensor Pixels Used in Ranked-Day Analysis

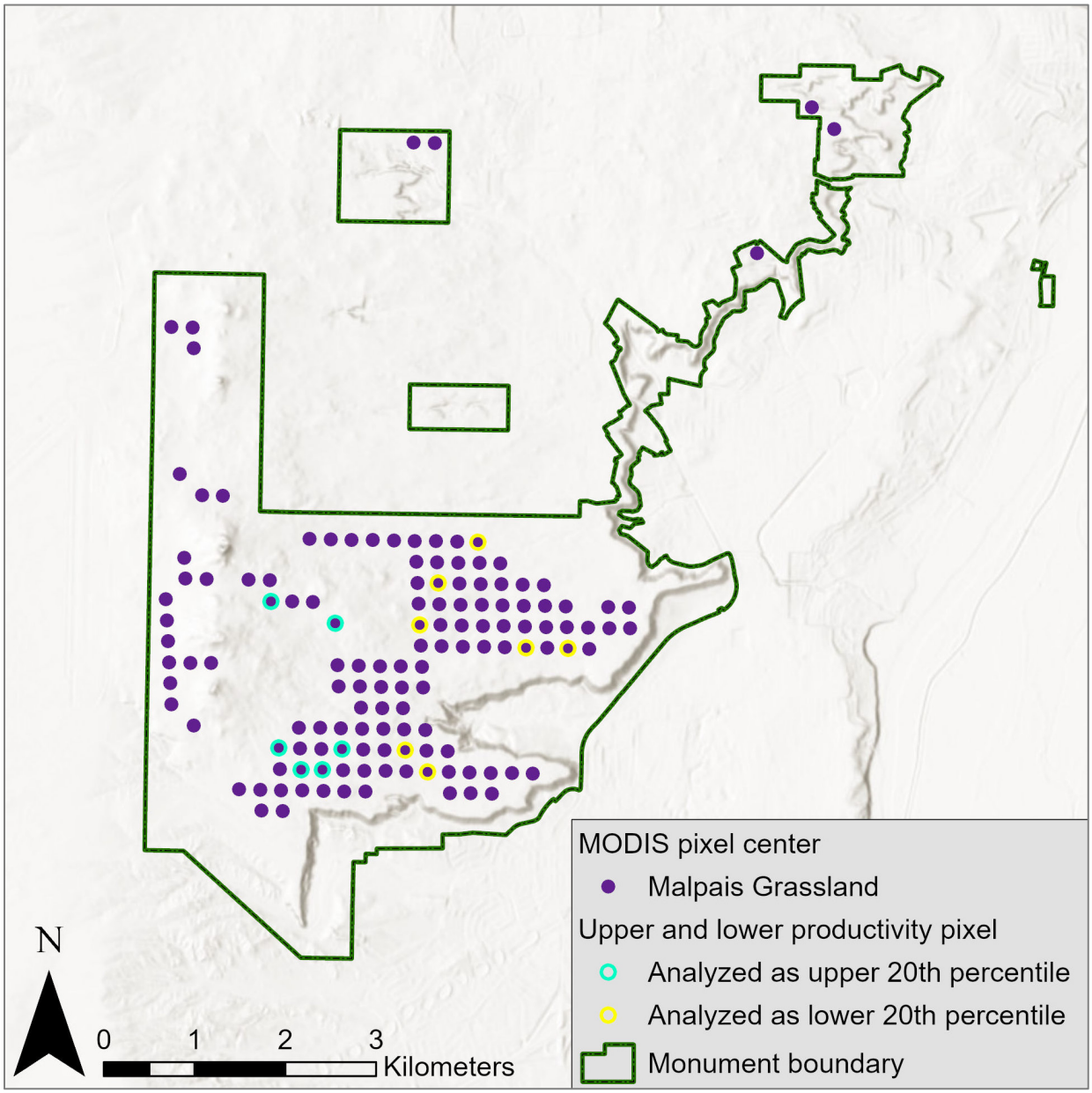


Figure 55. Map of MODIS pixel centers used for analysis at Petroglyph NM. Pixels analyzed as 20th and 80th percentile are limited to the 5% of pixels centered around the 20th and 80th percentiles of average greenness across the period of record (i.e., those pixels within the percentile ranges of 17.5%–22.5% and 77.5%–82.5%). This restriction was made to avoid possible outliers that might be incorrectly mapped as the target ecosystem and therefore which might fall at the extreme ends of the productivity distribution. *NPS / KRISTIN STRAKA*

Daily NDVI Data, Raster Graphs

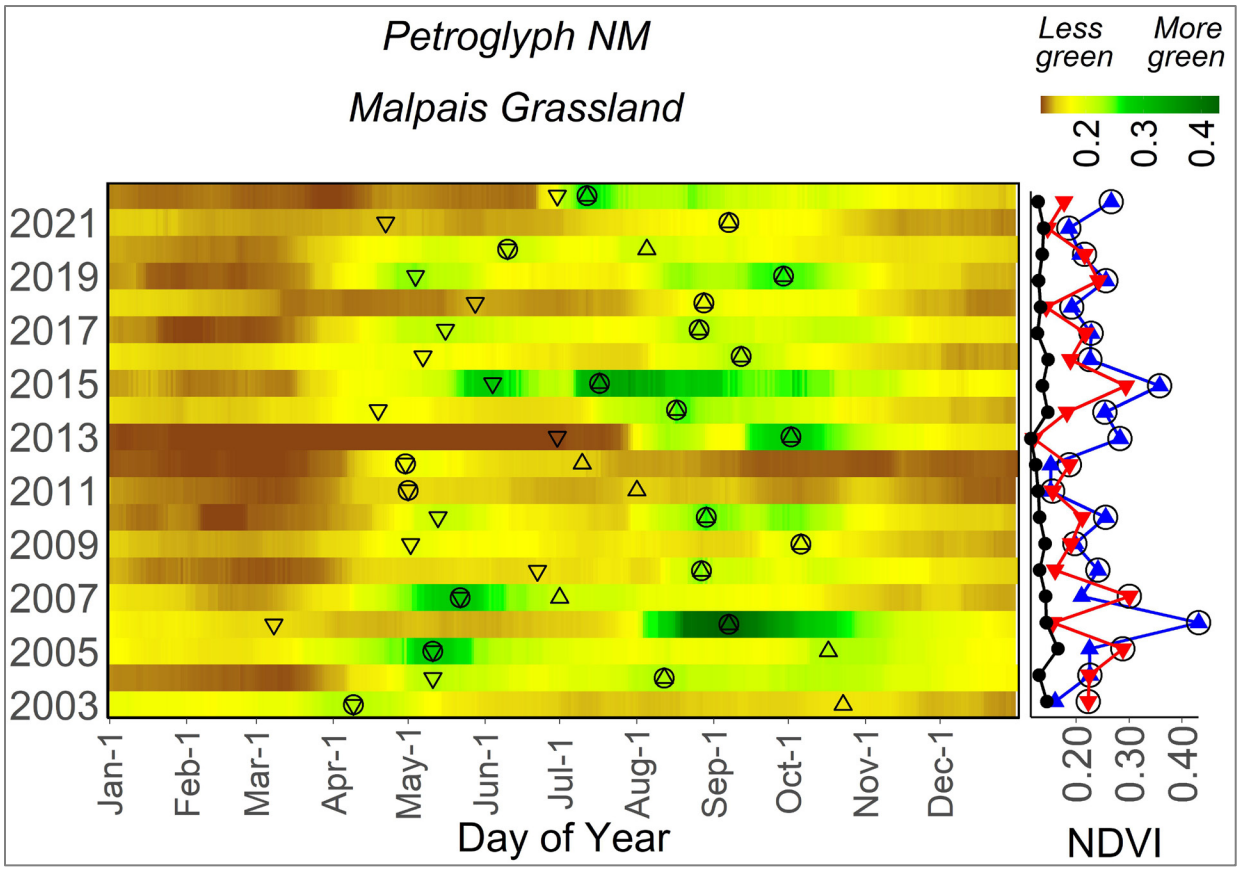


Figure 56. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Petroglyph NM Malpais Grassland study area. The graphs show that the study area has low greenness during the winter. About half of the years have prominent monsoon peaks, and several years have prominent spring peaks. Two years (2011 and 2012) have little or no greenup evident throughout the growing season, suggesting vegetation stress during those years. Circular and triangular symbols mark the timing and intensity of the peak-of-season dates for each year: downward and upward pointing triangles mark the spring (March–June) and monsoon peak (July–October) timing. Intensity of the spring peak and monsoon peak is similarly marked by a downward or upward pointing triangle on the marginal plot. Open circles mark the timing and intensity of the annual peak. Closed circles on the marginal plots mark the approximate annual minimum NDVI value, which is approximate and has no associated calendar date because of uncertainty introduced by snow cover.

NPS / JODI NORRIS

Ranked Daily Quantile Trends

Spring Trends

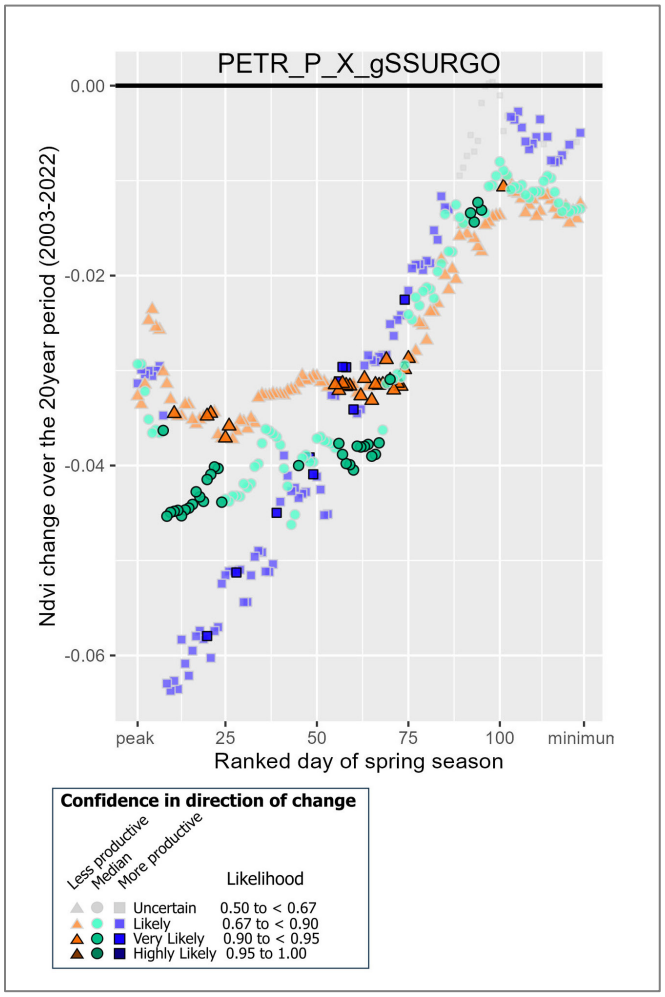


Figure 57. Ranked-day NDVI trend estimates for the spring season for the Petroglyph NM Malpais Grassland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the spring season (March–June), with the "Peak" being the annual peak values for the season and the "Min" being the annual minimum value for the season. The points between the "Peak" and "Min" represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the spring season is rank 122 (number of days in the spring season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the "Less productive" and "More productive" parts of the study area. Plot shows a pattern of negative NDVI trends for all days of the spring season. The largest trends are generally seen for declines in the peak and near-peak values. This pattern is consistent for all three productivity levels. The confidence for most of the change direction is likely, with some scattered "very likely" confidence levels for all three productivity levels. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

Monsoon Trends

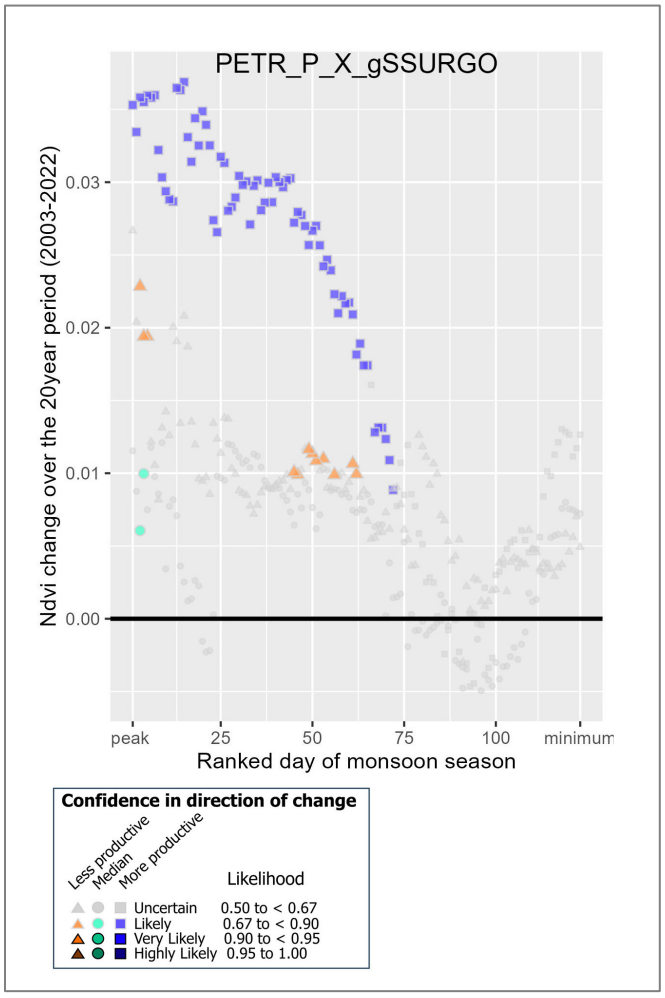


Figure 58. Ranked-day NDVI trend estimates for the monsoon season for the Petroglyph NM Malpais Grassland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the monsoon season (July–October), with the "Peak" being the annual peak values for the season and the "Min" being the annual minimum value for the season. The points between the "Peak" and "Min" represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the monsoon season is rank 123 (number of days in the monsoon season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the "Less productive" and "More productive" parts of the study area. Plot shows trends of increasing NDVI values for the most productive pixels for most days of the monsoon season. There are also small numbers of days of the season with a pattern of increasing NDVI for the study area median and for the less productive pixels. The highest confidence level seen in the direction of these trends is "likely". All productivity levels have some days with increasing trends at the "likely" confidence level, although the study area median and less productive pixels have only a small number of days with a "likely" trend. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

Seedlot Selection Tool Maps

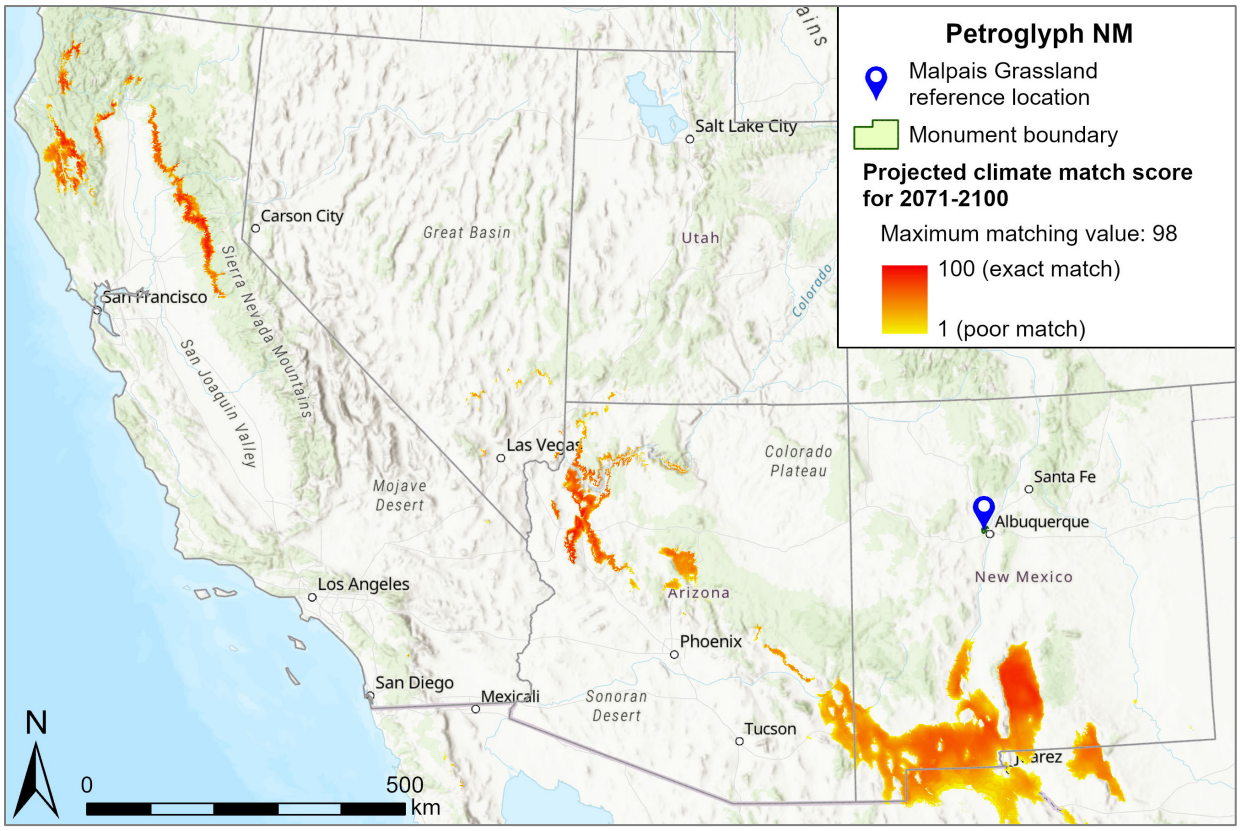


Figure 59. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Petroglyph NM Malpais Grassland study area. Data derived from Seedlot Selection Tool scores (St. Clair et al. 2022). Current climate was based on 1981–2010 normals. Projected climate was based on the years 2071–2100 using the RCP 8.5 scenario. Settings used allowed liberal definitions of matches, requiring similarity in only three variables: Mean Coldest Month Temperature, Summer Heat Moisture Index, and Frost-Free Period. Map shows possible future directions of natural or assisted migrations of species or of genetic strains within species. Data used to create this map are available in the associated data release.

NPS / KRISTIN STRAKA

Wupatki NM

MODIS Sensor Pixels Used in Ranked-Day Analysis

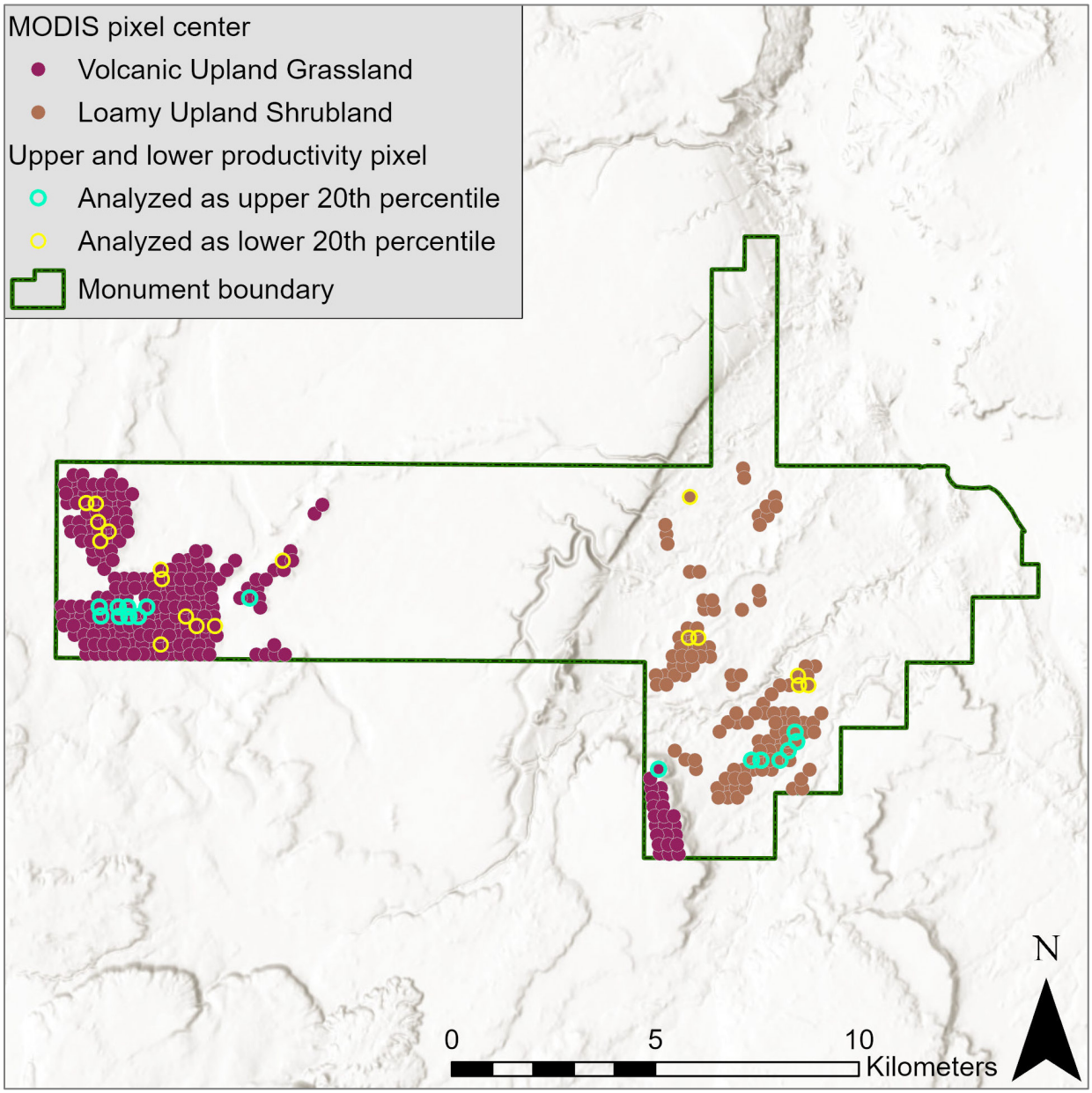


Figure 60. Map of MODIS pixel centers used for analysis at Wupatki NM. Pixels analyzed as 20th and 80th percentile are limited to the 5% of pixels centered around the 20th and 80th percentiles of average greenness across the period of record (i.e., those pixels within the percentile ranges of 17.5%–22.5% and 77.5%–82.5%). This restriction was made to avoid possible outliers that might be incorrectly mapped as the target ecosystem and therefore which might fall at the extreme ends of the productivity distribution.
NPS / KRISTIN STRAKA

Daily NDVI Data, Raster Graphs

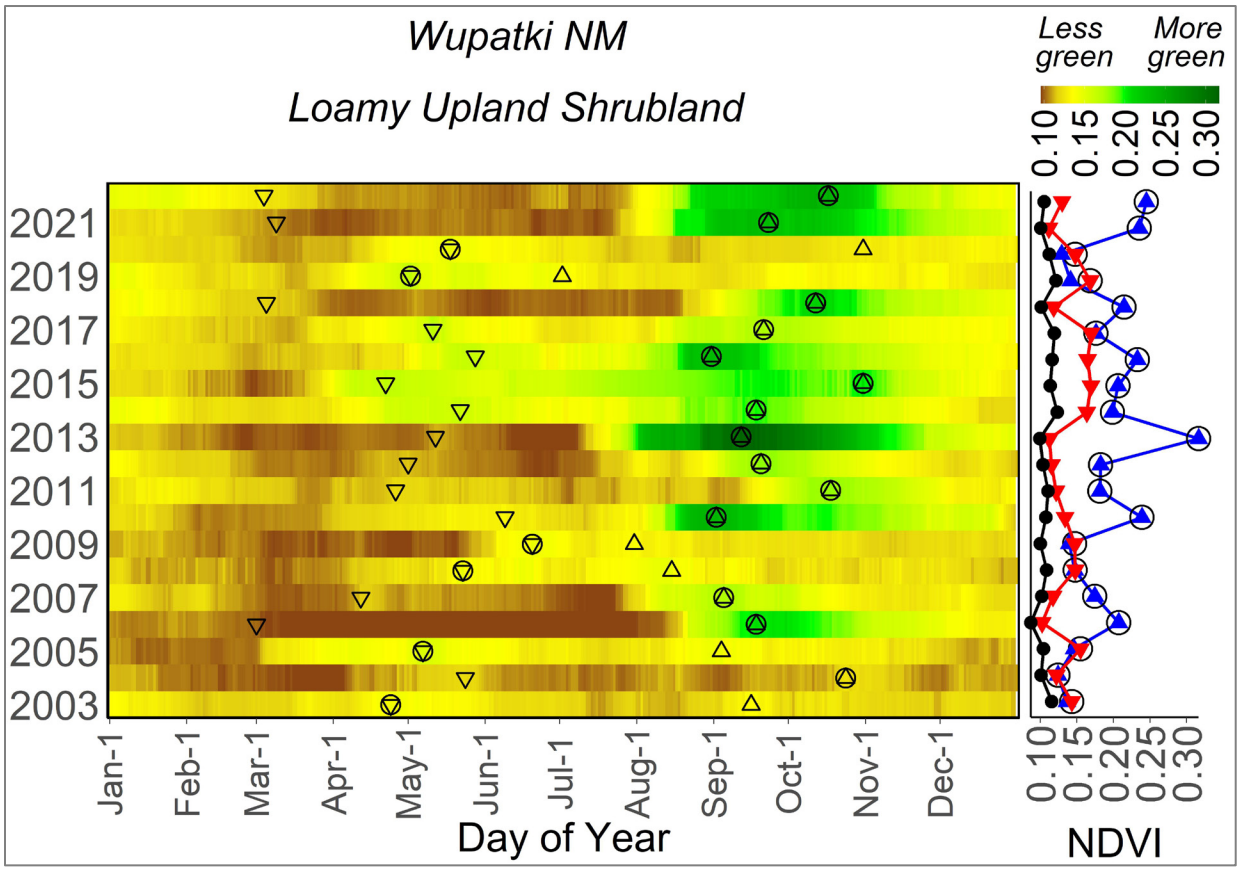


Figure 61. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Wupatki NM Loamy Upland Shrubland study area. The graphs show that the study area has low greenness during the winter. Most years have prominent monsoon peaks, and only a few years have noticeable spring peaks. Five years (2003, 2004, 2008, 2009, and 2020) have little or no greenup evident throughout the growing season, suggesting vegetation stress during those years. Circular and triangular symbols mark the timing and intensity of the peak-of-season dates for each year: downward and upward pointing triangles mark the spring (March–June) and monsoon peak (July–October) timing. Intensity of the spring peak and monsoon peak is similarly marked by a downward or upward pointing triangle on the marginal plot. Open circles mark the timing and intensity of the annual peak. Closed circles on the marginal plots mark the approximate annual minimum NDVI value, which is approximate and has no associated calendar date because of uncertainty introduced by snow cover.

NPS / JODI NORRIS

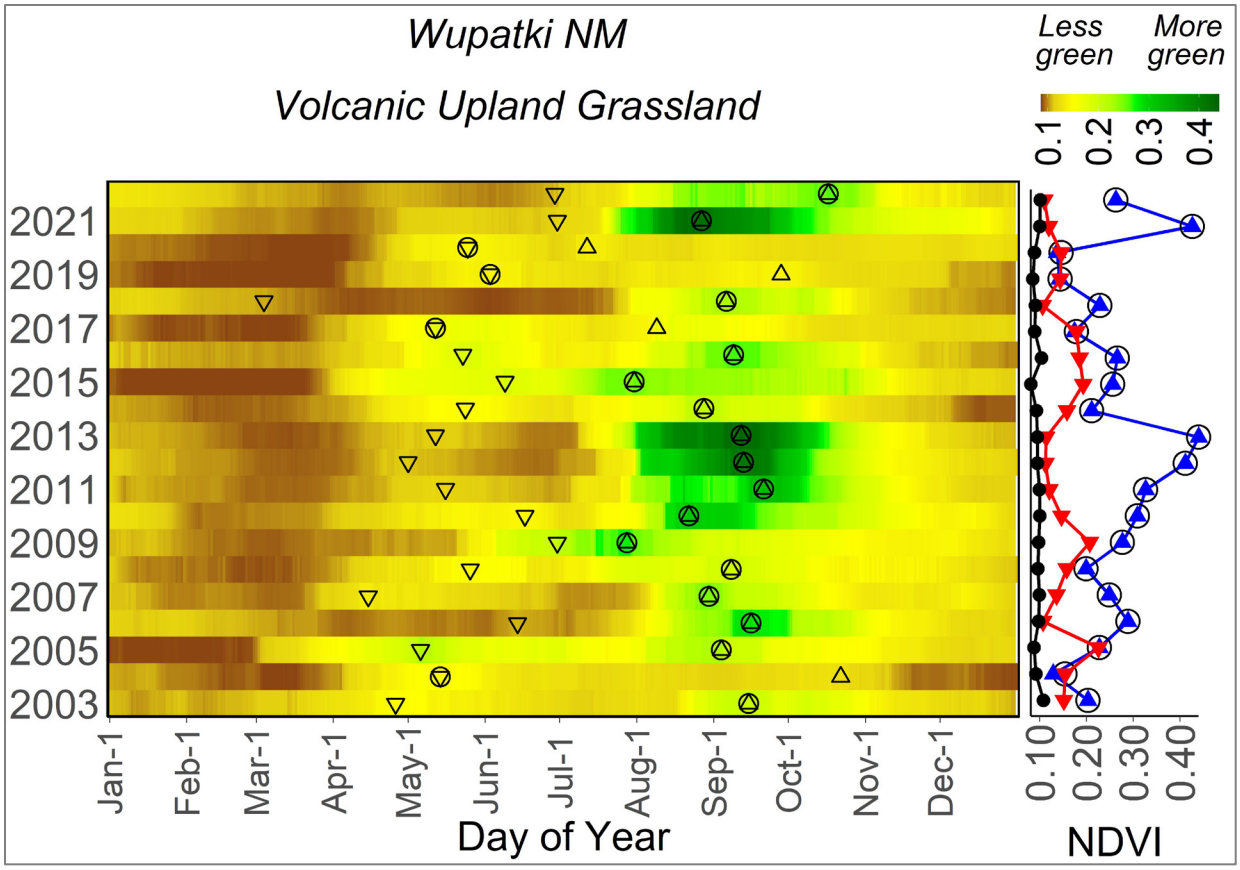


Figure 62. Raster graph and marginal graph of seasonal and annual peaks showing phenological patterns of smoothed NDVI for the 20-year analysis period (2003–2022) for the Wupatki NM Volcanic Upland Grassland study area. The graphs show that the study area has low greenness during the winter. Most years have prominent monsoon peaks, and only a few years have noticeable spring peaks. Three years (2004, 2019, and 2020) have little or no greenup evident throughout the growing season, suggesting vegetation stress during those years. Circular and triangular symbols mark the timing and intensity of the peak-of-season dates for each year: downward and upward pointing triangles mark the spring (March–June) and monsoon peak (July–October) timing. Intensity of the spring peak and monsoon peak is similarly marked by a downward or upward pointing triangle on the marginal plot. Open circles mark the timing and intensity of the annual peak. Closed circles on the marginal plots mark the approximate annual minimum NDVI value, which is approximate and has no associated calendar date because of uncertainty introduced by snow cover.

NPS / JODI NORRIS

Ranked Daily Quantile Trends

Spring Trends

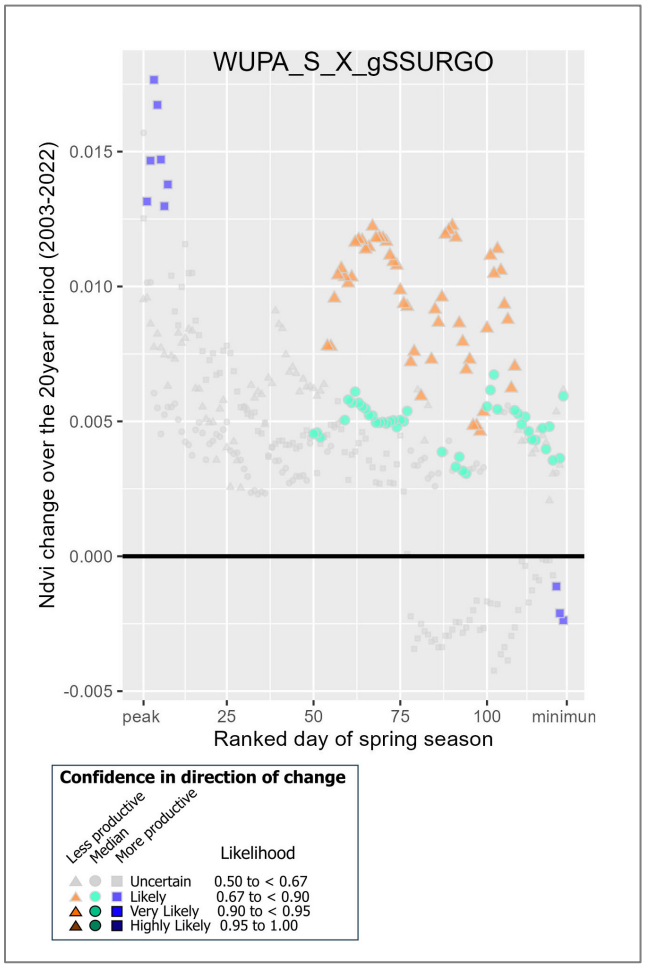


Figure 63. Ranked-day NDVI trend estimates for the spring season for the Wupatki NM Loamy Upland Shrubland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the spring season (March–June), with the "Peak" being the annual peak values for the season and the "Min" being the annual minimum value for the season. The points between the "Peak" and "Min" represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the spring season is rank 122 (number of days in the spring season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the "Less productive" and "More productive" parts of the study area. Plot shows trends of increasing NDVI values for most days of the spring season. The highest confidence level seen in these trends is "likely". The positive trends are generally evenly mixed between low confidence ("uncertain") and a "likely" level of confidence. The trends are most consistent among the median and less productive pixels; however, the most productive pixels near the peak days also show "likely" positive trends. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

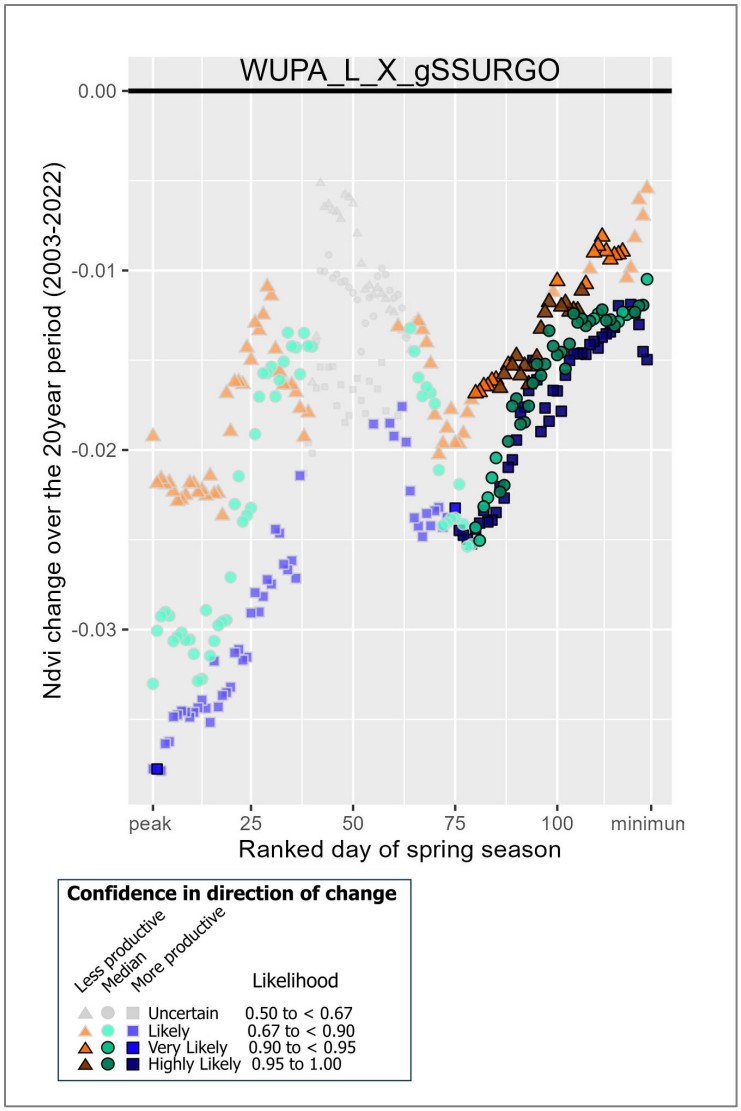


Figure 64. Ranked-day NDVI trend estimates for the spring season for the Wupatki NM Volcanic Upland Grassland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the spring season (March–June), with the "Peak" being the annual peak values for the season and the "Min" being the annual minimum value for the season. The points between the "Peak" and "Min" represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the spring season is rank 122 (number of days in the spring season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the "Less productive" and "More productive" parts of the study area. Plot shows trends of decreasing NDVI values for most days of the spring season. The largest declines are in the peak and near-peak values of the more productive pixels. The highest confidence level seen in the trends is "highly likely". The greatest confidence in negative trend is seen near the minimum days of the season. Most of the rank-days have a "likely" or higher level of confidence in a negative trend for all of the productivity levels. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

Monsoon Trends

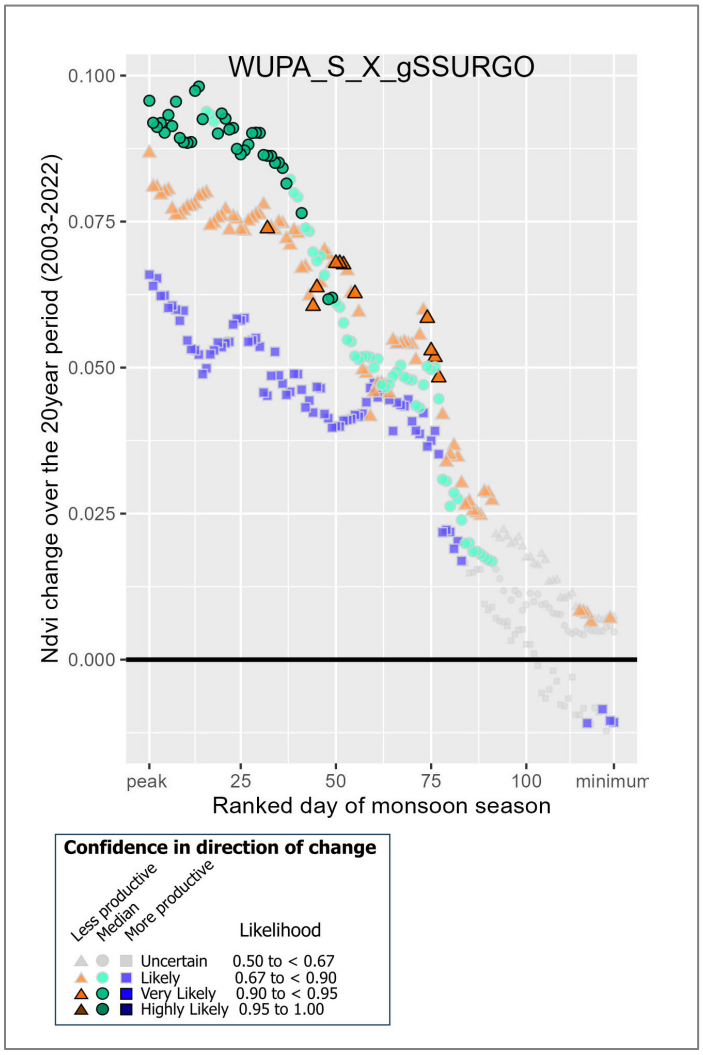


Figure 65. Ranked-day NDVI trend estimates for the monsoon season for the Wupatki NM Loamy Upland Shrubland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the monsoon season (July–October), with the "Peak" being the annual peak values for the season and the "Min" being the annual minimum value for the season. The points between the "Peak" and "Min" represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the monsoon season is rank 123 (number of days in the monsoon season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the "Less productive" and "More productive" parts of the study area. Plot shows trends of increasing NDVI values for all days of the monsoon season. The highest confidence level seen in these trends is "very likely". More than half of the rank-days have at least a "likely" level of confidence in a positive trend for at least one of the productivity levels. All productivity levels have more than half their days with increasing trends with "likely" or higher confidence. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct. *NPS / JODI NORRIS*

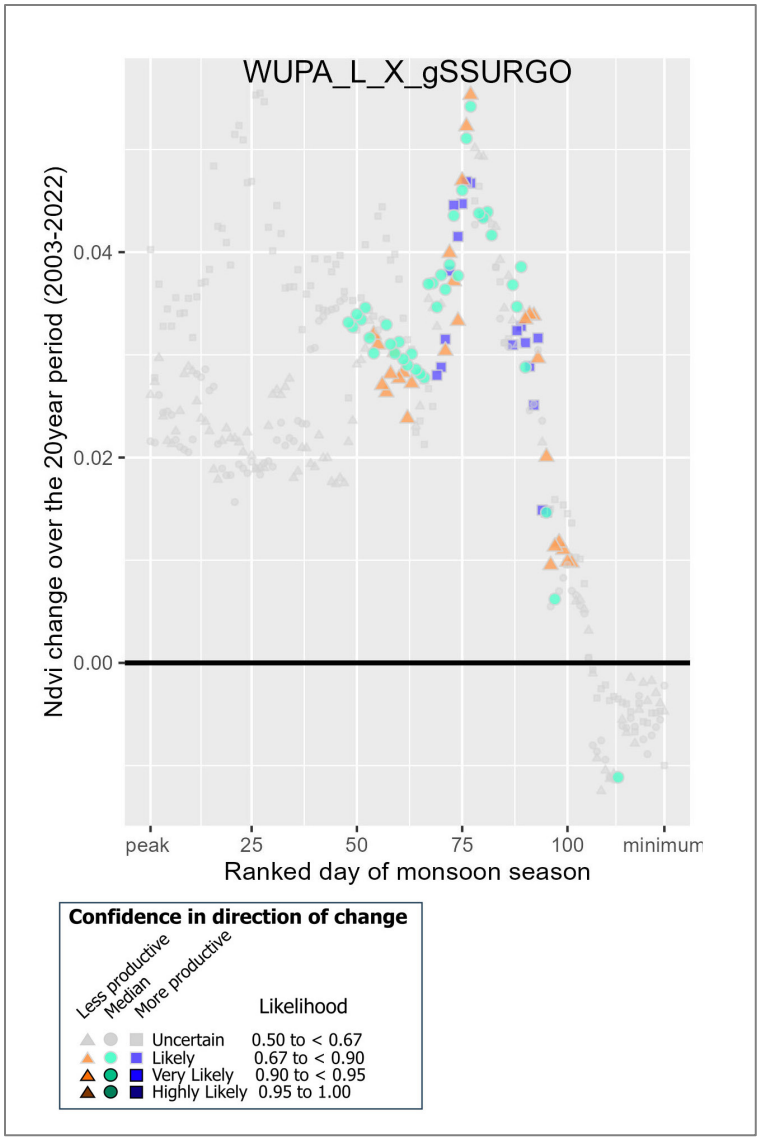


Figure 66. Ranked-day NDVI trend estimates for the monsoon season for the Wupatki NM Volcanic Upland Grassland study area. For conceptual example, see Figure 16. These graphs show estimates of total change through time (2003–2022) for each ranked day of the monsoon season (July–October), with the “Peak” being the annual peak values for the season and the “Min” being the annual minimum value for the season. The points between the “Peak” and “Min” represent days of the season, ranked by NDVI value, where the peak value is rank 1 and the minimum value for the monsoon season is rank 123 (number of days in the monsoon season). Colors indicate the three sets of pixels that were analyzed in most study areas: the entire set of pixels was used to calculate the study area median, and two subsets of pixels that had lower and higher average NDVI values were used to calculate values for the “Less productive” and “More productive” parts of the study area. Plot shows trends of increasing NDVI values for about half of the days of the monsoon season. The highest confidence level seen in these trends is “likely”, with most of the rank-days between rank 50 and rank 100 having a “likely” level of confidence in a positive trend for at least one of the productivity levels. Estimate of total change over the 20-year period was made using Thiel-Sen slope estimation. Color intensity is used to indicate likelihood that the direction of trend is correct.

NPS / JODI NORRIS

Seedlot Selection Tool Maps

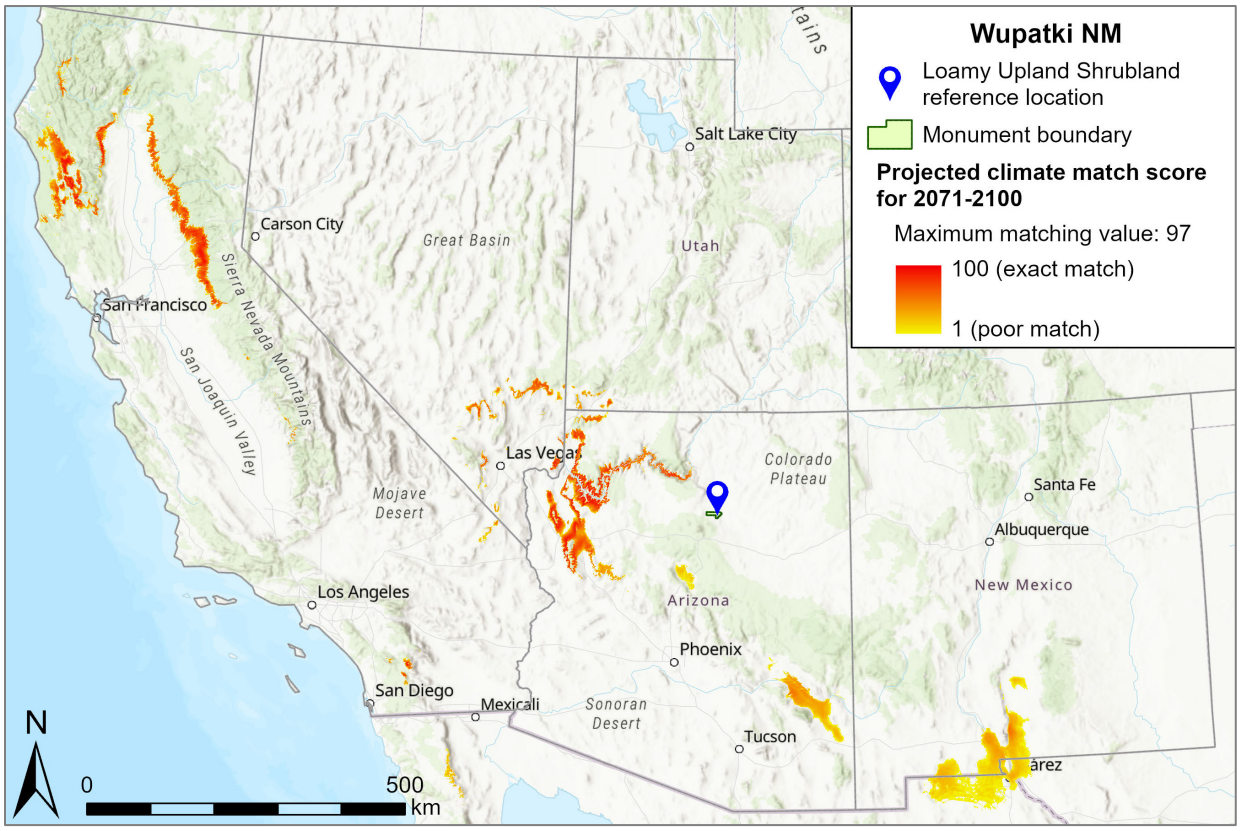


Figure 67. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Wupatki NM Loamy Upland Shrubland study area. Data derived from Seedlot Selection Tool scores (St. Clair et al. 2022). Current climate was based on 1981–2010 normals. Projected climate was based on the years 2071–2100 using the RCP 8.5 scenario. Settings used allowed liberal definitions of matches, requiring similarity in only three variables: Mean Coldest Month Temperature, Summer Heat Moisture Index, and Frost-Free Period. Map shows possible future directions of natural or assisted migrations of species or of genetic strains within species. Data used to create this map are available in the associated data release.

NPS / KRISTIN STRAKA

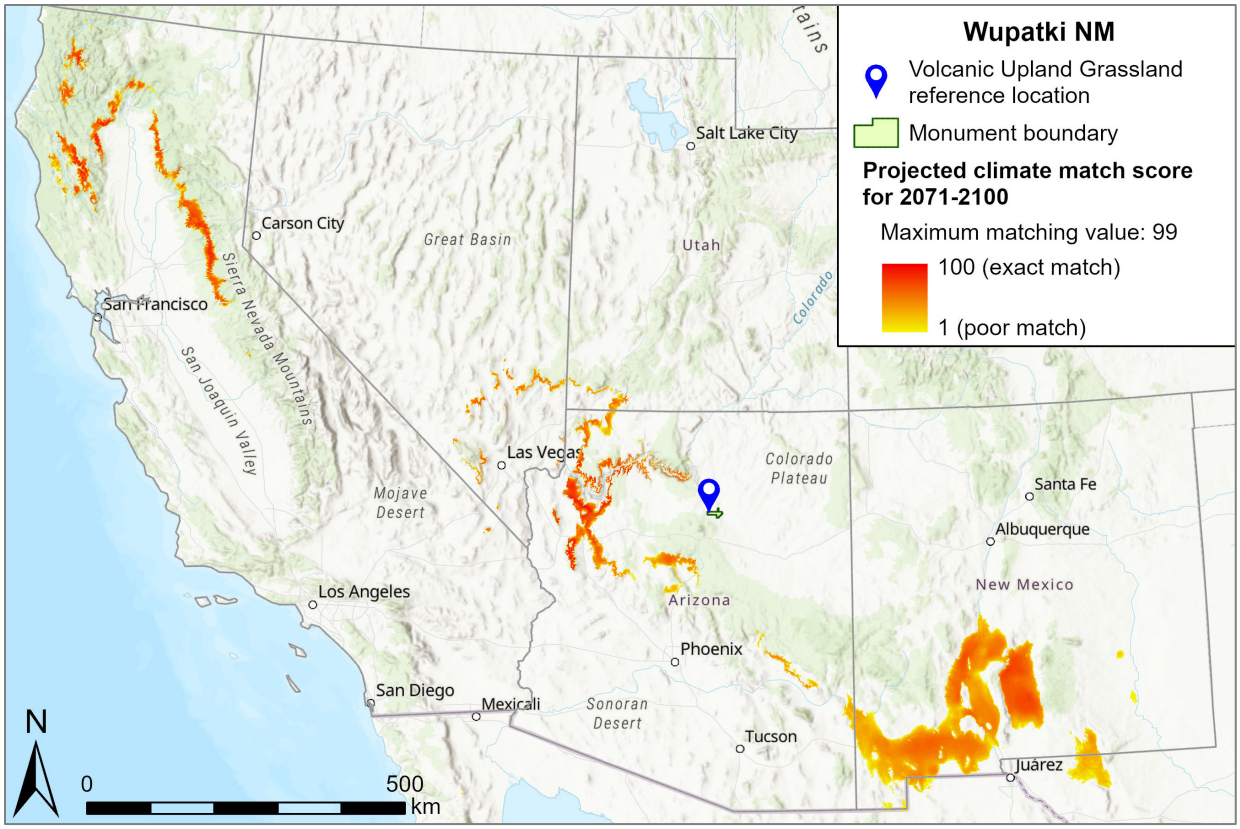


Figure 68. Map of locations whose current climate is similar to the projected climate (2071–2100) at the reference location in the Wupatki NM Volcanic Upland Grassland study area. Data derived from Seedlot Selection Tool scores (St. Clair et al. 2022). Current climate was based on 1981–2010 normals. Projected climate was based on the years 2071–2100 using the RCP 8.5 scenario. Settings used allowed liberal definitions of matches, requiring similarity in only three variables: Mean Coldest Month Temperature, Summer Heat Moisture Index, and Frost-Free Period. Map shows possible future directions of natural or assisted migrations of species or of genetic strains within species. Data used to create this map are available in the associated data release.

NPS / KRISTIN STRAKA

National Park Service
U.S. Department of the Interior

Science Report NPS/SR—2025/319
https://doi.org/10.36967/2312720



Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

NPS 960/197295, June 2025