



Grassland Ecosystems of Petrified Forest National Park

A Literature Review

Natural Resource Report NPS/SCPN/NRR—2019/2011



ON THE COVER

Grassland vegetation in Petrified Forest National Park.
(NPS/SCPN)

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Natural Resource Report NPS/SCPN/NRR—2019/2011

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Abstract

This literature review was written to provide an ecological background and context to the long-term vegetation and soils monitoring by the Southern Colorado Plateau Network. This review summarizes vegetation and soils research and other studies conducted in the grasslands and shrublands of Petrified Forest National Park. Other studies from across Southwestern United States are also discussed to fill in data gaps and to provide a regional context. This review includes discussion of the physical environment (climate, geology and soils), vegetation history (from paleo-history through Euro-American settlement), vegetation classification, spatiotemporal patterns of vegetation, and species of concern. The impact of natural and human disturbances on vegetation and soils are also examined: these include nonnative species, grazing, drought, soil erosion, and fire. Drought is examined in the context of how these ecosystems may respond to future climates. The goal of this review is to provide background information that will help develop hypotheses for analyzing trends in long-term vegetation and soils monitoring data.

Acknowledgments

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1 Introduction

At Petrified Forest National Park, the Southern Colorado Plateau Inventory and Monitoring Network (SCPN) monitors two grassland ecosystems for the Integrated Upland monitoring project. Grasslands are a dominant ecosystem within the park, occurring across the park's elevational gradient which ranges from 1700 to 2075 meters (5100 to 6235 feet) (Kierstead 1981). These grasslands face a number of threats including climate change, invasion of nonnative species, and soil erosion. This literature review provides a review of the studies of vegetation and soils conducted at Petrified Forest National Park (PEFO), including description of the soils, the structure and dynamics of vegetation, and natural and human disturbances that have impacted and many continue to impact the ecosystems. The influence of drought will be assessed in the context of impacts that may result from future climate change. Because the vegetation and soils of Petrified Forest National Park have not been well-studied, literature from grasslands across Southwestern United States have also been included in this review. These studies are cited to help inform the structure and dynamics of the grasslands of PEFO. The goal of this review is to help inform SCPN's monitoring of these ecosystems at PEFO. The review will focus on factors that are critical drivers and stressors for these ecosystems. This information may help in the development of hypotheses for analyzing trends in the long-term monitoring data.

Grasslands are an important vegetation type across the Colorado Plateau and southwestern United States, receiving between 230 and 460 mm of rain each year (Miller et al. 1977, McClaran 1995). Miller et al. (1977) describes grasslands forming "a continuous or nearly uninterrupted ground cover from 5,000 to 7,000 feet". On the upper elevations, grasslands generally grade into pinyon-juniper savannas, and at the lower elevations they generally grade into desert shrublands. Areas of shrublands can occur within the grassland matrix, however, as a result of differences in soils or disturbance regimes, with the grasslands often occurring on deeper soils (Kierstead 1981). Grassland species often extend their geographic distribution to non-grassland communities in both higher and lower elevations (McClaran 1995).

SCPN generally bases its sampling frames on ecological sites created by the Natural Resources Conservation Service (NRCS). These are landscape divisions whose classification is based on soil survey data which remain relatively static over relatively long periods of time, and have characteristic plant communities, hydrology and disturbance regimes (Butler *et al.* 2003). SCPN chose two ecological sites to monitor at Petrified Forest: the Clayey Fan ecological site (R035XB239AZ) and the Sandy Loam Upland ecological site (R035XA117AZ). These two ecological sites were chosen as they cover large portions of the park and are relatively undisturbed. The majority of these two ecological sites are comprised of grasslands, although they also contain vegetation classified as shrublands, dwarf-shrublands and shrub-herbaceous vegetation. For the sake of simplicity, when discussing these targeted ecosystems within the park, the term grassland will be used to include the grassland and shrubland systems of the targeted ecological sites. SCPN established 30 permanent plots in each of the ecological sites between 2007 and 2010, and have been sampling them on rotation of 2 times every 6 years. The plots are 0.5 ha and consist of three 50 m transects. Along these transects species foliar cover is measured using nested quadrats; soil

measurements include soil stability, amount of bare ground (basal gaps), and cover of soil surface features (DeCoster et al. 2012).

The park's boundary expanded through a series of acquisitions between 2007 and 2013. However, given that the SCPN sampling frames, the soils map and the vegetation map all predate this expansion, as well as the lack of studies conducted in the expansion lands, this review will focus on the vegetation and soils of the park boundaries prior to these expansions.

2 Climate, Geology and Soils

Between 1974 and 2017 mean annual precipitation at Petrified Forest National Park was 26.7 cm (Climate Analyzer 2018) (Figure 1). Precipitation occurs in a bimodal pattern, with the majority occurring in the winter as frontal systems, and in the summer as monsoons. More than half the precipitation occurs between July and October. Mean precipitation between July and October was 13.9 cm.

The Petrified Forest landscape consists of extensive mesa-like highlands, broad valleys, retreat escarpments and badlands (Miller et al. 1977). The southern part of the park is largely covered by the Chinle formation, which was formed in the late Triassic around 225 million years ago. Reaching a thickness of 300 meters, these are sedimentary rocks of soft, fine-grained mudstone, siltstone and claystone (Lubick 1996, Parker 2005). The Chinle formation was created when the area was part of the supercontinent Pangea, and at much lower latitudes, from 5 to 10 degrees N latitude (Baranyi et al. 2017). The park is currently at 34.9 N latitude. It is within this formation that the petrified wood was created. Prior to the advent of flowering plants, this area was a tropical lowland forest with gymnosperms including *Araucarioxylon arizonicum*, *Woodworthia arizonica* and *Schilderia adamanica*. Baranyi et al. (2017) identified different habitats within the area that is now the park: wetlands characterized by horsetails, ferns, seed ferns, Cycadophytes, Gnetales and Araucariaceae-Cupressaceae; lowlands dominated by seed ferns with horsetails, ferns and cycadophytes; and uplands, characterized by conifers and seed ferns. In addition to the various species of petrified wood, over 200 species of fossilized plants have been identified in this formation, including many ferns and cycads (Lubick 1996, Parker 2005).

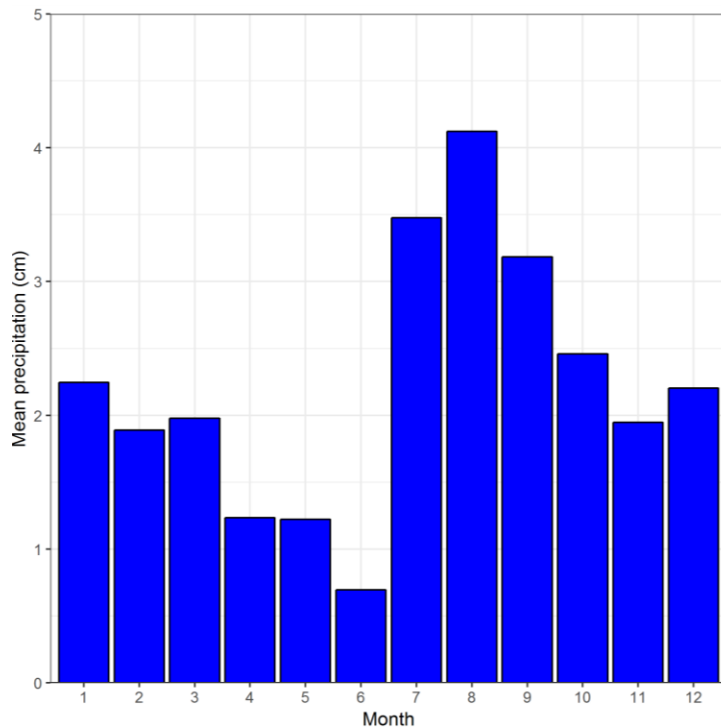


Figure 1. Mean monthly precipitation between 1974 and 2017 at the Painted Desert weather station near the Painted Desert Visitor Center (Station 26190) at Petrified Forest National Park (Climate Analyzer 2018).

On the northern side of the park is the Painted Desert Mesa, which is a volcanic remnant of the Mio-Pliocene Bidahochi Formation that was laid down as a caprock on top of the Chinle Formation (Parker 2005). Badland formations occur across the park and are comprised of shale deposits. There was a climatic shift in the Late Triassic towards a more arid environment, which was associated with the uplift of the Cordilleran arc and the northward shift of the North American continental plate (Baranyi et al. 2017).

The soils in the park formed from shales and sandstones derived from the underlying Chinle formation. The deepest and most fertile soils occur in the mid to upper elevations and are derived from a combination of alluvium and wind-blown sands of gneiss, schist, quartzite, sandstone and limestone. The soils are typically calcareous, moderately alkaline and contain less than 1% organic matter. Areas of heavy clay occur from the weathering of the shale hills in the badlands (Kierstead 1981, McClaran 1995). Aeolian deposits have added to the soils across the park. Aeolian landforms have been identified in 3 major drainage basins in the park: Lithodendron Wash, Dry Wash and Jim Camp Wash (Elwein 1997).

Biological soil crusts are a key feature in dryland soils in Southwestern United States. These crusts serve a variety of ecosystem functions including soil stabilization and reducing erosion. This is accomplished by several means. Lichens and mosses have anchoring structures that physically hold the soil in place. The crusts also secrete polysaccharides that contribute to soil aggregation, and increasing soil carbon (Belnap 2003, Belnap et al. 2003). The microtopography of many crusts also

reduces sheetflow, thus allowing greater infiltration. The cyanobacteria in the crusts fix nitrogen, providing nutrients to plants (Belnap et al. 2003). Biological soil crusts tend to flourish where there are extended periods where the soil surface remains wet, which occurs in areas of high winter precipitation. In contrast, the short wetting- drying cycles of summer monsoons causes respiration rates to exceed photosynthetic rates (Lange 2003, Schwinning et al. 2008). Nitrogen fixation is also greater during the winter (Schwinning et al. 2008). No detailed surveys have been conducted on the biological crusts of the grassland ecosystems of Petrified Forest National Park.

The soils map of Petrified Forest National Park shows a heterogeneous patchwork of sandy loams, loams and clay soils (NRCS 2002). The classification is complicated by the fact that the park straddles the Apache-Navajo county line, and the soil surveys of the 2 counties use different classifications (Figure 2). This results in large discrepancies along the boundary between the counties. The soil map units are often comprised of more than one soil component (for example Clovis-Palma association, and Jocity-Claysprings complex), and often contain small unnamed minor components, or inclusions. In the NRCS classification, each soil component is associated with an ecological site. Large areas of the park are covered by badlands and rocklands with sparse vegetation.

SCPN selected 2 ecological sites to monitor for their Integrated Upland project: Clayey Fan, 6-10" p.z. (R035XB239AZ) and Sandy Loam Upland (10-14" p.z.; R035XA117AZ). These two ecological sites were chosen because they comprise much of the grassland ecosystem of the park (Figure 3, Table 1). Because the soil surveys for the 2 counties were conducted independently of each other, neither of the two target ecological sites occur in the Navajo County Soil Survey on the western side of the park. The Clayey Fan ecological site comprise 2 soil map units: Jocity sandy clay loam

Legend

-  Park boundary (2007)
-  County line
- Apache County NRCS map unit (2002)**
 -  Badland and rock outcrop
 -  Claysprings
 -  Clovis loamy sand
 -  Clovis-Palma association
 -  Fruitland sandy loam
 -  Jocity-Claysprings complex
 -  Jocity sandy clay loam
 -  Navajo clay
 -  Palma-Sheppard association
 -  Sheppard loamy sand
 -  Tours clay loam
 -  Other soil
- Navajo County NRCS map unit (2002)**
 -  Badland and rock outcrop
 -  Brunswick sandy clay loam
 -  Brunswick-Marcou complex
 -  Calciorthids-Torriorthents-rock outcrop
 -  Claysprings
 -  Epikcom- Rock outcrop complex
 -  Grieta sandy loam
 -  Jocity sandy clay loam
 -  Purgatory fine sandy loam
 -  Sheppard-Grieta complex
 -  Sheppard loamy sand
 -  Other soil

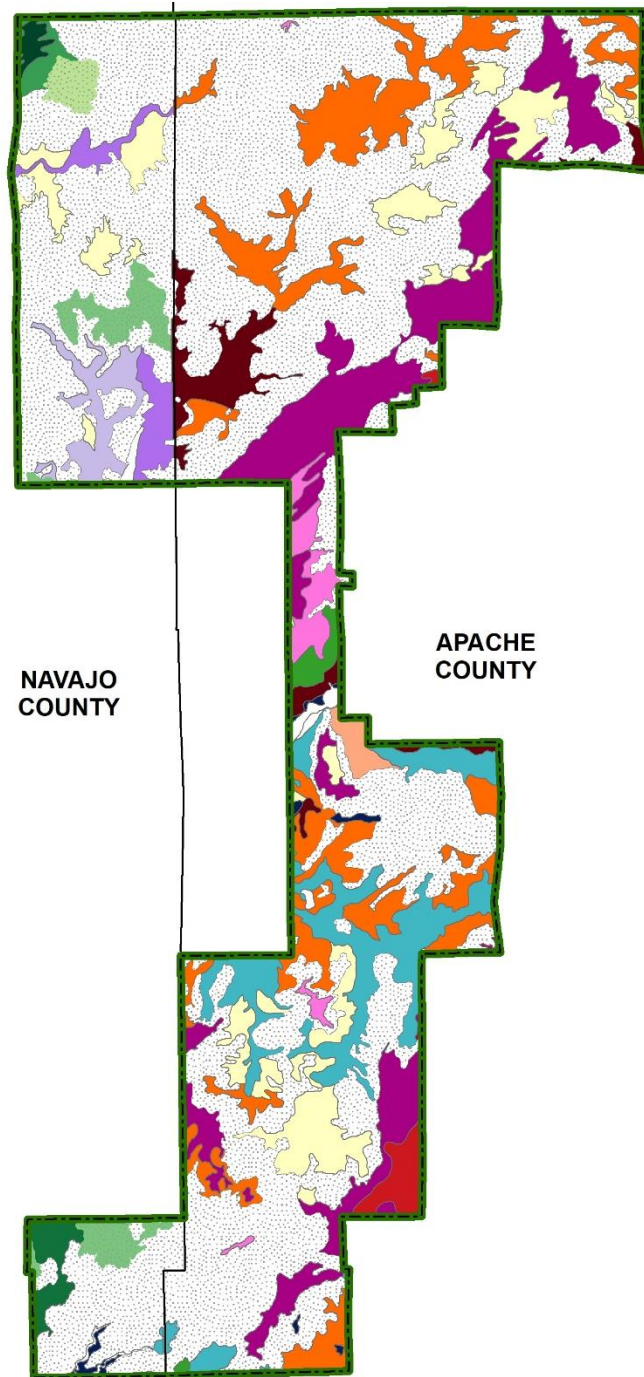


Figure 2. Soil map units in Petrified Forest National Park. Note that different soil surveys in Navajo County on the western side of the park and Apache County on the eastern side of the park result in a distinct discontinuity. The park boundary represents the 2007 boundary, prior to the park's expansion (from NRCS 2002).

Legend



Park boundary (2007)

Apache County NRCS map unit (2002)



Clovis loamy sand



Clovis-Palma association



Fruitland sandy loam



Jocity-Claysprings complex



Jocity sandy clay loam



Palma-Sheppard association



Figure 3. Soil map units associated with the Sandy Loam Upland ecological site and the Clayey Fan ecological site at Petrified Forest National Park. Jocity sandy clay loam and Jocity-Claysprings complex are associated with the Clayey Fan Ecological site; the other 4 soil map units are associated with the Sandy Loam ecological site. The park boundary represents the 2007 boundary, prior to the park's expansion. (from NRCS 2002).

Table 1. Ecological sites and soil map units associated with grasslands at Petrified Forest National Park. Since the map units generally contain more than one soil type, the estimated percentages of the ecological sites within the map units are provided.

Ecological site	Map unit	Estimated percentage of map unit associated with ecological site ¹
Clayey Fan 6-10" p.z. (R035XB239AZ)	Jocity-Claysprings complex	60
	Jocity sandy clay loam	100
Sandy Loam Upland 10-14" p.z. (R035XA117AZ)	Clovis loamy sand, 0 to 8 percent slopes	100
	Clovis – Palma association, undulating	100
	Fruitland sandy loam, 1 to 8% slopes	79
	Palma-Shepard association, undulating	50

¹ Because soil map units are often comprised of more than one soil component, including minor unnamed components, the estimated percentage of an ecological site is often less than 100%.

and Jocity-Claysprings complex (Table 2). Jocity is a very deep sandy-clay loam, with a relatively uniform texture throughout the soil profile. In the Jocity-Claysprings complex, an estimated 60% of the soil map unit is comprised of Jocity, while 40% of the soil map unit is comprised of Claysprings, which is not associated with the Clayey Fan ecological site. The Sandy Loam Upland ecological site is comprised of 4 soil map units all which are very deep: Clovis loamy sand, 0 to 8 percent slopes; Clovis-Palma association, undulating; Fruitland sandy loam, 1 to 8 percent slopes; and Palma-Sheppard association, undulating. The Fruitland soils are sandy loam, with gravel in the lowest horizon. The Clovis, Palma and Sheppard soils have loamy sand on the upper horizons. Clovis soils have layers of sandy clay loam and clay loam in the intermediate horizons, and sandy loams at the lowest horizon. Palma soils have sandy loam intermediate horizons and sandy clay loams on the lowest horizons. Sheppard soils are uniform loamy sands across all horizons.

Table 2. Typical profiles of soil series and landforms associated with the Clayey Fan and Sandy Loam ecological sites at Petrified Forest National Park. Profiles indicate soil textures with soil depth.

Soil Series	Landform	Soil textures with soil depths
Clovis	Plains, terraces	• 0–8 cm, loamy sand • 8–60 cm, sandy clay loam • 60–75 cm, clay loam • 75–147 cm, loamy sand • 147–163 cm, sandy loam
Fruitland	Alluvial fans	• 0–65 cm, sandy loam • 65–120 cm, fine sandy loam • 120–155 cm, gravelly sandy loam
Jocity	Fans	• 0–175 cm, sandy clay loam
Palma	Dunes, interdunes, terraces	• 0–8 cm, loamy sand • 8–30 cm, sandy loam • 30–104 cm, fine sandy loam • 104–150 cm
Sheppard	Dunes	• 0–175 cm loamy sand

3 History

3.1 Paleo and Puebloan vegetation history

The vegetation history of the past 10,000 years can be reconstructed through the examination of pollen and macrofossils in packrat middens (Betancourt et al. 1990) and sediments of lakes and wetlands (Davis 1969). While no studies have been undertaken in Petrified Forest National Park, Betancourt's study (1990) of the pollen record in Chaco Culture National Historic Park may give an approximation of the vegetation history at PEFO. Two caveats should be considered. First this study was conducted in upper Chaco Canyon which currently consists of pinyon-juniper communities, although grasslands are located nearby; second, packrat midden studies inevitably occur in canyons and other rocky areas, not in the mesa tops and broad valley with deep soils. Betancourt (1990) found that between 10,600 and 9,500 years before present (BP), the vegetation of upper Chaco Canyon was dominated by conifers including *Pseudotsuga menziesii* (Douglas fir) *Juniperus scopulorum* (Rocky Mountain juniper) and *Pinus flexilis* (limber pine), with an understory of *Artemisia tridentata* (big sagebrush) and succulents. In another study site 15 km to the west of Chaco Canyon, the vegetation during this period is described as mosaic of conifer forests and sagebrush steppe. He suggests that that the areas of the Southwest that are currently grasslands were *Pinus flexilis* parklands. Beginning around 9,000 years BP, *Pinus flexilis* and *Picea pungens* were replaced by *Pinus ponderosa* (ponderosa pine, *Pinus edulis* (twoneedle pinyon) and *Juniperus monosperma* (onsesed juniper). This scenario contradicts earlier studies. For example, Martin and Mehringer (1965) described the vegetation at the height of the glaciation as *Pinus ponderosa* pine parkland. Hall (1977) described the vegetation of Chaco Culture 7000 and 5800 years BP as *Pinus edulis* woodland. It is unclear from Betancourt's study when the vegetation transitioned from woodlands to grasslands. At a site in San Juan County, Utah that is currently dominated by shrubs, the packrat midden record shows a gradual increase in grass abundance beginning around 3740 years BP (Betancourt 1990).

Paleo-Indians began using the area following the Pleistocene, between 15,000 and 10,000 years BP (Cordell 1997). Throughout the Archaic period (6000 BCE to 200 CE), the people relied on hunting and gathering, and did not establish permanent settlements (NPS 2005). The Basketmaker Period began around 200 CE, marking the advent of permanent settlements with agriculture across the area of what is now the park (NPS 2005). The Pueblo Period followed in 800–1100 CE. Small pueblos were established, but population densities remained relatively low compared with centers such as Mesa Verde and Chaco Culture. Populations reach their maximum in the 12th and 13th centuries. The Rio Puerco site, the largest in Petrified Forest National Park, had 125 rooms (Lubick 1996). Populations declined in the 13th century, likely as a result of drought. While some have speculated that the Ancestral Pueblos used fire to manage vegetation (Bahre 1991), there is no concrete evidence. Native People probably had minor impact on the vegetation except near habitation and agricultural sites.

3.2 Euro-American settlement and vegetation history

Spanish explorers passed through the area in the 1500s including Coronado, Pedro de Tovar and Lopez de Cardenas. However, it was not until the nineteenth century that Euro-Americans settled in the region. Fur trappers were the first to arrive, followed by surveyors and finally settlers and

ranchers (Henderson 1966). Descriptions of the vegetation by these early travelers were sparse. Captain Sitgreaves described areas of grass, *Artemisia* (sagebrush) and large junipers in his 1851 survey. In a subsequent survey in 1857, Edward Beal described areas of black grama (*Bouteloua eriopoda*), galleta (*Hilaria jamesii*) and sacaton (*Sporobolus airoides*).

Livestock grazing first occurred in the region with the Navajo people. When passing through the region in 1776 Francisco Garcés described heavy grazing by cattle, sheep and goats and suggested that the livestock were either descendants of animals lost during the Coronado expedition, or were stolen from settlements further east in New Mexico (Miller et al. 1977). In the 1830's Mexicans drove sheep from Mexico to California through Northern Arizona, and these drives were subjected to raids by the Navajo. Miller et al. (1977) suggests that the open plains of the Petrified Forest area were sufficiently subjected to livestock raids that it was spared overgrazing.

European-Americans began establishing ranching operations in the area following the Civil War. In 1866 Juan Candelaria brought a flock of 700 sheep from Cubero, New Mexico, and began ranching approximately 30 miles southwest of what is now PEFO. Drought in California in 1870 and 1871 caused a large migration of sheepherders and cattle ranchers into Arizona. By 1876 there were many large ranches between Flagstaff and Apache counties, with up to 100,000 sheep in the Puerco and Little Colorado drainages (Henderson 1966). The completion of the railroad in 1883 was accompanied by an increase in ranching to the area, including large companies such as the Aztec Land and Cattle Company (Miller et al. 1977). Overgrazing by livestock, combined with drought conditions caused degradation of the grasslands. Soil erosion increased in the 1880s and 1890s from both wind and water; in particular, the summer monsoons of 1894 caused extensive soil erosion (Henderson 1966, Miller et al. 1977). The US Forest Service began regulating grazing in 1905 in the area of what is now PEFO (Henderson 1966).

Petrified National Park was established as a natural area in 1906 (Miller et al. 1977) and was administered by the National Park Service beginning in 1916. Grazing, however, continued in the park. Photos from the late 1920's and early 1930's show little grass and sagebrush, and large abundance of *Gutierrezia sarothrae* (broom snakeweed), an indicator of overgrazing and soil erosion (Henderson 1966, Ralphs 2011). Thomas et al. (2003), however cited several photographs from the 1930s that demonstrated grasslands with few shrubs. The park expanded its boundary in 1932 to include the northern Painted Desert section of the park (Miller et al. 1977), and in 1934 began erecting fencing along its borders to exclude grazing. Grazing continued in the northern portions of the park until 1960. In the early 1940's there were 150 cattle grazing on 10,640 acres (4,306 ha; Henderson 1966). The fencing along the northern boundary of the park was completed in 1963. Between 2007 and 2013, the park made a series of acquisitions of private and state lands totaling 45,586 acres (18,445 hectares), increasing the size of the park by approximately 50% (NPS 2018). The majority of these newly acquired lands have had a long history of livestock grazing, from the time of Euro-American settlement to shortly before their acquisition by the National Park Service. The lands also include several abandoned potash mines. The transfer of the lands included the purchase of the livestock leases, but the mineral rights remain in private ownership.

4 Vegetation

4.1 Vegetation classification

The most recent vegetation map of Petrified Forest National Park shows a mosaic of grasslands, shrublands, barrens/sparse vegetation, and a few woodlands (Thomas et al. 2009b; Figure 4). A data summarization from 186 relevés (Thomas et al. 2003) demonstrated that the most abundant perennial grasses were *Pleuraphis jamesii* (= *Hilaria jamesii*), *Sporobolus airoides* (alkali sacaton), *Achnatherum hymenoides* (Indian ricegrass) and *Bouteloua gracilis* (blue grama). The most abundant shrubs/subshrubs included *Gutierrezia sarothrae*, *Atriplex obovata* (New Mexico saltbush), *Atriplex confertifolia* (shadscale), *Atriplex canescens* (fourwing saltbush), *Ericameria nauseosa* (rubber rabbitbrush), *Artemisia bigelovii* (Bigelow's sagebrush), *Ephedra torreyana* (Torrey's jointfir), *Parryella filifolia* (common dunebroom) and *Isocoma drummondii* (Drummond's goldenbush). Common succulents included *Opuntia* spp. (pricklypear) and *Yucca angustissima* (narrowleaf yucca). Forbs were not abundant.

The ecological sites monitored for SCPN's Integrated Upland project comprise 10 vegetation map units in the vegetation map (Thomas et al. 2009b) (Table 3). Six of these map units are classified as grasslands (herbaceous vegetation), two are classified as shrublands, one is classified as dwarf-shrubland and one is classified as shrub-herbaceous vegetation. Three of the vegetation map units are associated with both ecological sites: these include Alkali Sacaton Herbaceous Vegetation, Blue Grama Herbaceous Vegetation and Fourwing Saltbush / Galleta Shrubland. The New Mexico Saltbush / Alkali Sacaton – Galleta Shrub Herbaceous Vegetation only occurs in the Clayey Fan ecological site. The remaining 6 vegetation map units only occur in the Sandy Loam ecological site. The 4 largest map units are New Mexico saltbush / Alkali Sacaton – Galleta Shrub Herbaceous Vegetation, Fourwing Saltbush / Galleta Shrubland, Sandsage Colorado Plateau Shrubland and Galleta – Alkali Sacaton Herbaceous Vegetation. Seven of the vegetation map units are comprised of a single vegetation association, while 3 vegetation map units are comprised of 2 vegetation associations that were indistinguishable in the aerial photography.

Legend

Sampling frame

-  Clayey Fan
-  Sandy Loam Upland
-  Park boundary (2007)

Vegetation map base class

-  Alkali Sacaton - Blue Grama Herbaceous Vegetation
-  Four-wing Saltbush / Galleta Shrubland
-  Galleta - Alkali Sacaton Herbaceous Vegetation
-  New Mexico Saltbush / Alkali Sacaton - Galleta Shrub Herbaceous Vegetation
-  Sandsage Colorado Plateau Shrubland
-  Snakeweed - (Prickly Pear) / Galleta Dwarf-shrubland
-  Miscellaneous vegetation
-  Barren, sparse vegetation and development



Figure 4. Vegetation map of Petrified Forest National Park. A number of map units for shrublands, barren/sparse vegetation and miscellaneous Vegetation have been lumped to allow greater focus on vegetation within the SCPN Integrated Upland sampling frames. The park boundary represents the 2007 boundary, prior to the park's expansion (from Thomas et al. 2009b).

Table 3. Vegetation map units, and associations found in the Clayey Fan and Sandy Loam Upland ecological sites at Petrified Forest National Park. Common names of species found in the association names are provided in parentheses.

Map unit name	Area ¹ (hectares)	Ecological site	Association
Alkali Sacaton Herbaceous Vegetation	125	Clayey Fan / Sandy Loam Upland	<i>Sporobolus airoides</i> Southern Plains Herbaceous Vegetation (alkali sacaton)
Alkali Sacaton - Blue Grama Herbaceous Vegetation	377	Sandy Loam Upland	<i>Sporobolus airoides</i> - <i>Bouteloua gracilis</i> Herbaceous Vegetation (alkali sacaton - blue grama)
Black Grama - Galleta Herbaceous Vegetation	24	Sandy Loam Upland	<i>Bouteloua eriopoda</i> - <i>Pleuraphis jamesii</i> Herbaceous Vegetation (black grama)
Blue Grama Herbaceous Vegetation	261	Clayey Fan / Sandy Loam Upland	<i>Bouteloua gracilis</i> Herbaceous Vegetation (blue grama)
Blue Grama - Galleta Herbaceous Vegetation	544	Sandy Loam Upland	<i>Bouteloua gracilis</i> - <i>Pleuraphis jamesii</i> Herbaceous Vegetation ² (blue grama – James' galleta)
Fourwing Saltbush / Galleta Shrubland	7340	Clayey Fan / Sandy Loam Upland	<i>Atriplex canescens</i> / <i>Pleuraphis jamesii</i> Shrubland (fourwing saltbush – James' galleta)
Galleta - Alkali Sacaton Herbaceous Vegetation	4143	Sandy Loam Upland	<i>Pleuraphis jamesii</i> - <i>Sporobolus airoides</i> Herbaceous Vegetation (James' galleta – alkali sacaton)
New Mexico Saltbush / Alkali Sacaton - Galleta Shrub Herbaceous Vegetation	11,046	Clayey Fan	<i>Atriplex obovata</i> / <i>Sporobolus airoides</i> - <i>Pleuraphis jamesii</i> Shrub Herbaceous Vegetation (mound saltbush- alkali sacaton) <i>Sporobolus coromandelianus</i> Herbaceous Vegetation (Madagascar dropseed)
Sandsage Colorado Plateau Shrubland	4492	Sandy Loam Upland	<i>Artemisia filifolia</i> / <i>Bouteloua eriopoda</i> Shrubland (sandsage-black grama) <i>Artemisia filifolia</i> Colorado Plateau Shrubland (sandsage)
Snakeweed – (Prickly Pear) / Galleta Dwarf-shrubland	439	Sandy Loam Upland	<i>Gutierrezia sarothrae</i> - (<i>Opuntia</i> spp.) / <i>Pleuraphis jamesii</i> Dwarf-shrubland (broom snakeweed - prickly pear/ James' galleta)

¹ The vegetation map includes a buffer around the park boundary, so the hectare figures overestimate the area of the map units within the 2007 park boundaries.

² *Pleuraphis jamesii* has been renamed *Hilaria jamesii* in Southwestern Environmental Information Network (2018) (SEINET).

4.2 Spatial and temporal patterns of composition

Few vegetation studies have been conducted at Petrified Forest National Park, leaving large gaps in the understanding of the factors that influence vegetation composition, structure and dynamics. Factors which control vegetation across the landscape include soil properties (texture, depth, mineral content), topography (slope, aspect), hydrology, microclimates, biotic factors (herbivory, competition) and disturbances. Burgess (1995) suggests that soil depth and texture are the most important factors in determining vegetation composition. Soil textures regulate soil hydrology, thus impacting bioavailability of water. Soil depth and texture influences rooting depth of plants. Nutrients are determined by the chemical composition of the soil, organic matter content and bacteria that regulate nutrient cycling.

In the most recent vegetation classification for the park, Thomas et al. (2009b) list soil attributes, topographic position and slopes found in the field measured relevés for the various associations. However, the sample size for many of the associations are often quite small, making it difficult to generalize the edaphic factors that are associated with mapped vegetation types. Associations with larger sample sizes, on the other hand, often show large variation in the edaphic factors. For example, the 9 relevés for *Bouteloua gracilis* Herbaceous Vegetation (blue grama) occur on upper, mid and lower slopes, in addition to talus slopes and sand sheets. In an older vegetation classification, Miller et al. (1977) identified soils with clays as being associated with *Pleuraphis jamesii* (= *Hilaria jamesii*) and *Sporobolus airoides* grasslands; they identified sandy loams and sandy soils as being associated with shrublands dominated by *Atriplex canescens*, *Artemisia filifolia* (sandsage) and *Artemisia bigelovii*.

Appendix A contains a species list for each association based on sampled relevés from the vegetation mapping and classification project (Thomas et al. 2009b). Many species are common across numerous associations. These include the grasses *Bouteloua gracilis*, *Hilaria jamesii*, *Sporobolus airoides* and the annual *Vulpia, octoflora* (sixweeks fescue). Shrubs that are present across many of the associations include *Atriplex canescens*, *Ephedra torreyana* and *Ericameria nauseosa*. There are many forbs that occur across most of the associations: these include the annual forbs *Chamaesyce fendleri* (= *Euphorbia*) (Fendler's sandmat), *Chenopodium fremontii* (Fremont's goosefoot), *Salsola tragus* (prickly Russian thistle), and *Townsendia annua* (annual Townsend daisy); and the perennial forbs *Machaeranthera canescens* (= *Dieteria*) (hoary tansyaster), *Mentzelia albicaulis* (whitestem blazingstar), *Phacelia crenulata* (clefthead wildheliotrope), *Senecio spartioides* (broomlike ragwort), and *Sphaeralcea incana* (gray globemallow). Other species occur in few of the association and some species only occur in a single association.

The various lifeforms found in the Southwestern grasslands/shrublands demonstrate different adaptations to xeric environments (Burgess 1995, McClaran 1995, Schwinning et al. 2008). Shrubs tend to have deep roots and are able to extract water from deep soil horizons, although some shrubs have both tap roots and lateral roots that can access water from both deep and shallow horizons. Cacti and succulents occur where moisture is variable and fires have not recently occurred. Annual forbs and grasses are adapted to variable precipitation by requiring a certain amount of moisture to germinate. Perennial grasses, along with most forbs and subshrubs, extract water from shallow

horizons. Apical meristems of grasses are located at the base of the tiller, which allows for growth following defoliation following grazing and fire. C₄ grasses are more abundant in warmer climates, as they have a higher temperature optimum; hence C₃ grasses increase in relative abundance with latitude while C₄ grasses decrease in abundance (Monson et al. 1983, Edwards and Still 1998). The majority of the grasses at Petrified Forest are perennial C₄ grasses. These grasses green up, grow, and flower between July and September. The few C₃ grass species that occur in the park include *Elymus elymoides* (squirreltail), *Achnatherum hymenoides* and *Hesperostipa comata* (needle and thread).

Temporal dynamics of grasslands and shrublands of the Southwest are largely controlled by variation in precipitation. Noy-Meir (1973) proposed a pulse model for deserts, whereby the ecosystem remains in largely inactive state until a pulse of precipitation activates biological processes, including growth and reproduction. Pulse dynamics appear to characterize the summer growing season of Colorado Plateau grasslands. Monsoonal precipitation provides short bursts of resources that rapidly taken up by herbaceous plants and shallow rooted subshrubs from the upper soil horizons. Two factors are key to this model. First, the summer monsoons from July through September correspond to seasonality of growth for C₄ grasses, which includes *Bouteloua eriopoda* and the dominant grasses of PEFO. Second, summer rains generally only penetrate to the top 30 cm of the soil profile, particularly in fine textured soils, where it is subject to high rates of evapotranspiration (Noy-Meir 1973, Muldavin et al. 2008). In a 6 year study in a *Bouteloua eriopoda* grassland in central New Mexico, Muldavin et al. (2008) found that summer precipitation events were responsible for increases in annual net primary production (ANPP) for the dominant grass and for the entire ecosystem.

While there was a positive relationship between annual precipitation and ANPP, and between summer precipitation and ANPP, Muldavin et al. (2008) found that soil moisture was the most important factor for determining ANPP, which is logical as this is the water that is available to plants. Other factors that were important for plant growth were large storms that presumably extended the duration of the pulse, and the early onset of monsoons. In contrast, Muldavin et al. (2008) found that ANPP in a *Larrea tridentata* (creosote bush) shrubland was largely controlled by winter precipitation. Longer duration precipitation events from frontal systems combined with low evapotranspiration allows water to percolate to lower soil horizons, where it accessible only to deep rooted shrubs (Monson et al. 1983, Burgess 1995, Schwinning et al. 2008). C₃ grasses also rely on reserves of soil water stored throughout the winter months when their growth commences in spring (Muldavin et al. 2008).

Several consecutive wet winters or wet summers can cause shifts in the dominance of the different functional groups. In the national parks in Southeast Utah, where there is higher abundance of C₃ grasses, Munson et al. (2011b) found that between 1985 and 1995 there was a decrease in C₃ grasses, and no change with C₄ grasses as a result of drought. In these same parks, Witwicki et al. (2016) however, found that cover of C₃ grasses showed little change between 2009 and 2014, while C₄ grasses showed interannual variation in cover at national parks on the Colorado Plateau at higher latitudes and elevations than Petrified Forest. Counter to expectations, the factors controlling the

cover of C₄ grasses were the growing season precipitation of the previous year, and the spring precipitation of the current growing season.

Changes in composition can also result in differing regeneration strategies of certain species. Between 1915 and 1968, Neilson (1968) only recorded 7 years where *Bouteloua eriopoda* established from seedlings at Jornada Experimental Station in Southern New Mexico. While the population dynamics of this species differ at PEFO as a result of a number of factors (soils, climate, genetics), this example illustrates that changes in community composition may occur from relatively rare events that influence germination and establishment of certain species.

In general, shrubs demonstrate less short-term variation than herbaceous species. Over longer-periods of time, researchers across the Southwest have documented changes in shrub abundance. Munson et al. (2011b) found an overall increase in shrub cover between 1988 and 1998, but a decrease in the cover of *Atriplex canescens*. In a long-term study in the Chihuahuan Desert, Torell et al. (2018) found that the subshrub *Gutierrezia sarothrae* showed large changes in cover and density, exhibiting die-offs during droughts, and also as a result of the round-headed root borer (*Crossidius puchellus*), and seedling recruitment in years with above average precipitation in the spring and summer. It is likely that shrubs at PEFO may demonstrate similar changes in abundance.

Over longer periods of time, researchers have recorded shifts in the composition and structure of grasslands—many grasslands of the Southwest have converted to shrublands. These changes are likely caused by disturbances including drought, changes in livestock grazing, and changes in fire regime (see Section 5; Archer 1994, Burgess 1995, Gibbens et al. 2005, Miller 2005, Van Auken 2009, Munson et al. 2011b). There is no quantitative evidence that such changes have occurred at PEFO. In a comparison of repeat photography at Petrified Forest National Park, Thomas et al. (2003) found a variety of changes in the composition and structure of the grasslands. Two photographs showed an increase in total vegetative cover and an increase in shrubs; in contrast, another photograph showed a decrease in grass cover.

4.3 Species of concern

There are 2 federally listed plants found in Petrified Forest National Park: *Astragalus xiphoides* (gladiator milkvetch) and *Sclerocactus papyracanthus* (= *Pediocactus*) (paperspine fishhook cactus) (Kierstead 1981, Thomas et al. 2009b). Neither occurs in the grassland/shrubland communities. *Astragalus xiphoides* is associated with badland formations (Arizona Native Plant Society 2018), and *Sclerocactus papyracanthus* occurs in pinyon-juniper woodlands (Thomas et al. 2009b). Kierstead (1981) also describes 2 species of special interest in the park: *Populus deltoides* spp. *wislizeni* (Rio Grande cottonwood) and *Gilia triodon* (= *Aliciella triodon* (coyote gilia)). While *Populus deltoides* spp. *wislizeni* occurs in the Puerco River floodplains, the habitat of *Gilia triodon* is unclear, and it may occur in the grassland/shrublands of the park. In their survey of the Rainbow Forest region, Nowak et al. (2007) identified 5 species that were new park records: *Chrysothamnus baileyi* (Bailey's rabbitbrush), *Machaeranthera canescens* var. *aristata* (hoary tansyaster), *Juniperus osteosperma* (Utah juniper), *Ephedra cutleri* (Cutler's jointfir) and *Chamaesyce nutans* (= *Euphorbia nutans*) (spotted sandmat).

5 Natural and human disturbance

5.1 Nonnative plants

The establishment of nonnative plant species in Petrified Forest National Park has been facilitated by human disturbances such as development and grazing, along with human and Aeolian (wind) vectors. In their invasive plant inventory and mapping project, Thomas et al. (2009a) surveyed 3 areas of the park between 2002 and 2005. The surveyed areas were divided into 1 ha cells, and covered a diversity of soils and vegetation types, with both disturbed and undisturbed areas, covering a total of 2730 ha. Over the 4 year period 40 nonnative species were identified. The most widespread were *Salsola tragus*, *Bromus tectorum* (cheatgrass), *Sisymbrium altissimum* (tall tumbled mustard) and *Erodium cicutarium* (redstem stork's bill). In their year of maximum abundance, *Salsola tragus* occurred in 78.1 % of the sampled cells, *Bromus tectorum* occurred in 59.8% of the cells, and *Erodium cicutarium* occurred in 25.4% of the cells. Table 4 lists species found in the survey that had moderate to high abundance (frequency of >2%, or cover of >5% in one of the 4 years), or have been identified as highly invasive by Arizona Wildlands Invasive Plant Working Group, the California Invasive Plant Council, NatureServe, or the Arizona Department of Agriculture. Species identified by Thomas et al. (2004) as occurring in undisturbed areas in the first 2 years of the study are also noted. While the study did not identify specific habitats for these species, *Tamarix chinensis* (tamarisk) and *Eleagnus pumila* (Russian olive) typically occur in floodplains, and would not occur in the grasslands and shrublands.

Nonnative species were concentrated in developed areas, transportation corridors and areas of human disturbance (e.g. former roadbeds of Route 66, sewage treatment ponds). Many of the nonnative species with low frequencies and cover were restricted to these disturbed areas, they have the potential to spread to the undisturbed areas. Thomas et al. (2004) found several species with low abundance in undisturbed areas; these included *Marrubium vulgare* (horehound), *Tragopogon dubius* (yellow salsify), *Verbascum blattaria* (moth mullein), and *Verbascum thapsus* (common mullein). It is important to recognize this survey only covered certain areas of the park, so other nonnative species may occur in other areas of the park. For example, in their survey of the Rainbow Forest area, Nowak et al. (2007) identified 12 nonnative species, 2 of which were not identified by Thomas et al. (2009a): *Bromus japonicus* (Japanese brome) and *Corispermum nitidum* (common bugseed).

Since many nonnative species are annuals, their abundances generally increase in the months following precipitation. Thomas et al. (2009a) not only found high nonnative abundance in years with heavy monsoon precipitation, but some species such as *Bromus tectorum*, *Sisymbrium altissimum* and *Erodium cicutarium* showed high abundances in a year with abundant spring precipitation. See Section 4.2.

There are many vectors for dispersal of nonnatives. Species concentrated around developed areas can be both intentionally planted and accidentally introduced. Species along transportation corridors likely occur as a result of soil disturbance, revegetation projects, surface runoff from roadways, and corridors that provide “a renewable source of propagules” via transport and release by passing vehicles (Thomas et al. 2009a). Species may also be introduced from seed mixtures. Bowman (1990)

noted that seed mixes for revegetation projects in the park contained natives such as *Bouteloua gracilis* and *Bouteloua curtipendula* (sideoats grama), but also contained native species that did not occur in the park such as *Ratibida columnifera* (upright prairie coneflower) and *Agropyron trachycaulum* (= *Elymus trachycaulus*) (slender wheatgrass), as well as nonnative species such as *Agropyron desertorum* (desert wheatgrass), *Bromus inermis* (smooth brome) and *Elymus hispidus* (= *Thinopyrum intermedium*) (intermediate wheatgrass). Wind acts as a dispersal vector for a number of nonnative species such as *Salsola tragus*. Increased abundance of this species is likely the result of migration from more disturbed lands outside the park (Thomas et al. 2009a).

Table 4. Nonnative species found in Petrified Forest National Park that had a maximum frequency > 2%, or maximum cover >5%, or were given a high invasiveness or noxious rating. Invasive/Noxious Codes are as follows: A= high rating from Arizona Wildlands Invasive Plant Working Group, C= high rating from California Invasive Plant Council, N= high rating from NatureServe, X= Arizona Prohibited, Regulated and Restricted Noxious Weeds as determined by the Arizona Department of Agriculture. All data is cited in Thomas et al. (2009a), except Occurrence in undisturbed areas which is from Thomas et al. 2004.

Scientific name	Common name	Maximum frequency (%)	Maximum cover	Invasive/ Noxious rating	Occurs in undisturbed areas
<i>Acroptilon repens</i>	hardheads	0.2	1 to <5%	A N X	X
<i>Aegilops cylindrica</i>	jointed goatgrass	0.1	<1%	X	–
<i>Alhagi maurorum</i>	camelthorn	0.2	1 to <5%	X	–
<i>Bromus rubens</i>	red brome	4.6	1 to <5%	A C	X
<i>Bromus tectorum</i>	cheatgrass	59.8	5 to <25%	A C N	X
<i>Cardaria draba</i>	whitetop	0.2	<1%	X	–
<i>Carduus acanthoides</i>	musk thistle	0.1	<1%	X	X
<i>Centaurea diffusa</i>	Diffuse knapweed	0.1	<1%	X	–
<i>Centaurea solstitialis</i>	Yellow starthistle	0.6	1 to <5%	A C X	–
<i>Cirsium arvense</i>	Canada thistle	0.1	<1%	X	–
<i>Convolvulus arvensis</i>	field bindweed	0.4	1 to <5%	X	–
<i>Cynodon dactylon</i>	Bermuda grass	0.3	5 to 25%	–	–
<i>Eleagnus angustifolia</i>	Russian Olive	4.7	25% or more	A N	–
<i>Erodium cicutarium</i>	stork's bill	–	5 to <25%	–	X
<i>Halogeton glomeratus</i>	saltlover	25.4	5 to <25%	N X	X
<i>Lactuca serriola</i>	prickly lettuce	0.3	1 to <5%	–	X
<i>Linaria dalmatica</i>	Dalmatian toadflax	6.2	1 to <5%	X	–
<i>Melilotus alba</i>	white sweetclover	0.1	1 to <5%	–	–
<i>Polypogon monspeliensis</i>	rabbitsfoot grass	0.2	<1%	N	–

Table 4 (continued). Nonnative species found in Petrified Forest National Park that had a maximum frequency > 2%, or maximum cover >5%, or were given a high invasiveness or noxious rating. Invasive/Noxious Codes are as follows: A= high rating from Arizona Wildlands Invasive Plant Working Group, C= high rating from California Invasive Plant Council, N= high rating from NatureServe, X= Arizona Prohibited, Regulated and Restricted Noxious Weeds as determined by the Arizona Department of Agriculture. All data is cited in Thomas et al. (2009a), except Occurrence in undisturbed areas which is from Thomas et al. 2004.

Scientific name	Common name	Maximum frequency (%)	Maximum cover	Invasive/ Noxious rating	Occurs in undisturbed areas
<i>Salsola tragus</i>	Russian thistle	0.7	25% +	–	X
<i>Sisymbrium altissimum</i>	tall tumble mustard	78.1	5 to <25%	–	–
<i>Tamarix chinensis</i>	tamarisk	31.2	25% +	A	X
<i>Tribulus terrestris</i>	puncturevine	17.9	5 to <25%	X	–
<i>Ulmus pumila</i>	Siberian elm	2.8	1 to <5%	–	X

5.2 Fire

Fires are not as common in the grasslands/shrublands of Northern Arizona compared to other grasslands, due to less biomass and the lack of fuel continuity (NPS 1986, Burgess 1995, Miller 2005). The fire history of grasslands are difficult to study due to the lack of trees to collect dendrochronological data. McPherson (1995) claims that fire frequency was at least 10 years for grasslands of the Chihuahuan and Sonoran Deserts. Lightning fires inevitably occurred, although how large they were would have depended on the fuel (amount and continuity) and weather (windspeed and humidity). It is unclear the extent to which fires were caused by Native Peoples prior to the arrival European-Americans: it is possible that fire were used for hunting, land management, warfare, in addition to accidental ignitions (Bahre 1991), but this is speculative. The fire frequency of the grasslands inevitably decreased with the arrival of European-Americans, although there may have been a short-term increase in accidental human-caused fires, followed by a decrease. Miller et al. (1977) suggest that fire suppression began around 1886. The decrease in fire frequency was the result of the reduction of fuel loads from grazing, and also from the direct suppression of fires (Bahre 1991, McPherson 1995). Fire regimes would further be altered by the interaction of overgrazing and droughts, causing increased erosion and subsequent changes in the structure and composition of the grasslands. (See Sections 5.3 and 5.4).

The fire history of Petrified Forest is not well documented. No fire history studies have been conducted. The national databases for fire occurrences—Wildland Fire Decision Support System (WFDSS) and Monitoring Trends in Burn Severity (MTBS)—show no historic or recent fire records for the park, but recorded an 897 ha fire in 1996 that occurred approximately 14 km east of current park boundary. According to the park’s Fire Management plan, between 1995 and 2005 there were 12 fires in the park, 2 of which were lightning caused and the remainder which were human-caused (NPS 2005). One identified source of human-caused fires was the Burlington Northern Santa Fe

Railroad which passes through the park. Presumably all human-caused fires were immediately suppressed. The two lightning-caused fires burned 2 acres (it is not clear if they were 2 acres each or 2 acres total), and were extinguished by rain.

Much of our understanding of the effects of fires on Southwestern grasslands come from the studies in the Chihuahuan and Sonoran Deserts (McPherson 1995). The different functional groups show different adaptations to fire. Grasses generally survive fires, due to their apical meristems being located at the base of their tillers (McClaran 1995). One exception is *Bouteloua eriopoda*, which is sensitive to fire, and is slow to recover (Burgess 1995, McPherson 1995). Many forbs also survive fires by sprouting from rhizomes. Similarly, shrubs may be top-killed, but can resprout following fires. Mortality of shrubs is also reported (Miller et al. 1977), and many researches have suggested that fires have at least in part been responsible for maintaining grasslands, and preventing “shrub invasion” (Archer 1994, Burgess 1995, Miller 2005, Van Auken 2009). Fires often stimulate germination of seeds, particularly of annual species. As a result, nonnative annual species can increase in abundance following fires. Nonnative annual grasses, *Bromus tectorum* in particular, can increase the fuel loads and cause an increase in fire frequency (McPherson 1995). Succulents have been shown to have varying responses from fire, from receiving little damage, to having their protective spines removed, to sustaining high mortality. While McPherson (1995) argues that the overall impact of fires on southwestern grasslands is relatively benign, with biomass recovers in 1 to 3 years, he notes that there are exceptions. High mortality of grasses may occur when fire is followed by drought, and fires can promote the establishment of nonnative species which in turn can cause changes in ecosystem functions.

5.3 Grazing

Generally speaking, short-term impacts of livestock grazing involved the removal of palatable species causing a removal of biomass and a shift in the relative abundance towards the nonpalatable species (Burgess 1995, Schwinning et al. 2008). On the Colorado Plateau, palatable species include the perennial grass *Achnatherum hymenoides*, and the shrub *Krascheninnikovia lanata* (winterfat): these species decline in abundance while non palatable species, including the shrubs *Gutierrezia sarothrae* and *Ericameria nauseosa*, and annual *Salsola tragus* and the annual species *Bromus tectorum* increase. Grass species are generally favored over shrub species by the grazers, thus causing a shift towards shrubs (Chew 1982). Walker (1938) also suggested that *Aristida* (threeawn grass) is a non-palatable species, as it was abundant in the overgrazed areas outside the park. Given the widespread extent of grazing, most studies examining the impacts focus on the vegetative response following the cessation of grazing. Chew (1982) found only minor increases in grass cover 18 years after cattle had been excluded from a grazed area in Chihuahuan Desert grasslands in southeastern Arizona. In a 59 year study in southwestern Utah, Alzérreca-Angel et al. (1998) documented a slow increase in the cover of grasses *Sporobolus cryptandrus* (sand dropseed), *Achnatherum hymenoides*, and *Hilaria jamesii*, although some of the changes were the result of responses to favorable climate.

The removal of perennial grasses generally increases soil erosion, as their fibrous roots hold soil in place (McAuliffe 1995, Davenport et al. 1998). Overgrazing and droughts accelerate the process.

Historically ranchers have increased their herds when abundant rains have caused increased grass production. When droughts follow, overgrazing occurred, essentially removing the perennial grasses that hold together the soil. In addition to increased soil erosion, grazing also causes long-term changes to the soil properties, including soil compaction, destruction of biological soil crusts, and recycling/redistribution of nutrients (Neff et al. 2005, Schwinning et al. 2008, Ferrenberg et al. 2015). Neff et al. (2005) found that 30 years after the cessation of grazing in Canyonlands National Park in southeastern Utah, grassland soils had less silt, less organic matter, lower levels of elemental soil magnesium, sodium, phosphorous and manganese.

Although grazing was not as intensive in the Petrified Forest region, grazing in the late 19th century and early 20th centuries impacted the grasslands. Henderson (1966) used photographs in the park from the late 1920's and early 1930's to demonstrate large abundances of shrubs, primarily *Gutierrezia sarothrae*, *Artemisia* spp. and *Atriplex* spp., and very little grass (Henderson 1966); Thomas et al. (2003, in contrast, located photographs from this time period that showed abundant grasses. As the boundary fences were erected, and livestock grazing was eliminated from the park, perennial grasses began increasing in abundance. Following the cessation of grazing in the park, Walker (1938) noted an increase in *Stipa* (= *Hesperostipa*) (needle and thread), *Sporobolus* (dropseed), *Hilaria* (galleta), *Oryzopsis* (= *Achnatherum*) (ricegrass), *Bouteloua* (grama), *Aristida* and "bluestem" (probably *Schizachyrium scoparium*). (The rebound of *Aristida* following the cessation of grazing contradicts Walker's (1938) previously cited assertion that it is non-palatable species). Large abundances of *Gutierrezia sarothrae* and annual species are other indications of intense grazing (Henderson 1966, Ralphs 2011). In their interpretation of repeat photographs, Thomas et al. (2003) suggest the grasslands may have recovered from grazing in some areas, but in other areas they have not completely recovered (see Section 4.2).

5.4 Soil erosion

Soil erosion has had a major impact on the grasslands and shrublands of the Southwest. Increases in soil erosion has occurred following grazing and droughts through a combination of aeolian and fluvial processes (Munson et al. 2011a). Three factors are important for determining soil erosion: perennial plant cover, soil factors and climatic factors (Davenport et al. 1998).

Perennial plant cover is inversely related to the amount of erosion. Perennial grasses with their fibrous roots are particularly good at holding soil in place (McAuliffe 1995). Plant cover is inversely related to bare ground cover: as plant cover decreases, and bare ground cover increases (Munson et al. 2011a). A reduction in grass cover from processes such as grazing, fire and/or drought can accelerate erosion rates (Williams et al. 1995a, Williams et al. 1995b, Belnap et al. 2009, Munson et al. 2011a). Since plant cover varies from year to year, there is potential for greater erosion in drought years, and in the first year following the drought before the vegetation has had time to recover.

There have been few studies examining soil erosion in southwestern grasslands and shrublands. Munson et al. (2011a) inputted 20 years of vegetation monitoring data and soil stability data from grasslands and shrublands in southern Utah into a wind erosion model. They found that decreases in vegetative cover resulted in an exponential increases in wind erosion. Research conducted in pinyon-juniper woodlands at Bandelier National Monument in New Mexico found that the climatic factors

that influence soil erosion include total annual precipitation, temporal variability and seasonal distribution of precipitation and intensity and duration of precipitation events (Davenport et al. 1998). The amount and intensity of rainfall has been shown to be particularly important. In another study at Bandelier National Monument, Hastings et al. (1998) found that the majority of erosion occurred during extreme rainfall events. The majority of the sediment load resulted from one or 2 rainstorm events of 16.8 mm/hour. While water erosion in grasslands is likely to be substantially less than in pinyon-juniper woodlands as a result of less exposed soil, the factors responsible for influencing soil erosion are likely to be similar.

Geomorphic factors that influence soil erosion include slope (gradient shape, length and aspect), and soil characteristics such as texture, porosity, hydraulic conductivity, surface crusts, and soil structure (Davenport et al. 1998). Biological soil crusts are thought to be important in reducing both soil and wind erosion. The microtopography of many crusts also reduces sheetflow, thus allowing greater infiltration (Belnap et al. 2003). Munson et al. (2011a) found that well-developed crusts with lichens and moss provides increased protection of the soils from wind erosion. Conversely, destruction through livestock trampling and other disturbances inevitably leads to increased rates of erosion (Belnap et al. 2003, 2009, Munson et al. 2011a). Soil compaction from livestock also reduces infiltration, thus increasing erosion through increased runoff.

Most evidence of erosion in the park is anecdotal and hence qualitative. Large amounts of erosion occurred in the Petrified Forest region in the 1880s, in the first major drought that followed the introduction of livestock grazing to the region (Henderson 1966). By the 1930's gulches had been created, but erosion rates decreased when fencing was erected and livestock were removed (Walker 1938). Colbert (1956, 1966) measured erosion rates on Chinle badland formations within the park, and found a removal of 5.7 cm of soil per year. The unvegetated nature of these features, however, provides little insight into erosion rates of the grasslands and shrublands.

The tight linkage between vegetation and soils suggests the presence of positive feedback loops (Miller 2005). One evident positive feedback loop occurs when herbaceous species are prevented from colonizing unstable surfaces caused by erosion, which in turn promotes more erosion (Wilcox et al. 2003).

5.5 Drought and climate change

Droughts are a cyclical disturbance regime impacting the composition and structure in the grasslands of Petrified Forest National Park, as well as across the Southwest. Historically, droughts have regularly occurred across the southwestern U.S., impacting the grasslands and shrublands. Williams et al. (2013) identified an extreme drought that occurred across the southwestern US in 1247–1296, as well as droughts occurring in 1572–1587, 1899–1904, 1945–1964, and 2000–2012. Droughts in the 1200s may have played a role in the abandonment of the Ancestral Puebloan pueblos at Mesa Verde, Chaco Culture and elsewhere across the Colorado Plateau (Wyckoff 1977, Nabhan et al. 2004).

Droughts in Southwestern United States are a cyclical phenomenon influenced by ocean and atmospheric patterns at different time scales that occurs on a scale of 4 to 7 years. The El Niño

Southern Oscillation (ENSO) are periodic variations from sea surface temperatures in the Pacific Ocean that operate on the scale of years. Warmer sea surface temperatures in the eastern Pacific Ocean (the El Niño phase) generally bring increased variability in warm season precipitation and above normal cool season precipitation; in contrast, cooler sea surface temperatures (La Niña phase) bring lower variability in warm season precipitation, and below normal cool season precipitation (Hereford et al. 2002).

Two other climatic phenomena that act on the scale of decades that influence climate patterns of the Southwest: the Pacific Decadal Oscillation (PDO) reflects variations in sea surface temperatures in the north Pacific Ocean, and the Atlantic Multidecadal Oscillation (AMO) reflects sea surface temperatures in the north Atlantic Ocean. The negative, cool phase of the PDO is associated with decreased precipitation in the Southwestern US, while the positive, warm phase is associated with increased precipitation. Hereford et al. (2002) described warm-wet phases of the PDO as occurring from 1905 to 1941 and from 1978 to 1998, and cool-dry phases occurring from 1942 to 1977 and beginning in 1999. Gray et al. (2003) described similar periodicities: warm-wet phases of the PDO occurring from 1925 to 1946 and from 1977 to 1998, and cool-dry phases occurring from 1890 to 1924 and from 1947 to 1976. Gray et al. (2003) also described similar phases of the AMO with warm phases occurring from 1860 to 1890 and 1930 to 1960, and cool phases occurring from 1905 to 1925 and from 1970 to 1990. The coupling of the cool phase of the PDO and the warm phase of the AMO has resulted in the severe drought conditions of the 1950's (Gray et al. 2003).

Generally, drought stress in plants results in the slowing or cessation of growth. As the drought severity increases, tissue damage can occur, and ultimately plant mortality (Burgess 1995). Evolutionary adaptations have allowed plants to tolerate drought stress, including C₄ metabolism, Crassulacean Acid Metabolism (CAM), root structures that allow access to deep water or catching precipitation close to the soil surface, and increased capacity water storage in stems and roots (Burgess 1995, Schwinning et al. 2008) (See Section 4.2). These adaptations suggest functional types of plants that are adapted to certain precipitation regimes, and consequently respond differently to droughts. For example, deep rooted shrubs rely on winter precipitation, and are not responsive to variability in summer precipitation (Schwinning et al. 2008, Muldavin et al. 2008). Researchers in southern Utah have examined the responses of various functional groups to droughts. Munson et al. (2011b) found a decrease in abundance of C₃ grasses over an 11 year period as a result of drought, but no change in the abundance of C₄ grasses. Hoover et al. (2015) similarly found C₃ grasses most sensitive to droughts. Contrary to expectation, they found C₄ grasses had intermediate sensitivities to drought, and were the least sensitive. Witwicki et al. (2016) found little variation in cover of C₃ grasses, but C₄ grasses showed interannual changes due to droughts. Munson et al. (2011b) found impacts were smaller in systems with sandy soil: this is likely the result of water being allowed to move below the high evaporative zone. Some of these responses to droughts may be the result of not only the severity of the droughts, but the length, seasonality and periodicity of the droughts. Plants will respond differently to press droughts, or chronic reduction in water availability, than to short-term pulse droughts. Impacts of droughts have not been well-studied. A ten year experiment to simulate anthropogenic climate change showed that increased temperature caused biological soil

crusts to degrade to earlier successional states with decreased moss and lichen cover and increased cyanobacteria cover (Ferrenberg et al. 2015).

Critical to the management of the grasslands and shrublands at Petrified Forest is how these systems will change in the next century, and specifically how climate change will impact these systems. While droughts have been a natural disturbance regime, more recent variations in climate have been influenced by anthropogenic changes in the atmosphere, thus blurring the distinction between natural and human disturbance. There is a general agreement among climate models that the southwestern United States will become hotter and drier as a result of climate change. Specifically the following changes are predicted (Garfin et al. 2013):

- Hotter and longer summers with hotter heat waves
- Greater precipitation extremes in winter
- Decrease in late-season snowpack
- Decrease in soil moisture
- Hotter, more severe and more frequent droughts
- Decrease in average winter precipitation in the southern southwest and perhaps an increase in winter precipitation the northern Southwest.

These six predictions are all expressed with high to medium-high confidence with the exception of the last one which was cited with medium-low confidence. The ensemble mean of numerous climate models indicate that by 2050 projected droughts will be more severe than any drought since 1000 CE (Williams et al. 2013).

At Petrified Forest National Park, annual precipitation showed large among year variation between 1950 and 2017 (PRISM Climate Group 2018) (Figure 5). Precipitation was less than 15 cm for 3 of these years: 1950, 1956 and 2009. A detailed analysis of the climate data at Petrified Forest National Park between 1901 and 2012 suggests that climatic conditions have moved outside the range of historical range of variability. Monahan and Fisichelli (2014) used 10, 20 and 30 year moving windows to compare recent temperatures and precipitation variables to historical records, and comparing the most recent intervals to the previous intervals going back to 1901. They found that in the recent time intervals 3 of 7 temperature variables exceeded the 95th percentile of their historical range, and that 2 of 7 precipitation variables were less than the 5th percentile. Annual mean temperature, maximum temperature of the warmest month and mean temperature of the warmest quarter showed recent values that exceeded the 95th percentile, indicating “extreme warm”. Precipitation of the wettest quarter and precipitation of the driest quarter exceeded the 5th percentile, indicating “extreme dry”.

Longer summers with hotter, more severe and more frequent droughts suggest that the impacts evident in current droughts will become more pervasive. Vegetative cover will inevitably decrease –

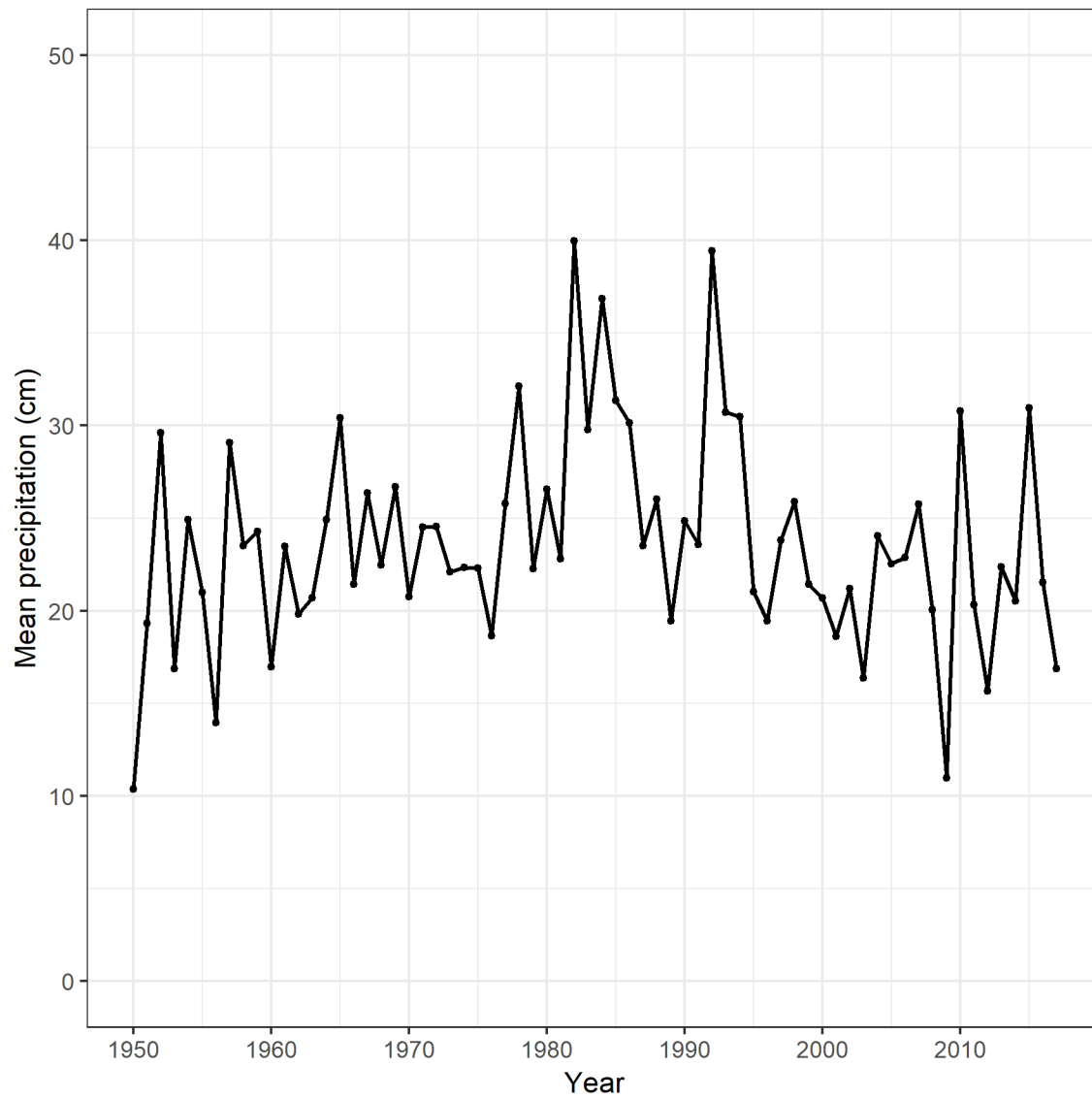


Figure 5. Annual precipitation in cm between 1950 and 2017 across Petrified Forest National Park (current boundaries) using PRISM data (PRISM Climate Group 2018).

particularly for perennial grasses and forbs. C_3 grasses could become extirpated. Impacts will be greater in the Clayey Fan ecological site, compared to the Sandy Loam Upland ecological site, as sandy sites appear to be more resilient to drought, perhaps as a result of greater water availability in the lower soil horizons (Munson et al. 2011b). An increase in winter precipitation and/or a shift from summer dominated to winter dominated precipitation would likely cause further increases in shrubs, as they would be better able to access the deep stored soil moisture than herbaceous species (Romme et al. 2009). Munson et al. (2011a) projects that an increase in 1°C in temperature in Southern Utah grasslands will cause an 8% decline in cover of perennial grasses. A reduction in herbaceous cover would be accompanied by an increase in erosion and an increase in shrubs (Munson et al. 2011b).

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Appendix A

Species lists for vegetation associations based on sampled relevés in the Sandy Loam Upland and Clayey Fan ecological sites at Petrified Forest National Park (Thomas et al. 2009). The following codes are used:

SPAI = *Sporobolus airoides* Southern Plains Herbaceous Vegetation
 SPCR= *Sporobolus cryptandrus* Great Basin Herbaceous Vegetation
 SPAI-BOGR= *Sporobolus airoides* –*Bouteloua gracilis* Herbaceous Vegetation
 BOER=*Bouteloua eriopoda*-*Pleuraphis jamesii* Herbaceous Vegetation
 BOGR-PLJA = *Bouteloua gracilis* -*Pleuraphis jamesii* Herbaceous Vegetation
 BOGR=*Bouteloua gracilis* Herbaceous Vegetation
 ATCA=*Atriplex canescens* /*Pleuraphis jamesii* Shrubland
 PLJA-SPAI= *Pleuraphis jamesii*-*Sporobolus airoides* Herbaceous Vegetation
 ATOB= *Atriplex obovata* /*Sporobolus airoides*-*Pleuraphis jamesii* Shrub Herbaceous Vegetation
 SPCO – *Sporobolus coromandelianus* Herbaceous Vegetation
 ARFI-BOER=*Artemisia filifolia*/*Bouteloua eriopoda* Shrubland
 ARFI= *Artemisia filifolia* Colorado Plateau Shrubland
 GUSA= *Gutierrezia sarothrae*- (*Opuntia* spp.) / *Pleuraphis jamesii* Dwarf Shrubland.

Table A1. Species lists for vegetation associations. X = species is present in the vegetation association.

Lifeform	Species	Common name	SPAI	SPCR	SPAI-BOGR	BOER-PLJA	BOGR-PLJA	BOGR	ATCA	PLJA-SPAI	ATOB	SPCO	ARFI-BOER	ARFI	GUSA
Grasses	<i>Achnatherum hymenoides</i>	Indian rice grass	–	–	X	X	–	X	X	X	X	–	X	X	X
	<i>Aristida adscensionis</i>	sixweeks threeawn	–	–	–	X	X	–	–	X	–	–	–	–	–
	<i>Aristida purpurea</i>	Fendler's threeawn	–	–	X	–	X	X	X	–	X	–	X	X	X
	<i>Bouteloua barbata</i>	sixweeks grama	–	–	X	X	X	–	–	–	X	X	–	X	–

Table A1 (continued). Species lists for vegetation associations. X = species present in the vegetation association.

Lifeform	Species	Common name	SPAI	SPCR	SPAI-BOGR	BOER-PLJA	BOGR-PLJA	BOGR	ATCA	PLJA-SPAI	ATOB	SPCO	ARFI-BOER	ARFI	GUSA
Grasses, cont.	<i>Bouteloua eriopoda</i>	black grama	–	–	X	X	X	X	X	–	–	–	X	–	X
	<i>Bouteloua gracilis</i>	blue grama	–	–	X	X	X	X	X	X	X	X	X	X	X
	<i>Bouteloua simplex</i>	matted grama	–	–	–	–	–	–	–	–	X	–	–	–	–
	<i>Bromus japonicus</i> (=B. arvensis)	field brome	–	–	–	–	–	–	X	–	–	–	–	–	–
	<i>Bromus rubens</i>	red brome	–	–	X	–	–	–	X	–	–	–	–	–	–
	<i>Bromus tectorum</i>	cheatgrass	–	–	X	X	–	–	X	X	X	–	X	X	X
	<i>Dasyochloa pulchella</i>	low woollygrass	X	–	X	X	–	X	–	–	–	–	X	X	X
	<i>Distichlis spicata</i>	saltgrass	–	–	–	–	–	–	–	–	–	–	–	–	–
	<i>Elymus elymoides</i>	squirreltail	X	–	X	–	–	–	X	–	X	X	X	X	–
	<i>Eragrostis spectabilis</i>	purple lovegrass	–	–	–	–	–	–	–	–	X	–	–	–	–
	<i>Hesperostipa neomexicana</i>	New Mexico feathergrass	–	–	X	–	–	X	–	–	–	–	X	X	–
	<i>Hesperostipa</i> sp.	needle and thread	–	–	–	X	–	–	–	–	–	–	–	–	–
	<i>Hordeum pusillum</i>	little barley	–	–	–	–	–	–	–	–	X	–	–	–	–
	<i>Hordeum</i> sp.	barley	X	–	–	–	–	–	–	–		X	–	–	–
	<i>Munroa squarrosa</i> (=Munroa)	false buffalograss	–	–	X	–	–	X	–	–	X	–	–	X	X

Table A1 (continued). Species lists for vegetation associations. X = species is present in the vegetation association.

Lifeform	Species	Common name	SPAI	SPCR	SPAI-BOGR	BOER-PLJA	BOGR-PLJA	BOGR	ATCA	PLJA-SPAI	ATOB	SPCO	ARFI-BOER	ARFI	GUSA
Grasses, cont.	<i>Muhlenbergia pungens</i>	sandhill muhly	–	–	–	X	–	X	–	X	–	–	X	X	X
	<i>Muhlenbergia torreyi</i>	ring muhly	–	–	–	X	–	X	–	–	–	–	X	–	X
	<i>Panicum hirticaule</i>	Mexican panicgrass	–	–	–	–	–	–	–	–	–	X	–	–	–
	<i>Pleuraphis jamesii</i> (=Hilaria)	James' galleta	–	–	X	X	X	X	X	X	–	X	X	X	X
	<i>Sporobolus airoides</i>	alkali sacaton	X	–	X	X	X	X	X	X	X	–	–	X	X
	<i>Sporobolus contractus</i>	spike dropseed	–	–	X	–	–	X	–	–	–	–	X	X	–
	<i>Sporobolus coromandelianus</i>	Madagascar dropseed	–	–	–	–	–	–	–	–	X	X	–	–	–
	<i>Sporobolus cryptandrus</i>	sand dropseed	–	X	X	X	–	–	–	–	X	–	–	X	X
	<i>Sporobolus flexuosus</i>	mesa dropseed	–	–	–	X	–	–	–	–	–	–	–	X	X
	<i>Sporobolus giganteus</i>	giant dropseed	–	–	–	–	–	–	–	–	–	–	X	X	–
	<i>Vulpia octoflora</i>	sixweeks fescue	–	–	X	X	X	X	X	X	X	X	X	X	X
Shrubs	<i>Artemisia bigelovii</i>	Bigelow sage	–	–	X	X	X	X	–	–	X	–	X	X	X
	<i>Artemisia filifolia</i>	sandsage	–	–	X	X	–	X	X	–	–	–	X	X	–
	<i>Atriplex canescens</i>	fourwing saltbush	–	–	X	X	X	X	X	X	X	–	X	X	X
	<i>Atriplex confertifolia</i>	shadscale saltbush	–	–	X	–	X	X	–	X	X	X	–	–	X
	<i>Atriplex obovata</i>	mound saltbush	X	X	X	–	X	X	–	–	X	X	–	–	–

Table A1 (continued). Species lists for vegetation associations. X = species is present in the vegetation association.

Lifeform	Species	Common name	SPAI	SPCR	SPAI-BOGR	BOER-PLJA	BOGR-PLJA	BOGR	ATCA	PLJA-SPAI	ATOB	SPCO	ARFI-BOER	ARFI	GUSA
Shrubs, cont.	<i>Atriplex powellii</i>	Powell's saltweed	–	–	–	–	–	–	X	–	–	–	–	–	–
	<i>Chrysothamnus greenei</i>	Greene's rabbitbrush	–	–	–	–	–	X	–	X	–	–	X	X	X
	<i>Ephedra torreyana</i>	Torrey's jointfir	–	–	X	X	X	X	X	X	X	–	X	X	X
	<i>Ephedra viridis</i>	Mormon tea	–	–	–	–	–	–	–	–	–	–	–	X	–
	<i>Ericameria nauseosa</i>	rubber rabbitbrush	–	X	X	X	X	X	X	–	X	–	X	X	X
	<i>Eriogonum leptocladon</i>	sand buckwheat	–	–	X	X	–	X	–	–	–	–	X	X	X
	<i>Eriogonum leptophyllum</i>	slenderleaf buckwheat	–	–	–	–	–	–	–	X	–	–	–	–	–
	<i>Gutierrezia microcephala</i>	threadleaf snakeweed	–	–	–	–	X	–	X	–	X	–	–	–	–
	<i>Gutierrezia sarothrae</i>	broom snakeweed	–	–	X	X	X	X	X	X	X	–	X	X	X
	<i>Isocoma drummondii</i>	Drummond's goldenbush	–	–	–	–	–	X	–	–	X	–	–	X	–
	<i>Kochia americana</i>	green molly	–	–	–	–	–	–	–	–	X	–	–	–	–
	<i>Krascheninnikovia lanata</i>	Winterfat	–	–	X	X	X	X	X	–	–	–	–	X	X
	<i>Lycium pallidum</i>	pale desert-thorn	–	–	–	X	–	–	X	–	–	–	–	–	–
	<i>Parryella filifolia</i>	common dunebroom	–	–	–	–	X	X	–	X	X	–	X	X	X
	<i>Sarcobatus vermiculatus</i>	greasewood	X	–	–	–	–	–	–	–	X	–	–	–	–
	<i>Suaeda moquinii</i>	Mojave seablite	–	X	–	–	–	–	–	–	–	–	–	–	–

Table A1 (continued). Species lists for vegetation associations. X = species is present in the vegetation association.

Lifeform	Species	Common name	SPAI	SPCR	SPAI-BOGR	BOER-PLJA	BOGR-PLJA	BOGR	ATCA	PLJA-SPAI	ATOB	SPCO	ARFI-BOER	ARFI	GUSA
Forbs	<i>Abronia elliptica</i>	fragrant white sand verbena	–	–	–	X	–	–	–	–	–	–	–	X	–
	<i>Ambrosia acanthicarpa</i>	flatspine bur ragweed	–	–	–	–	–	–	–	–	–	–	–	X	–
	<i>Astragalus amphioxys</i>	Crescent milkvetch	–	–	X	X	–	X	X	X	X	X	X	–	X
	<i>Boerhavia spicata</i>	creeping spiderling	–	–	–	–	–	–	–	–	X	–	–	–	–
	<i>Caesalpinia jamesii</i> (=Pomaria)	James' holdback	–	–	–	X	–	X	–	–	–	–	X	X	–
	<i>Calochortus aureus</i>	golden mariposa lily	–	–	X	–	–	X	–	X	X	X	X	–	–
	<i>Chaetopappa ericoides</i>	rose heath	–	–	X	X	X	X	X	X	X	–	X	X	–
	<i>Chamaesyce albomarginata</i>	whitemargin sandmat	–	–	–	–	–	–	–	–	–	X	–	–	–
	<i>Chamaesyce fendleri</i> (=Euphorbia)	Fendler's sandmat	X	–	X	X	X	X	X	X	X	X	–	X	X
	<i>Chenopodium fremontii</i>	Fremont's goosefoot	X	–	X	X	–	X	X	X	X	X	X	X	–
	<i>Chenopodium leptophyllum</i>	narrowleaf goosefoot	X	–	X	X	–	X	X	–	X	X	X	X	–
	<i>Comandra umbellata</i>	bastard toadflax	–	–	–	X	–	–	–	–	–	–	X	X	–
	<i>Cordylanthus wrightii</i>	Wright's bird's beak	–	–	–	X	–	–	X	–	–	–	X	–	X

Table A1 (continued). Species lists for vegetation associations. X = species is present in the vegetation association.

Lifeform	Species	Common name	SPAI	SPCR	SPAI-BOGR	BOER-PLJA	BOGR-PLJA	BOGR	ATCA	PLJA-SPAI	ATOB	SPCO	ARFI-BOER	ARFI	GUSA
Forbs, cont.	<i>Corispermum nitidum</i>	shiny bugseed	–	–	–	–	–	–	–	–	–	–	–	X	–
	<i>Cryptantha crassisejala</i>	thicksepal cryptantha	–	–	X	X	–	X	X	X	X	–	X	X	X
	<i>Cryptantha fulvocanescens</i>	tawny cryptantha	–	–	–	X	–	–	–	–	–	–	–	–	–
	<i>Cryptantha</i> sp.	cryptantha	–	–	–	–	X	–	–	–	–	–	–	–	–
	<i>Dalea lanata</i>	wooly prairie clover	–	–	–	–	–	–	–	–	–	–	–	X	–
	<i>Dimorphocarpa wislizeni</i>	touristplant	–	–	X	X	–	X	–	X	–	–	X	X	–
	<i>Erigeron concinnus</i>	Navajo fleabane	–	–	–	X	–	–	X	–	–	–	X	–	–
	<i>Eriogonum deflexum</i>	flatcrown buckwheat	–	–	–	–	–	X	–	X	–	–	X	X	–
	<i>Eriogonum divaricatum</i>	divergent buckwheat	–	–	–	–	X	X	–	X	X	–	X	X	–
	<i>Evolvulus nuttallianus</i>	shaggy dwarf morning-glory	–	–	–	X	–	X	–	–	–	–	X	–	–
	<i>Gaillardia pinnatifida</i>	red dome blanketflower	–	–	–	X	–	X	–	–	–	–	–	–	–
	<i>Gilia</i> sp.	gilia	–	–	–	X	–	–	–	–	–	–	X	X	–
	<i>Helianthus annuus</i>	common sunflower	–	–	–	–	–	–	–	–	–	–	–	X	–
	<i>Heliomeris multiflora</i>	showy goldeneye	–	–	X	–	–	–	–	X	–	–	–	–	–
	<i>Hymenopappus filifolius</i>	fineleaf hymenopappus	–	–	–	–	–	–	X	–	–	–	–	–	–

Table A1 (continued). Species lists for vegetation associations. X = species is present in the vegetation association.

Lifeform	Species	Common name	SPAI	SPCR	SPAI-BOGR	BOER-PLJA	BOGR-PLJA	BOGR	ATCA	PLJA-SPAI	ATOB	SPCO	ARFI-BOER	ARFI	GUSA
Forbs, cont.	<i>Hymenopappus flavescens</i>	Collegeflower	–	–	X	X	–	X	–	X	X	–	X	–	–
	<i>Ipomopsis longiflora</i>	whiteflower ipomopsis	–	–	X	X	X	X	X	X	–	–	X	X	–
	<i>Ipomopsis multiflora</i>	manyflowered ipomopsis	–	–	–	–	–	–	X	X	–	–	–	–	X
	<i>Ipomopsis pumila</i>	dwarf ipomopsis	–	–	–	–	–	–	–	–	X	–	–	–	–
	<i>Lesquerella fendleri</i>	Fendler's bladderpod	–	–	–	–	–	–	–	–	–	–	–	X	–
	<i>Linum aristatum</i>	bristle flax	–	–	X	X	X	X	X	X	X	–	X	X	X
	<i>Machaeranthera canescens</i> (=Dieteria)	hoary tansyaster	–	–	X	X	X	X	X	X	X	–	X	X	X
	<i>Machaeranthera gracilis</i> (=Dieteria)	slender goldenweed	–	–	X	–	–	–	–	–	–	–	–	X	–
	<i>Mentzelia albicaulis</i>	whitestem blazingstar	X	–	X	–	X	X	X	X	X	X	–	X	X
	<i>Mentzelia pumila</i>	dwarf mentzelia	–	–	X	X	X	X	X	X	X	–	X	X	X
	<i>Oenothera albicaulis</i>	whitest evening primrose	–	–	X	–	–	X	–	–	X	–	X	X	–
	<i>Oenothera caespitosa</i>	tufted evening primrose	–	–	–	X	–	–	–	–	–	–	–	–	–
	<i>Oenothera pallida</i>	pale evening primrose	–	–	–	–	–	X	–	–	–	–	–	X	X
	<i>Pectis angustifolia</i>	lemonscent	–	–	X	X	–	–	–	X	X	X	X	X	–

Table A1 (continued). Species lists for vegetation associations. X = species is present in the vegetation association.

Lifeform	Species	Common name	SPAI	SPCR	SPAI-BOGR	BOER-PLJA	BOGR-PLJA	BOGR	ATCA	PLJA-SPAI	ATOB	SPCO	ARFI-BOER	ARFI	GUSA
Forbs, cont.	<i>Phacelia crenulata</i>	cleftleaf wildheliotrope	X	–	X	X	X	X	X	X	X	X	X	X	X
	<i>Phacelia integrifolia</i>	gypsum phacelia	–	–	–	X	–	–	–	–	–	–	–	–	–
	<i>Plantago patagonica</i>	wooly plantain	–	–	X	X	X	X	–	X	–	X	X	–	X
	<i>Portulaca oleracea</i>	little hogweed	X	–	X	–	X	–	X	X	X	–	–	X	–
	<i>Salsola tragus</i>	prickly Russian thistle	X	–	X	X	X	X	X	X	X	X	–	X	–
	<i>Sanvitalia abertii</i>	creeping zinnia	–	–	–	–	–	–	–	–	X	–	–	–	–
	<i>Senecio flaccidus</i>	threadleaf ragwort	–	–	–	–	–	X	–	–	X	–	–	–	–
	<i>Senecio spartioides</i>	broomlike ragwort	–	–	X	X	X	X	X	X	X	–	X	X	X
	<i>Sphaeralcea ambigua</i>	desert globemallow	–	–	X	–	–	X	–	X	X	–	X	X	X
	<i>Sphaeralcea incana</i>	gray globemallow	X	–	X	X	X	X	X	X	X	X	X	X	X
	<i>Stephanomeria exigua</i>	small wirelettuce	–	–	X	X	–	X	–	–	–	–	X	X	–
	<i>Thelesperma megapotamicum</i>	Hopi tea greenthread	–	–	–	X	–	–	–	–	–	–	X	–	–
	<i>Townsendia annua</i>	annual Townsend daisy	X	–	X	X	X	X	X	X	X	X	X	X	X
	<i>Townsendia incana</i>	hoary Townsend daisy	–	–	–	–	–	–	–	–	–	–	X	–	–

Table A1 (continued). Species lists for vegetation associations. X = species is present in the vegetation association.

Lifeform	Species	Common name	SPAI	SPCR	SPAI-BOGR	BOER-PLJA	BOGR-PLJA	BOGR	ATCA	PLJA-SPAI	ATOB	SPCO	ARFI-BOER	ARFI	GUSA
Succulents	<i>Echinocereus</i> sp.	hedgehog cactus	–	–	X	–	X	–	X	–	X	–	–	–	–
	<i>Opuntia polyacantha</i>	plains pricklypear	X	X	X	X	X	–	X	X	X	X	X	X	X
	<i>Opuntia whipplei</i> (= <i>Cylindropuntia</i>)	Whipple cholla	–	–	X	X	–	–	X	X	X	X	–	X	–
	<i>Yucca angustissima</i>	narrowleaf yucca	–	–	X	X	–	X	X	–	X	–	X	X	X
	<i>Yucca baccata</i>	banana yucca	–	–	–	–	–	–	–	–	–	–	X	–	X

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.

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