



1995–2017 Analysis of Vegetation Change Using NDVI Data at Glen Canyon National Recreation Area

Focused Condition Assessment Report

Natural Resource Report NPS/GLCA/NRR—2023/2533



ON THE COVER

Desert Sand Ecological Site (plot DS031), Wahweap, 2013, showing open sandy substrates, with sand sagebrush (*Artemisia filifolia*) and vanclevea (*Chrysothamnus stylosa*).

NPS

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Abstract

This Focused Condition Assessment examines the impacts of the recent 2000–2020 long-term drought on the vegetation and soils of Glen Canyon National Recreation Area (GLCA). With support from the NASA DEVELOP Program, summer (June–August) Normalized Difference Vegetation Index (NDVI) values from 1995 to 2017 (excluding 2012 which was not available), measuring greenness and phenology in the vegetation, were analyzed for two periods. The first period from 1995–1999 included the pre-drought period, when precipitation was average to above average. Most years of the second period, 2000–2020, were drier than average as part of the severe drought that began in late 1999 and has continued to present (Lukas and Payton 2020). The NDVI values included mean values and were analyzed for 42 soil units, 20 associated NRCS Ecological Sites (ecosites), and the 10 most widespread vegetation alliances derived from the GLCA vegetation classification. Unvegetated rock outcrops, other exposed bedrock areas, and cliffs, which are extensive in GLCA, were not included.

With the exception of some riparian areas, mean NDVI values for all upland soils, ecosites and alliances declined from pre-drought conditions. The areas showing the largest declines were clay soils, shallow sandy loam and other shallow soils and associated ecosites and alliances. Talus vegetation and mid- to upper elevation pinyon-juniper (*Pinus edulis-Juniperus osteosperma*) woodlands showed the smallest declines. Deeper sandy and sandy loam sites showed intermediate declines. Particularly large declines occurred in shallow soil arid sites dominated by shadscale (*Atriplex confertifolia*) and other saltbush species. Blackbrush (*Coleogyne ramosissima*), one of the dominant species in the park, showed moderate declines, primarily on shallower soils. No evidence for widespread death in either blackbrush or pinyon-juniper woodlands were noted, although recent severe drought and a weakened Arizona Monsoon since 2018 may be causing impacts to the woodland species.

Relationships with livestock grazing are also examined, based on data collected on long-term monitoring plots established between 2008 and 2020. There is evidence that areas with intensive livestock grazing have shown larger declines than ungrazed areas, but these impacts need to be explored more fully at the local allotment and pasture level, and correlated with actual grazing animal unit months (AUM)'s.

Several management recommendations are made, including additional plot-based long-term monitoring, exploration of cultural resource inventories and erodible soils, how these observed changes can affect livestock grazing management decisions in the park, and further exploration using NDVI data from 2018 and forward.

Acknowledgements

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Introduction

Glen Canyon National Recreation Area (GLCA) is the largest NPS unit where domestic livestock grazing is a permitted land-use activity (505,857 ha or 1.25 million acres). As directed by the park's enabling legislation, adjoining field offices of the Bureau of Land Management administer all 34 grazing allotments that occur partially or entirely within the park, with approximately 308,518 ha (762,365 ac) currently subject to livestock grazing and an additional 48,691 ha (120,318 ac) where livestock grazing has occurred within the previous 30 years. Due to arid climatic conditions (mean annual precipitation is less than 200 mm across most of GLCA) and a multi-decadal ongoing severe drought throughout the Colorado Plateau region, dryland ecosystems in GLCA are characterized by both recent drought impacts and a generally low degree of resilience to grazing-related impacts (Spence 2017).

Field data from long-term monitoring plots established between 2008 and 2016 indicate that portions of the park's grazed rangelands have moved away from pre-European settlement conditions into new altered states. Based on a combination of subjective rangeland health assessments and quantitative assessment of soils and vegetation, 85% of sampled areas show significant departures from reference conditions (Spence 2017). If vegetation and soil resource conditions continue to deteriorate and expand into other areas of GLCA, due to climate change and land use practices, they will have profound implications for the management of natural and cultural resources within GLCA.

This Focused Condition Assessment (FCA) has the goals of assessing current terrestrial vegetation conditions and potential risk/vulnerability relative to existing or emerging condition-change drivers including climate change and ongoing grazing. This effort is critical because of on-going extreme drought and increasing climate change effects.

The Management Team at GLCA is very interested in gathering information that can inform current and long-term decisions related to rangelands in the park and how to manage and protect important plant communities that provide wildlife habitat, protect soils, and allow for mandated uses by livestock. As outlined below the primary focus will be on desert grasslands, blackbrush shrublands, and pinyon-juniper woodland plant communities within the park.

Principal outcomes and products from this FCA include the following:

- Documentation of changes in plant community composition indicating that, either in specific areas or parkwide, GLCA is transitioning from grassland or mixed grass/shrub communities to desert shrub and annual plant communities.
- Indications that aridification/desertification is occurring parkwide and further impacting both natural and cultural resources through loss of plant cover and biological soil crusts, thereby increasing soil erosion.
- Identification of specific areas that show minor to major declines in primary production in vegetative composition over the past 22 years and/or that are experiencing loss of vegetation cover due to climate change and associated aridification/desertification.

- Identifying which specific soil-vegetation community combinations are most at-risk from the impacts of ongoing climate change.
- Determining specific resource indicators that show that climate change is impacting terrestrial landscapes (livestock/human accessible areas, relict areas or both) and that grazing livestock is and may further accelerate those impacts.
- Maps, compiled range data and GIS layers showing results of the project. These layers will include extrapolated rangeland health conditions for specific allotments based on a variety of data sources, including NDVI-based change layers to help prioritize management actions.

The results of this project will inform management decisions and future stewardship activities for vegetation, soil, cultural, paleontological, and wildlife resources in GLCA. Potential actions include:

- Allowing GLCA to prioritize areas of the park experiencing loss of vegetative components or groundcover including specific grazing allotments needing management adjustments (i.e., changes to numbers permitted to graze, timing of grazing, or enhanced rotational grazing).
- Help identify current climate change impacts (i.e., the “New Norm” for precipitation/temperatures/seasons) and better forecast potential future impacts in order to consider and recommend management actions for the protection of natural and cultural resources.

Methods

The primary focus was to complete additional GIS analysis of the NASA DEVELOP park maps prepared in 2018 and 2019, which show sequential changes over the past 22 years, and which included an initial assessment of plant cover and productivity (Spence and Cushing 2019).

GLCA staff will ground truth both the NASA DEVELOP maps and GLCA 2017 parkwide vegetation map by completing additional long-term vegetation plots in areas of the park that are not currently covered. Quantitative methods will focus on new plots in vegetation types not covered in previous monitoring, in particular pinyon-juniper woodlands. Currently, there are 103 permanent long-term monitoring plots in the park (methods are outlined in Spence 2017) with quantitative data collected, and an additional 10 for which less data has been collected. Data derived from these plots include current plant community composition, biological soil crusts, and soil conditions. Using this data, it will be possible to identify the loss of key plant components such as Indian ricegrass (*Achnatherum hymenoides*) or blue grama (*Bouteloua gracilis*) and show any shifts to different future vegetation composition. These will describe key indicators of aridification and the resultant increase in bare and eroding soils (NRCS 2010).

Summer NDVI data is available for the period of 1995 to 2017 for the entire park. Using GIS analyses, this data will be overlaid with soils and vegetation data from the 2017 GLCA vegetation classification (Tendick et al. 2017).

The NDVI data used in this study are the raw mean values. These values can be affected by a variety of factors, including presence of clouds or ground fog, atmospheric opacity, elevation, and ozone concentrations among others. These factors can be controlled using MODIS spectral analysis (e.g., Potter 2019) approaches. However, this was beyond the scope and resources available for this current study. It is likely that using 3-month mean values might reduce some effects of atmospheric conditions, and the assumption is made that any alterations to raw data would be minor. Future more detailed work using the MODIS corrections are desirable.

To examine regional differences in changes in NDVI across NRCS ecosites and vegetation alliances, the park was stratified into 4 regions: Upper, San Juan-Middle, Escalante and Lower. These divisions are mapped in and summarized in Appendices C–E. There is some minor overlap between the four regions. Full GIS workflows and methods for the soil units, NRCS ecosites, and vegetation alliances can be found in Appendix F.

Species distribution models (SDM's) are currently available from the USGS for two critical plant species, pinyon pine (*Pinus edulis*) and Utah juniper (*Juniperus osteosperma*; Copeland et al. 2018). SDM's are not available for blackbrush or grass species. These SDM's will be used in combination with the most current downscaled GCM's for climate projections to model changes over time based on predicted future climates in GLCA. Weather station data from the region will also be consulted (see also Spence and Cushing 2019).

Cultural resource condition reports and data are available for selected grazing allotments in GLCA as well. In addition, a cultural site density model has been applied to the park and correlated with soil, vegetation and NDVI data. The results of this FCA will be useful for future cultural resource inventories and condition assessments in the park.

We used estimated variable from the GCLA soil survey (NRCS 2010) to investigate overall soil erodibility as well as susceptibility to wind erosion. The first variable is K_w , which is a general variable of potential erodibility, primarily based on water erosion, and can vary throughout a soil depth profile although generally by relatively small values. For an examination of overall K_w , each soils depth profile K_w values were summed and averaged. Then this value was multiplied by the overall percent NDVI change to give an approximate estimate of current potential desertification (CPD), based on declines in NDVI values and K_w for each soil, as:

$$CPD = \text{Mean } K_w \times \% \text{change in mean NDVI pre- and post-drought}$$

A second measure includes a similar calculation for current wind erosion potential (CWEP), as:

$$CWEP = \text{Wind Erosion Factor} \times \% \text{change in mean NDVI pre- and post-drought} / 100$$

Results

Climate Change

GLCA is in a semiarid environment characterized by hot summers and cold winters, with high spatiotemporal variability in precipitation and temperature (Spence 2001; Tendick et al. 2017). Winter temperatures often dip well below freezing for extended periods, while summer temperatures can reach as high as 38°C (110°F) (Spence 2001) and last for several days at a time. Lees Ferry, at an elevation of 978 m (3,208 ft), receives approximately 153 mm (6 in) of precipitation per year while the Escalante climate station, at 1776 m (5,825 ft), averages 278 mm (11 in) per year (Spence 2001; Spence and Cushing 2019). The wide altitudinal range (1,389 m [4,556 ft]) across GLCA accounts for large differences in temperature and precipitation from one part of the park to another (Spence 2001). Although precipitation is variable, the general pattern is weakly bimodal, with the largest peak occurring during the late summer monsoon (30–35% of total annual precipitation) and a smaller peak occurring in late winter (Spence 2001).

The early and middle 1990s were a relatively wet period, with mean precipitation ca. 20% above average for the park. The Lake Powell reservoir was at or near full pool for much of this time. The current drought started in the 1999–2000 winter, and has more or less continued since then, with a few wet years (e.g., 2010, 2013) interspersed among some record breaking hot and/or dry years. Based on Page data, the three driest years since 1995 were 2012 (86.6 mm), 2002 (102.4 mm) and 2014 (104.1) with a mean value of 98 mm. The drought has continued to present, 2020 was the driest on record with 51 mm in Page. Regionally, 2020 appears to be the driest year going back at least 1000 years. The 2019 and 2020 monsoons did not develop, which represents a substantial impact of loss of precipitation to plants enduring very hot summer temperatures. Lake Powell has fallen to levels of 40% to 60% of full pool during this entire time period with only a few short periods where it was over 60% full. Downriver, Lake Mead has held at a steady 35% to 45% of full capacity since the mid-2000s.

John Bradford, of the U. S. Geological Survey (USGS) provided downscaled climate analyses for GLCA at a 6-km (3.7 mi) resolution. Trends in annual temperature, precipitation, soil moisture, and transpiration were provided for 1915 to 2015, along with estimates of these variables under two standard future (present-2100) climate scenarios, or Representative Concentration Pathways (RCPs): RCP 4.5 and RCP 8.5. RCP 4.5 represents an intermediate scenario of slowly declining greenhouse gas emissions while RCP 8.5 represents a “worst case” scenario of rising emissions (IPCC 2014; Wuebbles et al. 2017). The results are summarized in Figures 1 and 2.

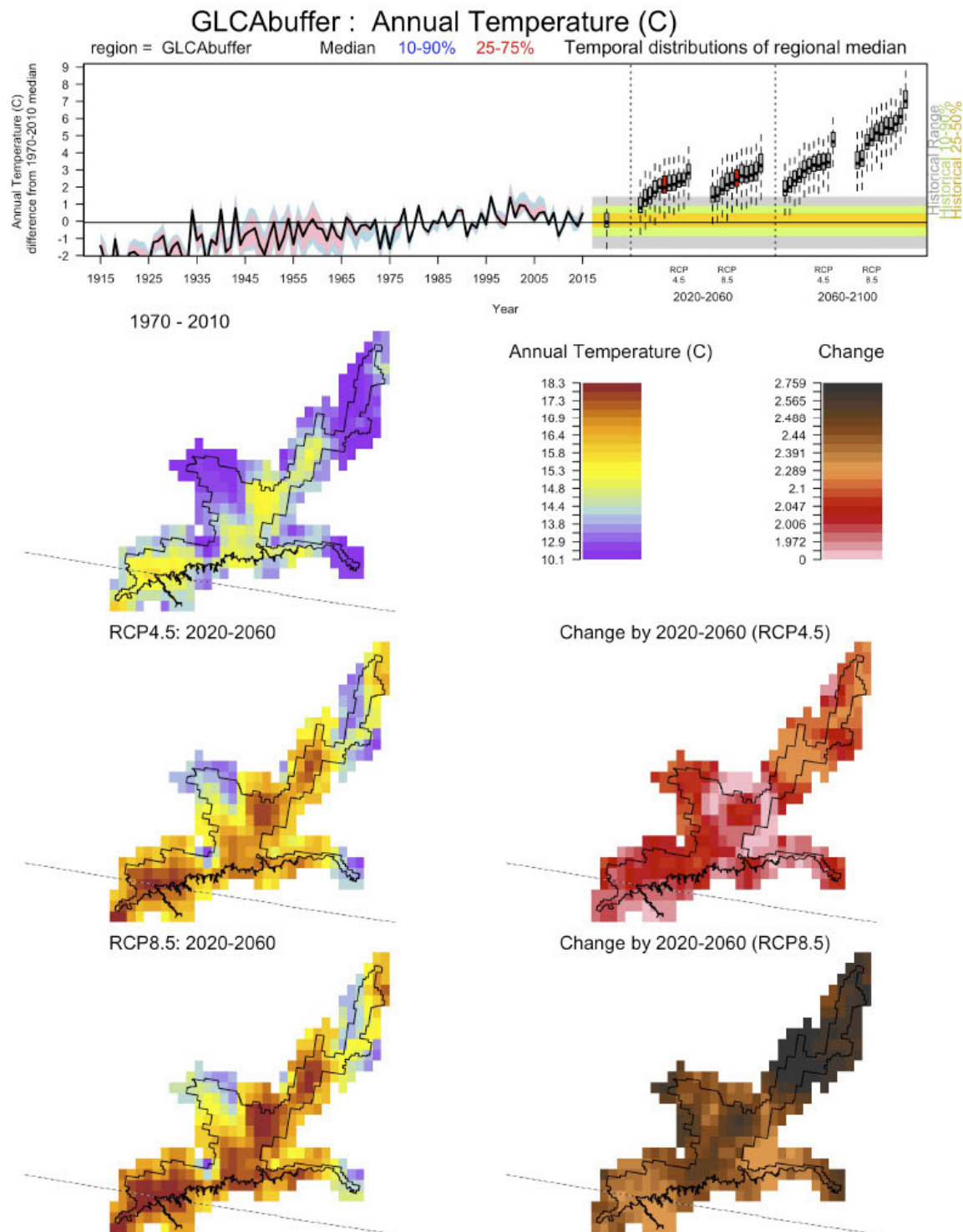


Figure 1. Historical (1915–2015) and predicted (2020–2100) departure from baseline (1970–2010) median temperature under RCP 4.5 and RCP 8.5. Figure created by John Bradford, research ecologist, USGS Southwest Biological Science Center.

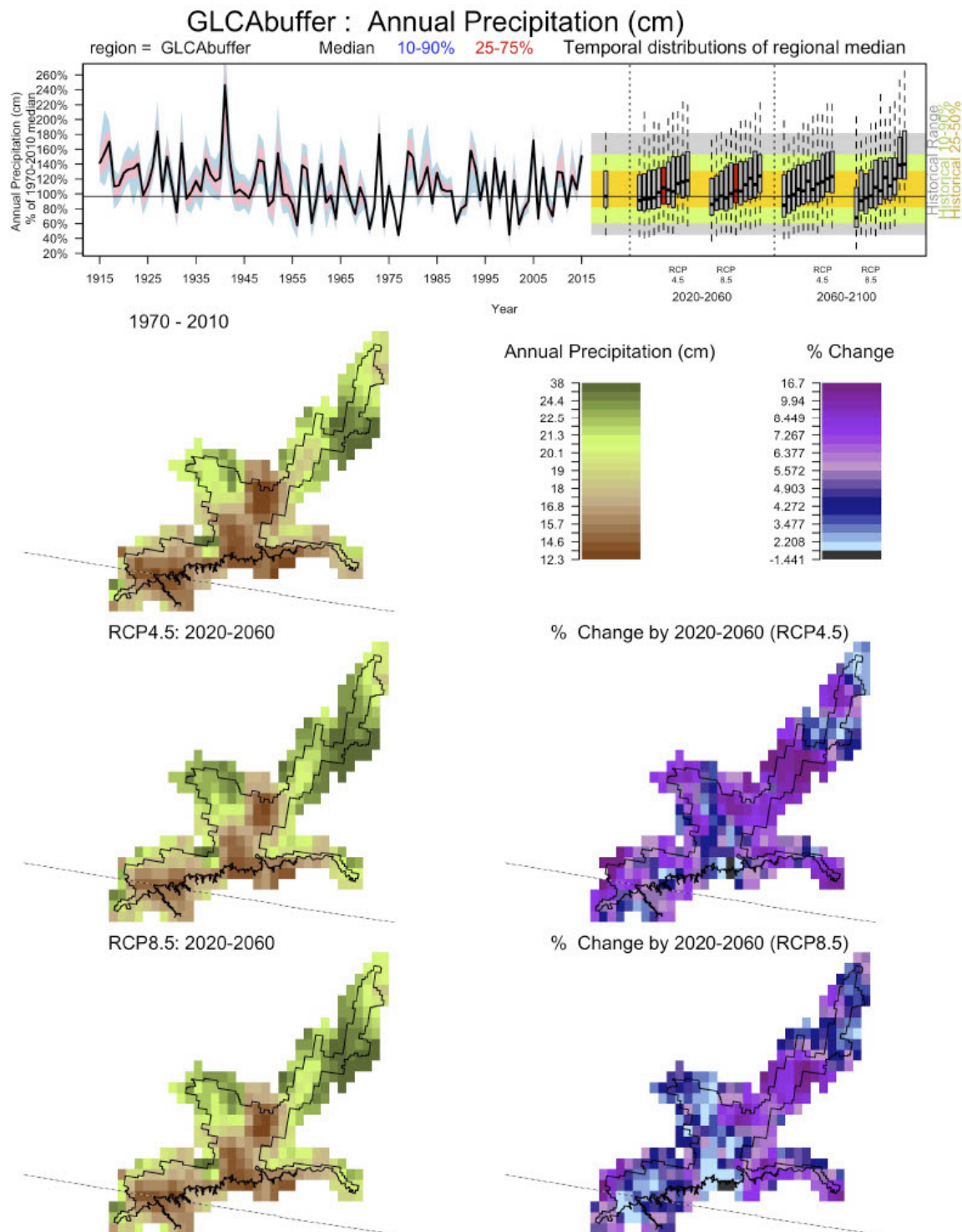


Figure 2. Historical (1915–2015) and predicted (2020–2100) percent departure from baseline (1970–2010) median precipitation under RCP 4.5 and RCP 8.5. Figure created by John Bradford, research ecologist, USGS Southwest Biological Science Center.

In recent decades, mean annual temperature in GLCA has increased $\sim 1^{\circ}\text{C}$ ($\sim 1.8^{\circ}\text{F}$) (Spence and Cushing 2019). Monahan and Fisichelli (2014) found that annual mean temperature, maximum

temperature of the warmest month, and mean temperature of the warmest quarter exceeded 95% of their historic range of variability (1901–2012) (Monahan and Fisichelli 2014). Temperature is expected to continue rising under both RCPs (Figure 2). These changes have been confirmed by Battaglin et al. (2020), who suggest a potential increase of $\sim 0.5^{\circ}\text{C}$ in the next decade in some parts of the US. By 2060, median temperatures will have exceeded the historical range of variation. Temperature changes will likely be more severe for the southern and lower elevations of the recreation area than for northern and higher elevations.

In contrast, there have been no discernable trends in precipitation (Gonzales et al. 2018); however, Spence (2001) noted a slight increase in winter precipitation, based on analyzed climate records prior to 1999. Changes in future precipitation are expected to be far less extreme than for temperature (Figure 2). Under both RCP, precipitation is predicted to remain largely within the historical range with perhaps a small increase. Despite no apparent trends in precipitation, droughts have become more common in the Southwest and are expected to worsen (Wuebbles et al. 2017; Battaglin et al. 2020). The current rate of warming, without any change in precipitation, will likely result in multi-decadal droughts that exceed even the driest centuries of the last 500 years by end of the 21st century (Lukas and Payton 2020). Runoff is also expected to decline by 10–30% by the end of the 21st century, with a 50% chance that live storage in Lakes Mead and Powell could be eliminated by 2022 (Gonzales et al. 2018).

The interaction of temperature and precipitation in arid environments controls the amount of soil moisture available to plants (Tendick et al. 2017). Soil moisture is the key limiting factor for plant growth in the region (Tendick et al. 2017). Plants on the Colorado Plateau can tolerate higher temperatures as long as water is not limiting (Munson et al. 2011). While shrubs rely more on late winter precipitation, grasses rely more on summer soil moisture (Gremer et al. 2015). However, higher temperatures can result in lower soil moisture content even if there are no changes in precipitation. This is supported by several studies that have found an increase in drought-tolerant shrubs (Munson et al. 2011; Wertin et al. 2015; Thoma et al. 2016).

Summary of NDVI Analyses and Cross Tabulations

Tables and maps showing changes in mean NDVI values for soils, NRCS ecosites and vegetation alliances (henceforth alliances) can be found in Appendices A–E. Below changes in NDVI values are ranked for dominant ecosites and vegetation alliances. Soils are not included as there are >40 soil series and many are quite small. For ecosites, the 14 major ones ($\geq 10,000$ acres) are listed in Table 1 ranked by size of change in NDVI. Although there are 28 ecosites documented in the park (NRCS 2010), many of them are spatially limited and consist of a few hundred hectares each. The 10 dominant vegetation alliances in GLCA are also ranked from largest to smallest change in NDVI. Not included are roughly 100,000 hectares (247,000 acres) of slickrock tablelands, cliffs and other bedrock lacking significant vegetation cover. Because there is not a 1:1 relationship between ecosites and alliances, we provide a cross walk figure (Figure 3).

Table 1. Ranked changes in dominant ecosites and major vegetation alliances. The ranking is from 1 (largest declines) to 10 or 15 (smallest declines) between predrought (1995–1999) and post-drought (2000–2017) periods. For ecosites, only those which represent at least 10,000 acres are included.

Rank	Ecosites (427,063 hectares/1,054,847 acres) ^a	Alliances (349,000 hectares/862,000 acres)
1	Desert Shallow Clay (Atco, Atcor)	Mat Saltbush-Shadscale
2	Desert Stony Loam (Cora)	Torrey Jointfir-Buckwheat Bush-Shadscale
3	Desert and Semidesert Sand (Atca)	Blackbrush
4	Semidesert Shallow Clay (Atco, Juos)	Mormon-tea-Blackbrush-Sand Shrub
5	Desert Stony Loam (Atco)	Mormon-tea-Wildrye-Buckwheat Bush
6	Desert Shallow Sandy Loam (Cora)	Sand Sagebrush
7	Semidesert Shallow Sandy Loam (Juos, Cora)	Pinyon-Juniper-Shrub
8	Desert Shallow Sandy Loam (Atco)	Tamarisk-ruderal Stream/Lake
9	Desert Very Steep Stony Loam (Atco)	Talus Scrub
10	Desert Sandy Loam (Cora)	Juniper (Pinyon)-Shrub-Grass
11	Semidesert Shallow Sand (Pied, Juos)	N/A
12	Semidesert Very Steep Stony Loam (Pied, Juos)	N/A
13	Talus and other steep slopes (Cora, Atco)	N/A
14	Sandstone Rockland	N/A

^a Species: Atca=*Atriplex canescens*; Atco=*A. confertifolia*; Atcor=*A. corrugata*; Cora=*Coleogyne ramosissima*; Juos=*Juniperus osteosperma*; Pied=*Pinus edulis*.

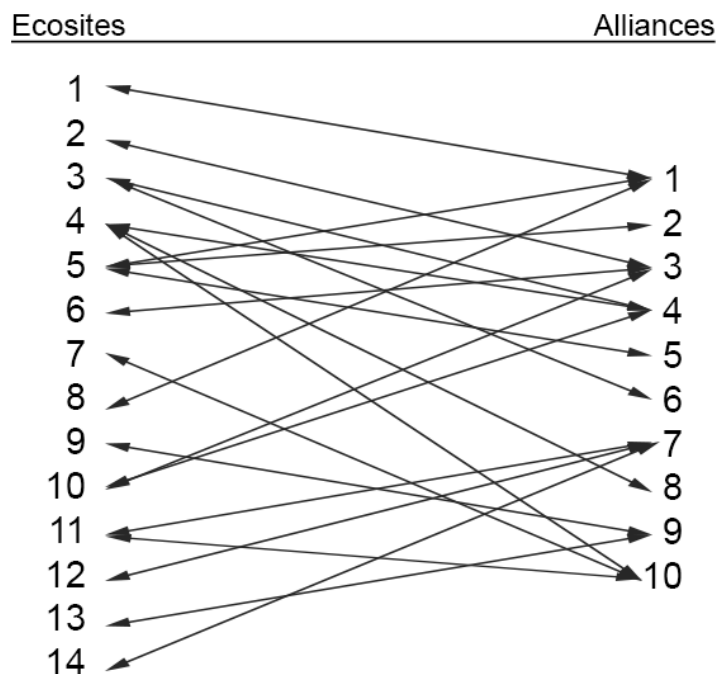


Figure 3. Cross-Correlation Diagram of Major Ecosites and Dominant Vegetation Alliances Based on Similar vegetation, ranked for departure from pre-drought conditions. See Table 1 for definitions and descriptions. This figure shows that ecosites can support more than one vegetation alliance and there is not a 1:1 correspondence between the two classifications.

The results show that for both ecosites and alliances shallow clay substrates with dwarf shrubs dominated by species of *Atriplex* (shadscale, saltbush) have shown the largest declines in NDVI values. Other groups with relatively large declines include ecosites and alliances with shallow sandy and rocky soils, such as Desert Stony Loam (DSL) and Torrey Jointfir alliance, which is often co-dominated by shadscale. Desert Sandy Loam ecosite, which is dominated by blackbrush, shows less change than the blackbrush alliance. This is likely because of to the presence of blackbrush on a variety of non-DSL substrates including many shallow rock and sandy soils where declines have been larger. For Desert and Semi-Desert sandy loam sites, the ecosite is ranked higher than the corresponding alliance (four-winged saltbush). There are differences between Desert and Semidesert Sandy Loams, with the latter showing larger declines. On the other end of the ranking, steep talus, pinyon-juniper woodlands and riparian and sandy channel sites showed the least change. The NRCS ecosite corresponding to the tamarisk-ruderal stream and lake alliance only mapped pristine sites away from Lake Powell and consists of only about 2,500 acres. The least change, as expected, is in the sandstone slickrock and cliff communities which support minimal vegetation.

The three ecosites with the largest decline represent ca. 45,000 acres, while the three alliances showing the greatest declines represent ca. 230,000 acres. Thus, when using these results, one needs use more focused on specific questions due to the relatively weak overlap between the types. Some of the larger alliances (e.g., blackbrush, jointfir) include several different ecosites and soils with varying levels of NDVI decline.

Regional Comparisons

Regional comparisons were made for ecosites and alliances (see Appendix B for regions). The results are summarized in Table 2. For most areas, upland alliance results are similar to the overall park-wide results. Saltbush communities on shallow clay soils and badlands exhibited the largest declines, except for the Upper region, which includes the areas north and east of Cataract Canyon and the Dirty Devil River. In this region, with generally higher elevations and relatively few clay substrates, the sandy site sagebrush-grass vegetation exhibited the largest declines. This is reflected mostly in the Semidesert Sand ecosite and may be related in part to livestock grazing (see below). The alliances showing the least change were similar across the regions, except for the Escalante region which showed the least declines in open pinyon-juniper woodlands. One unusual result is in the riparian tamarisk-ruderal scrub alliance, which showed significant gains in the Lower region, and major losses in the Escalante region. The reason for the gains in the Lower region is unknown, but the major declines in the Escalante River area are likely a result of the long-term control efforts on Russian olive (*Elaeagnus angustifolia*), which was initiated in 2001 (although most vegetation removal has occurred after 2009). For all alliances combined by region, the largest declines overall were in the Upper region, and the smallest declines in the Escalante and San Juan regions. Appendices A and E provide more details and rankings on these differences among regions.

Table 2. Differences in mean percent change in NDVI pre- and post-drought in four different regions of GLCA (see maps, Appendix E).

Vegetation Alliance	Upper	Escalante	San Juan	Lower
Shadscale Saltbush Scrub Alliance	-22.3	-20.3 ^b	-21.6 ^b	-22.9 ^{a,b}
Torrey's Joint-fir Shrubland Alliance	-21.3 ^a	-19.1	-19.4	N/A
Blackbrush Colorado Plateau Shrubland Alliance	-22.9 ^a	-17.3	-16.8	-18.1
Mormon-tea Colorado Plateau Shrubland Alliance	-22.9 ^a	-18.0	-16.2	-20.7
Joint-fir species - Saline Wildrye - Crispleaf Buckwheat Badlands Cold Desert Sparse Vegetation Alliance	-18.1	-14.1	-18.5 ^a	-17.1
Sand Sagebrush Desert Sand Scrub Alliance	-24.8 ^{a,b}	-13.8	-15.3	-16.4
Two-needle Pinyon - Utah Juniper / Shrub Understory Colorado Plateau Woodland & Scrub Alliance	-19.8 ^a	-12.2	-14.0	-17.2
Tamarisk species Ruderal Riparian Scrub Alliance	-15.9	-35.3 ^a	-30.2	+27.5
Singleleaf Ash - Skunkbush Sumac - Cliff Fendlerbush Talus & Rock Outcrop Shrubland Alliance	-16.8 ^{a,c}	-13.1	-13.6 ^c	-14.3 ^c
Two-needle Pinyon - Utah Juniper / Shrub Understory Foothill & Lower Montane Dry-Mesic Woodland Alliance	-17.0	-7.9 ^c	-14.9	-18.0 ^a
Upland Vegetation Mean NDVI Change ^d	-20.7	-15.1	-16.7	-18.1

^a Largest departure by region for each alliance, also shown in gray cell shading.

^b Highest departure in NDVI for each region in upland vegetation.

^c Lowest departure in NDVI for each region in upland vegetation.

^d Excluding the tamarisk/riparian scrub alliance

Soils

There are 42 soils units mapped in GLCA (Appendix A, C). However, many of these are limited in extent. Soils by themselves do not reflect changes through NDVI as that is a measure of plant greenness. However, vegetation declines on mapped soils can be used in a variety of ways based on loss of vegetation over time. Vegetation cover, especially of grasses, along with biological soil crusts, is one factor controlling erosion. Table 3 includes the 10 largest soil units and their erodibility based on the *K_w* factor and wind erosion potential. Ranges for these variables are: Mean *K_w* (0.1, 0.4); CDP (+0.09, -9.02); wind erosion factor (38, 250); CWEP (+0.35, -61.30). The Torriorthents include unclassified talus deposits and soils on steep slopes. The results indicate that the most erosion prone soils and those with the largest declines in NDVI include primarily shallow sandy and sandy-loam units, although DSL and DS ecosites showed very high levels of wind erosion combined with vegetation decline, as expected from the locally observable sand deposits.

Table 3. The major soils in GLCA with erosion variables and synthetic desertification variables (NRCS 2010).

Soil Unit (acres)	Ecosites ^a	Mean Kw	CDP	Wind Erosion Factor	CWEP
Needle (267,634)	DShSL, DSL	0.20	-2.40	250 ^b	-29.99
Torriorthents (192,311)	DVStStL	0.30	-4.44	86	-12.74
Arches (155,593)	SDS, SDSShS	0.20	-2.90	250 ^b	-26.25
Farb (66,743)	DShSL	0.37	-7.19	86	-16.70
Reef (66,432)	SDShSL, SDVStStL	0.36	-4.77	43	-5.70
Rizno (44,184)	SDShSL	0.26	-5.06	56	-10.91
Pagina-Denazar (45,321)	DSL, DS	0.22	-3.83	177	-30.83 ^b
Moenkopie (44,085)	DShSL	0.38	-6.62	134	-23.36
Ustic Torriorthents (36,160)	Unclass. Talus	0.34	-5.00	48	-7.06
Tsaya (30,693)	DVStStL	0.39 ^b	-8.36 ^b	38	-8.14

^a DS=Desert Sand; DSL=Desert Sandy Loam; DShSL=Desert Shallow Sandy Loam; SDS=Semidesert Sand; SDSShS=Semidesert Shallow Sand; DVStStL=Desert Very Steep Stony Loam; SDVStStL=Semidesert Very Steep Stony Loam.

^b The highest values for Kw, CDP, Wind Erosion and CWEP, also shown in gray cell shading.

NRCS Ecological Sites (Ecosites)

The overall results for all NRCS ecosites are summarized in Table 4, ranked from the largest changes pre- to post-drought to the smallest changes in NDVI mean values. Slickrock outcrops, cliffs and other non-vegetated surfaces are not included in the analyses. The largest changes are in lower elevation desert ecosites including Desert Shallow Clay, Desert Stony Loam, Desert Sandy Loam and Desert Shallow Sandy Loam. The Alkali Bottom ecosite is the least represented in the park with only ca. 240 acres. Those ecosites showing the smallest change include upland sites, riparian and channel areas, talus and other steep slopes, and pinyon-juniper ecosites. Overall results for ecosites indicate that declines in NDVI have been greatest in low elevation desert regions of the park, especially those on shallow and/or clay soils which retain less water at depth than deeper soils or bind the water more tightly. These areas represent >350,000 acres of the park, including many active grazing allotments. Maps can be found in Appendix D.

Table 4. All mapped NRCS ecological sites (ecosites) in GLCA, along with acres, pre- and post-drought mean NDVI values, and ranked percent change from pre- to post-drought.

NRCS Ecosite	Acres	Post Mean NDVI	Pre Mean NDVI	% Change
Desert_Shallow_Clay_ATCO4	8,254.39	0.06	0.09	-34.70%
Desert_Shallow_Clay_CORA	3,878.12	0.05	0.07	-34.67%
Desert_Stony_Loam_CORA	14,079.80	0.10	0.14	-25.41%
Alkali_Bottom_SAVE4_and_Desert_Sandy_Loam_ATCA2	240.19	0.11	0.15	-25.01%
Desert_Sandy_Loam_CORA_and_Desert_Shallow_Sandy_Loam_CORA	4,902.02	0.10	0.13	-23.91%
Semidesert_Sandy_Loam_CORA	866.89	0.12	0.15	-23.78%
Desert_Very_Shallow_Gypsum_EPTO	866.45	0.09	0.12	-23.68%
Semidesert_Sand_ATCA2	12,861.30	0.14	0.18	-23.40%
Semidesert_Shallow_Clay_ATCO_JUOS	11,060.12	0.14	0.18	-20.73%
Desert_Stony_Loam_ATCO_PICRO	9,949.04	0.10	0.13	-20.60%
Desert_Shallow_Sandy_Loam_CORA	85,088.36	0.10	0.12	-19.73%
Semidesert_Shallow_Sandy_Loam_JUOS_CORA	59,645.09	0.14	0.18	-19.57%
Desert_Shallow_Sandy_Loam_ATCO	75,875.89	0.10	0.13	-18.96%
Semidesert_Stony_Loam_JUOS_PIED	8,789.92	0.16	0.20	-18.45%
Desert_Very_Steep_Stony_Loam_ATCO	85,129.50	0.11	0.13	-18.35%
Desert_Sandy_Loam_CORA	50,065.89	0.10	0.13	-17.37%
Desert_Sand_ARFI2	4,203.26	0.10	0.12	-15.64%
Desert_Shallow_Loam_ATCO	683.64	0.08	0.10	-14.65%
Semidesert_Shallow_Sand_JUOS_PIED	155,593.42	0.13	0.15	-14.50%
Semidesert_Very_Steep_Stony_Loam_PIED_JUOS	96,470.73	0.14	0.16	-13.09%
Sandy_Wash	2,070.94	0.15	0.17	-13.05%
Talus_Slope_CORA_ATCO	119,530.82	0.11	0.13	-13.02%
Sandstone_Rockland	267,364.22	0.11	0.13	-12.00%
Upland_Loam_ARTRT	867.56	0.31	0.34	-9.61%
Upland_Stony_Loam_PIED_JUOS	876.01	0.37	0.40	-5.83%
Upland_Shallow_Loam_PIED_JUOS	3,283.43	0.35	0.37	-5.35%
Semiwet_Saline_Streambank_POFR2	2,433.44	0.31	0.31	-0.75%
Total Acres	1,084,931	0.14	0.18	-18.0%

Vegetation Alliances

The vegetation classification and map included 27 alliances and >200 floristic associations (Tendick et al. 2017). Many of the alliances were relatively small in acreage and included numerous spring and riparian systems. The 10 most widespread alliances represent ca. 80% of the park upland landscapes,

with most of the remainder being slickrock and cliffs lacking well developed vegetation. As in the previous analyses using soils and ecosites, the largest declines in NDVI values over the last 22 years were in shrub vegetation on clay and shallow rocky soils (Table 5). In particular, the saltbush and Torrey's jointfir alliances, both of which dominate on shallow clay and rocky soils and badlands showed the greatest declines. The blackbrush alliance also showed significant declines, but this widespread alliance comprises significant differences in soils and ecosites, with most of the declines occurring on shallower rocky soils (Table 4, Appendix A). Alliances showing the least decline include talus and other steep slopes, pinyon-juniper woodlands, and riparian and lakeshore tamarisk dominated scrub and wetlands. The sand sagebrush alliance showed intermediate change, but also encompasses both the Desert and Semidesert Sand ecosites, of which the latter shows large declines. Maps can be found in Appendix E.

Table 5. The 10 major vegetation alliances in GLCA, along with acres, pre- and post-drought mean NDVI values, and ranked percent change from pre- to post-drought.

Alliance	Acres	Pre NDVI Median	Post NDVI Median	% Change
Shadscale Saltbush Scrub Alliance	41,548	0.116	0.091	-21.6%
Torrey's Joint-fir Shrubland Alliance	56,383	0.136	0.109	-20.1%
Blackbrush Colorado Plateau Shrubland Alliance	135,963	0.142	0.114	-19.2%
Mormon-tea Colorado Plateau Shrubland Alliance	46,762	0.134	0.108	-18.9%
Joint-fir species - Saline Wildrye - Crispleaf Buckwheat Badlands Cold Desert Sparse Vegetation Alliance	127,219	0.134	0.111	-16.9%
Sand Sagebrush Desert Sand Scrub Alliance	29,629	0.134	0.114	-15.2%
Two-needle Pinyon - Utah Juniper / Shrub Understory Colorado Plateau Woodland & Scrub Alliance	237,335	0.153	0.130	-15.1%
Tamarisk species Ruderal Riparian Scrub Alliance	26,338	0.146	0.125	-14.4%
Singleleaf Ash - Skunkbush Sumac - Cliff Fendlerbush Talus & Rock Outcrop Shrubland Alliance	120,531	0.120	0.104	-13.7%
Two-needle Pinyon - Utah Juniper / Shrub Understory Foothill & Lower Montane Dry-Mesic Woodland Alliance	40,103	0.203	0.177	-12.6%
Total Acres	861,811	X = 0.142	X = 1.180	X = -16.8%

Livestock Grazing

There are 28 active allotments in GLCA, covering ca. 283,000 hectares (700,000 acres). The only livestock class present are cattle, with from 10,000–20,000 AUM's in a typical grazing season, which is predominantly October–April, although there are a few year-round allotments (NPS 1999). A few small feral herds (<20 animals) of cattle come and go from the park and are dealt with by the BLM and NPS when possible.

Feral horses venture into the park occasionally, especially in areas that border Navajo Nation lands. There are also populations of feral burros in some areas of the park, particularly in the Upper region in the Hans Flat area and along the San Juan River. These feral populations are increasing rapidly, and now number in the hundreds of animals although most remain on public lands to the west of the park. They will likely have significant future impacts on vegetation and soils while the park and neighboring land managers determine a control strategy.

Spence (2017) summarized quantitative and qualitative results from long-term monitoring plots in seven ecosites across the park, primarily in shrub and grassland vegetation. Using Indicators of Rangeland Health (Pellant et al. 2005) in combination with quantitative data on vegetation cover, biological soil crusts, and soil properties, these seven ecosites were ranked in terms of departure from rangeland health and for the potential for future declines related to both livestock grazing and climate change. The ecosites that showed the most intact condition and also appeared to be most resistant to livestock grazing were the Desert Sandy Loam and Semidesert Sandy Loam, dominated by blackbrush. Intermediate conditions occurred in Semidesert Sand, Desert Stony Loam, then Desert Sand, while the largest departures were found in Desert Shallow Sandy Loam and Semidesert Shallow Sandy Loam.

These ranking were based in part on qualitative and subjective IRH values, and thus are not directly relatable to the results from NDVI data. However, the results, except for perhaps the Desert Sandy Loam ecosite, are roughly comparable to the results of the NDVI analyses, where sites on shallow soils show the most change as well as potential predicted future declines. Spence (2017) also summarized the available regional studies on livestock grazing impacts and climate change, in particular their interactions, and this paper should be reviewed for this summary. Spence and Cushing (2019) further looked at specific plant species and the potential changes to their distributions based on climate change, including blackbrush, two-needle pinyon pine and Utah juniper. They also discerned a potential signal of regional impact of livestock grazing in one allotment, where within the same ecosite declines were much greater in areas where there were water sources and where cattle grazing was concentrated. However, even in the absence of grazing there were significant declines on several investigated relict mesas, particularly in perennial grass cover, suggesting a potential climate-induced signal (Spence 2017). In the current FCA report, focus on NDVI on individual grazing allotments was not attempted (but see Management Recommendations).

Conclusions

The combination of NDVI result for soils, ecological sites, vegetation alliances, as well as quantitative plot data and rangeland health (Spence 2017) show that the largest changes to upland vegetation and associated resources are in shallow clay, rocky and sandy soils. Saltbush communities on clay and shallow sandy loam soils show the greatest declines. Shadscale (*Atriplex confertifolia*) is an arid-adapted species with a fairly shallow root system, high seed production and wind pollination. Its overall abundance and ecology suggest that two factors may be involved in its decline. First, the species is most dominant in cool-desert regions such as in the central Great Basin where winters are often cold and summers are not quite as hot as the Southwest U.S. due to higher elevations, thus increasing temperatures may be part of the reason for its decline. More importantly, however, drought has had significant impacts on the species, as well as likely other saltbush species. Since the turn of the century (ca. 2000), many stands of shadscale have declined and shown significant die off in GLCA (J. Spence, pers. obs.). Declines in NDVI values of 20–35% are relatively large for these sparsely vegetated areas, suggesting that many desert communities may be showing the beginning signs of desertification.

For declines in other ecosites and alliances, the reasons remain unclear, in particular as to which species or functional groups may be responsible for the NDVI values. Using summer data removes the responses related to spring annuals, which usually senesce by May. Also, there are relatively few summer annuals in GLCA, mostly those associated lakeshores such as Russian thistle ((Spence 2017). Mormon-tea and jointfir (*Ephedra* sp.) tend to be extremely drought-tolerant and with deep root systems, except for the sandy-site *E. cutleri*. Thus, many of the declines in these communities may also be the result of shadscale losses, as that species is often co-dominant. Spence (2017) noted that there have been significant declines in cool season grass species in Desert and Semidesert ecosites, represented by Indian ricegrass (*Achnatherum hymenoides*) and needle-and-thread (*Hesperostipa comata*).

Results suggest that the combination of long-term grazing and recent climate change may be responsible for the declines in these palatable species. However, even on relict mesas (see Spence 2017), these species declined in the shallower Desert Shallow Sandy Loam ecosites more than in the deeper Desert Sandy Loam ecosites. Significant research on important perennial grass species have been conducted on the Colorado Plateau (e.g., Munson et al. 2011; Wertin et al. 2015; Thoma et al. 2016; Witwicki et al. 2016). These studies show that both cool season and warm season grasses may be highly vulnerable to climate change, depending on when precipitation occurs and when drought conditions occur during the year. For example, increased temperatures and summer drought (i.e., the lack of a summer monsoon period) would likely significantly impact warm season grasses such as galleta (*Hilaria jamesii*) and blue grama (*Bouteloua gracilis*). Although it is difficult to determine the relative importance of livestock grazing and climate change on grass declines, by using “natural experiments” including plots sampled at different times as well as similar plots in space contrasted between grazed and ungrazed areas, some preliminary suggestions can be made. Bayesian theory statistics can be used to examine this question (Hilborn and Mangel 1997). Using data from ca. 50 plots which represent differences in time and space in GLCA, the relative importance of these two

factors in changes in ricegrass and needle-and-thread were calculated (J.R. Spence, pers. comm. 2020). Applying the Bayesian theorem to the data, an interesting contrast for these species was revealed. The estimates were that grazing is somewhat more important in declines in these two cool season grasses than climate change over the last 25–30 years. The approximate apportionment is 60% of the decline can be attributed to livestock grazing, while 40% is the result of climate change. These results are based on simple contrasts based on field observations rather than designed experiments, so are very preliminary and should be interpreted with caution.

Blackbrush (*Coleogyne ramosissima*) is an enigmatic relictual species in the Rosaceae family that dominates large expanses of GLCA below ca. 5000'. It is ecologically and biologically quite distinct from shadscale (Summers et al. 2009). The species rarely recruits seedlings, but is long-lived and extremely drought tolerant, with roots that penetrate deeply into soil and rock profiles. Until now, there have been few signs of declines in this species, although relatively minor mortality has been noted in long-term vegetation plots. Thus, the declines in mean NDVI results in this alliance and associated ecosites may be due to species other than blackbrush. However, many stands are almost monospecific, thus it is also possible that declines may be related to branch and leaf shedding and dieback during particularly stressful drought events which can occur in the species.

For higher elevation juniper savanna and pinyon-juniper woodlands, declines are generally much smaller than in shrubland and grassland communities. Floyd et al. (2008) did not see signs of mortality in pinyon-juniper woodlands on Navajo Point through 2007. Despite widespread mortality after the 2000–2004 period on the Colorado Plateau (Breashers et al. 2005), populations in GLCA have remained relatively stable, although there was some die off in the Upper region in the Hans Flat-Spur-Flint Trail area. This area has not been grazed since 2001, although there are trespass cattle and burros present. The NDVI analyses do not include the severe current drought and collapse of the Arizona Monsoon since 2018, however. Recent long-term plot sampling in the Upper region in 2020 showed the beginning of a potential serious mortality event primarily in pinyon pine (J.R. Spence, pers. comm. 2020). Another result of this work is that blue grama (*Bouteloua gracilis*), which is the dominant understory species in these woodlands, appears to be dying off, with significant mortality noted in all sampled plots. This may be part of the reason for the declines noted in the NDVI analyses, and the 2020 data suggest that these losses may be accelerating. Based on modeling results, Copeland et al. (2018) indicates that the two tree species may largely disappear from GLCA by mid-to late-century, as also suggested by Spence and Cushing (2019).

NDVI data do not easily capture the presence and changes in biological soil crusts (BSC), which are critical in many ecosystems on the Colorado Plateau. There is recent research that shows that BSC is vulnerable to severe drought and can show significant declines in cover over time (Ferrenberg et al. 2015; Reed et al. 2017). There is an urgent need to develop landscape level approaches using remote sensing to capture cover and trends in BSC's in the park and on the Colorado Plateau. This is especially true for the soils and ecological sites exhibiting the biggest deviations in NDVI scores.

Spence (2017) discussed the interaction between livestock grazing and climate change in GLCA using a variety of approaches, including scenario planning (Petersen et al. 2003). These results suggested that compositional changes in vegetation in arid and semi-arid regions of the park will be

largely a result of declines in perennial grasses, with more mixed results for shrub species. However, the NDVI results suggest that at least some shrub species in particular shadscale, have been and will likely continue to be impacted by drought and temperature increases. Part of the decline in vegetation across GLCA is almost certainly due to a combination of drought and continued livestock grazing. A management strategy and management practices that reduce impacts from livestock grazing are clearly needed to prevent continued destabilization and loss of vegetation and soils in the presence of ongoing climate change.

Whether the NDVI results are showing signs of aridification and possibly desertification depends on future trends in precipitation in conjunction with conditions created by the ever-increasing regional temperatures. If the current drought conditions cease or a “wetter period” climatic shift occurs, perhaps due to a flip in the PDO, it will be interesting to see if there are signs of vegetation recovery, and which species will respond. With the presence of >100 long-term plots as well as ca. 60 Southern Colorado Plateau Network (SCPN) plots (but using different methods) these potential changes can be tracked with future monitoring efforts. Even if the drought ends, the continued increase in growing season temperatures will have impacts on snowpacks and timing of spring snow melt, exacerbate water stress in many species especially during hotter summers, and increase overall evapotranspiration rates affecting many if not most plant species in the park.

Management Recommendations

Based on the results of this analysis, the following management recommendations can be made for upland vegetation in GLCA. Bradford et al. (2018) provides general guidance and approaches that are also useful:

- The current grazing management partnership, as outlined in GLCA's enabling legislation, does lead to management inefficiencies as BLM manages the grazing program while GLCA tries to manage and protect the natural and cultural resources. It will be up to the NPS to refine this unique relationship while improving the overall ability of both agencies to: 1) track ongoing and seasonal drought episodes; 2) make timely resource protecting adjustments in numbers of livestock and season of use for both the short and longer-term droughts; 3) make longer-term adjustments in authorized AUM (animal unit months) allocations and seasons of use in specific grazing allotments where plant communities are exhibiting or heading towards large-scale changes in plant species composition. This is especially true if cool season grasses or shadscale have or are disappearing from the regional landscape;
- Continue GLCA and NPS Inventory & Monitoring monitoring of the 103 long-term vegetation plots (see Spence 2018);
- Establish additional long-term plots in ecosites and alliances currently at-threat, but not well represented, such as the jointfir vegetation and PJ woodlands;
- Collect additional NDVI data starting with 2018 to capture the recent severe drought and collapse of the Arizona monsoon period in both 2019 and 2020;
- In future work, focus on NDVI results at the specific allotment, and possibly even the pasture, level. Apply the results of the analyses to examine management options and adjustments that can be discussed with BLM managers related to livestock grazing. This was done for one pasture on the Rock Creek-Mudhole allotment, Grand Bench pasture by Spence and Cushing (2019);
- Look for other remote-sensed data sets, especially those that might detect biological soil crusts, or find research partners who could help develop a methodology using newer remote sensing tools;
- Use the cultural resource presence model and the soils data to identify areas in the park where erosion rates may be increasing or already high in order to monitor climate change related impacts on cultural resources such as hearths, roasting pits and surface lithics, and determine whether *K_w* and wind erosion factors are useful surrogates for erosion;
- Use available long-term plot data from the vital signs programs of the NPS's Northern Colorado Plateau or Southern Colorado Plateau Inventory and Monitoring Networks (NCPN, SCPN) to help inform the NDVI results and determine what species may be showing the largest declines over time. Timely decisions should then be made on what management actions should be taken, especially in relation to grazing numbers and timing;

- Work with USGS to develop species distribution models (SDM's) for keystone plant species in the park. Currently only two-needled pinyon pine and Utah juniper have been modeled. SDM's of other dominant species would be extremely valuable, including for blackbrush, shadscale, *Ephedra* species and selected perennial cool or warm season grass species;
- Apply refugial theory (Keppel et al. 2012) to determine which areas of the park may support declining species long-term and on a larger scale (i.e., higher elevations with more precipitation) or provide unique refugia where small pockets of priority native plant species may survive (see Spence and Cushing 2019 for a preliminary analysis);
- Continue cooperation and involvement in the SE Utah Group of parks—Capitol Reef–GLCA drought working group which includes investigations into the impacts of climate change on pinyon-juniper woodlands and grasslands on these NPS units within the Colorado Plateau region.

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Appendix A. Soils and regional differences in vegetation alliances in mean NDVI values

Table A-1. All soils mapped in GLCA with NDVI values pre- and post-drought, % change, and dominant NRCS ecological sites.

Dominant Soil	Ecosite ^a	Acres	Hectares	Post Mean NDVI	Pre Mean NDVI	% Change
Claysprings	DShClay	8,254.39	3,340.51	0.06	0.09	-34.70
Cowboy	DShClay	3,878.12	1,569.45	0.05	0.07	-34.67
Moepitz_family	DStLoam	6,044.68	2,446.25	0.11	0.15	-25.82
Dient	DStLoam, DShClay	8,035.11	3,251.77	0.10	0.13	-25.04
Monue_and_Trail	DSLoam	240.19	97.20	0.11	0.15	-25.01
Bluechief	DShSLoam	381.41	154.35	0.10	0.13	-24.52
Sheppard_Tsaya_families	DSand, DSLoam	4,902.02	1,983.82	0.10	0.13	-23.91
Sazi	SDSLoam	866.89	350.83	0.12	0.15	-23.78
Goblin	DVShGypsum	866.45	350.65	0.09	0.12	-23.68
Seeg	DStLoam	2,739.23	1,108.55	0.09	0.11	-23.56
Earlweed	SDSand	12,861.30	5,204.90	0.14	0.18	-23.40
Juanalo_family	DShSLoam	12,479.44	5,050.36	0.08	0.11	-23.30
Tsaya_family	DShSLoam	9,551.18	3,865.31	0.10	0.13	-21.54
Tsaya	DVStStLoam	30,693.11	12,421.33	0.11	0.13	-21.43
Westmion	SDShClay	11,060.12	4,475.97	0.14	0.18	-20.73
Myton	DStLoam, DShClay	7,209.81	2,917.77	0.11	0.13	-19.63
Rizno	SDShSLoam	48,183.99	19,499.79	0.14	0.18	-19.48
Farb	DShSLoam	66,743.70	27,010.81	0.10	0.12	-19.42
Jaconita_family	SDStLoam	8,789.92	3,557.23	0.16	0.20	-18.45

^a DS=Desert Sand; DSL=Desert Sandy Loam; DShSL=Desert Shallow Sandy Loam; SDS=Semidesert Sand; SDShClay=Semidesert Shallow Clay; SDShSL=Semidesert Shallow Sandy Loam; SDShS=Semidesert Shallow Sand; DVStStL=Desert Very Steep Stony Loam; SDVStStL=Semidesert Very Steep Stony Loam; UStLoam=Upland Stony Loam; ULoam=Upland loam; UShLoam=Upland Shallow Loam

Table A-1 (continued). All soils mapped in GLCA with NDVI values pre- and post-drought, % change, and dominant NRCS ecological sites.

Dominant Soil	Ecosite ^a	Acres	Hectares	Post Mean NDVI	Pre Mean NDVI	% Change
Somorent_family	DShSLoam	9,760.67	3,950.09	0.12	0.14	-18.34
Remorris_family	SDShSLoam	3,242.96	1,312.41	0.13	0.16	-17.88
Moenkopie	DShSLoam	44,084.59	17,840.79	0.10	0.13	-17.43
Pagina, Denazar	DSLoam, DSand	45,320.89	18,341.11	0.10	0.12	-17.42
Redhouse_family	DSLoam	4,363.60	1,765.93	0.12	0.14	-16.52
Sheppard	DSand	4,203.26	1,701.03	0.10	0.12	-15.64
Atchee	SDVStStonyLoam	2,086.51	844.40	0.19	0.23	-15.24
Torriorthents	DVStStLoam	192,311.86	77,827.54	0.11	0.13	-14.81
Ustic_Torriorthents	Talus	36,160.01	14,633.76	0.14	0.17	-14.71
Pennell	DShLoam	683.64	276.67	0.08	0.10	-14.65
Arches	SDShSand, SDSand	155,593.42	62,967.79	0.13	0.15	-14.50
Reef	SDShSL, SDVStStLoam	66,442.36	26,888.85	0.14	0.16	-13.25
Razito	Dry steam channels	2,070.94	838.10	0.15	0.17	-13.05
Needle	DShSLoam, DSLoam	267,364.22	108,200.82	0.11	0.13	-12.00
Parkelei	ULoam, UShLoam	867.56	351.10	0.31	0.34	-9.61
Oxyaquic_Torripsamments	Streambank	414.54	167.76	0.27	0.28	-6.73
Kydestea	UStLoam	876.01	354.52	0.37	0.40	-5.83
Gladel	UShLoam	3,283.43	1,328.79	0.35	0.37	-5.35
Oxyaquic_Torrifluvents	Streambank	2,018.90	817.04	0.32	0.32	0.26
Total	-	1,084,930.98	439,065.55	-	-	-

^a DS=Desert Sand; DSL=Desert Sandy Loam; DShSL=Desert Shallow Sandy Loam; SDS=Semidesert Sand; SDShClay=Semidesert Shallow Clay; SDShSL=Semidesert Shallow Sandy Loam; SDShS=Semidesert Shallow Sand; DVStStL=Desert Very Steep Stony Loam; SDVStStL=Semidesert Very Steep Stony Loam; UStLoam=Upland Stony Loam; ULoam=Upland loam; UShLoam=Upland Shallow Loam

Table A-2. All soils mapped in GLCA with general erosion factor (Kw), wind erosion factor, and synthetic variables based on %change in NDVI values pre- and post-drought.

Dominant Soil	Kw	Wind	Kw x % Change	% Change x Wind/100
Claysprings	0.26	86	-9.02	-29.84
Cowboy	0.26	86	-9.01	-29.81
Moepitz_family	0.28	48	-7.23	-12.39
Dient	0.26	48	-6.51	-12.02
Monue_and_Trail	0.34	134	-8.50	-33.52
Bluechief	0.24	250	-5.88	-61.30
Sheppard_Tsaya_families	0.26	168	-6.22	-40.17
Sazi	0.27	86	-6.42	-20.45
Goblin	0.28	48	-6.63	-11.36
Seeg	0.30	56	-7.07	-13.19
Earlweed	0.26	134	-6.08	-31.36
Juanalo_family	0.37	56	-8.62	-13.05
Tsaya_family	0.30	86	-6.46	-18.53
Tsaya	0.39	38	-8.36	-8.14
Westmion	0.24	56	-4.97	-11.61
Myton	0.23	48	-4.51	-9.42
Rizno	0.26	56	-5.06	-10.91
Farb	0.37	86	-7.19	-16.70
Jaconita_family	0.17	134	-3.14	-24.73
Somorent_family	0.26	56	-4.77	-10.27
Remorris_family	0.32	86	-5.72	-15.37
Moenkopie	0.38	134	-6.62	-23.36
Pagina, Denazar	0.22	177	-3.83	-30.83
Redhouse_family	0.37	86	-6.11	-14.20
Sheppard	0.11	220	-1.72	-34.40
Atchee	0.33	56	-5.03	-8.53
Torriorthents	0.30	86	-4.44	-12.74
Ustic_Torriorthents	0.34	48	-5.00	-7.06
Pennell	0.32	48	-4.69	-7.03
Arches	0.20	250	-2.90	-36.25
Reef	0.36	43	-4.77	-5.70
Razito	0.13	220	-1.70	-28.70
Needle	0.20	250	-2.40	-29.99
Parkelei	0.40	86	-3.84	-8.26

Table A-2 (continued). All soils mapped in GLCA with general erosion factor (Kw), wind erosion factor, and synthetic variables based on %change in NDVI values pre- and post-drought.

Dominant Soil	Kw	Wind	Kw x % Change	% Change x Wind/100
Oxyaquic_Torripsamments	0.24	134	-1.61	-9.01
Kydestea	0.27	56	-1.57	-3.26
Gladel	0.32	86	-1.71	-4.60
Oxyaquic_Torrifluvents	0.35	134	0.09	0.35

Table A-3. Ranked NDVI declines from largest to smallest for the park and 4 different regions. Park-Wide Median NOVI and Percent Change between Pre and Post-Drought Periods.

Alliance Group	Percent Change	Pre-Drought NOVI	Post-Drought NOVI
TAMAR Tamarisk species Ruderal Riparian Scrub Alliance	-14.43	0.146	0.125
SHSALT Shadscale Saltbush Scrub Alliance	-21.61	0.116	0.091
TJFSHRUB Torrey's Joint-fir Shrubland Alliance	-20.06	0.136	0.109
SSAGE Sand Sagebrush Desert Sand Scrub Alliance	-15.21	0.134	0.114
MORTEA Mormon-tea Colorado Plateau Shrubland Alliance	-18.87	0.134	0.108
BLCKSHRUB Blackbrush Colorado Plateau Shrubland Alliance	-19.2	0.142	0.114
PJ-LMONTAN Two-needle Pinyon - Utah Juniper / Shrub Understory Foothill & Lower Montane Dry-Mesic Woodland Alliance	-12.58	0.203	0.177
PJ-WOOD Two-needle Pinyon - Utah Juniper / Shrub Understory Colorado Plateau Woodland & Scrub Alliance	-15.07	0.153	0.13
SINA-SKUNS Singleleaf Ash - Skunkbush Sumac - Cliff Fendlerbush Talus & Rock Outcrop Shrubland Alliance	-13.72	0.12	0.104
SALW-BUCKW Joint-fir species - Saline Wildrye - Crispleaf Buckwheat Badlands Cold Desert Sparse Vegetation Alliance	-16.88	0.134	0.111

Table A-4. Alliance rankings, high to low.

Rank	Alliance Group
1	SHSALT Shadscale Saltbush Scrub Alliance
2	MORTEA Mormon-tea Colorado Plateau Shrubland Alliance
3	BLCKSHRUB Blackbrush Colorado Plateau Shrubland Alliance
4	TJFSHRUB Torrey's Joint-fir Shrubland Alliance
5	TAMAR Tamarisk species Ruderal Riparian Scrub Alliance
6	SSAGE Sand Sagebrush Desert Sand Scrub Alliance
7	SALW-BUCKW Joint-fir species - Saline Wildrye - Crispleaf Buckwheat Badlands Cold Desert Sparse Vegetation Alliance
8	PJ-WOOD Two-needle Pinyon - Utah Juniper / Shrub Understory Colorado Plateau Woodland & Scrub Alliance
9	PJ-LMONTAN Two-needle Pinyon - Utah Juniper / Shrub Understory Foothill & Lower Montane Dry-Mesic Woodland Alliance
10	SINA-SKUNS Singleleaf Ash - Skunkbush Sumac - Cliff Fendlerbush Talus & Rock Outcrop Shrubland Alliance

Table A-5. Ranking analysis, percent change.

Alliance Group	Escalante	San Juan	Upper	Lower	Totals
TAMAR Tamarisk species Ruderal Riparian Scrub Alliance	1	1	10	10	22
SHSALT Shadscale Saltbush Scrub Alliance	2	2	4	1	9
TJFSHRUB Torrey's Joint-fir Shrubland Alliance	3	3	4	9	19
MORTEA Mormon-tea Colorado Plateau Shrubland Alliance	4	6	2	2	14
BLCKSHRUB Blackbrush Colorado Plateau Shrubland Alliance	5	5	3	3	16

Table A-5 (continued). Ranking analysis, percent change.

Alliance Group	Escalante	San Juan	Upper	Lower	Totals
SALW-BUCKW Joint-fir species - Saline Wildrye - Crispleaf Buckwheat Badlands Cold Desert Sparse Vegetation Alliance	6	4	7	6	23
SSAGE Sand Sagebrush Desert Sand Scrub Alliance	7	7	1	7	22
SINA-SKUNS Singleleaf Ash - Skunkbush Sumac - Cliff Fendlerbush Talus & Rock Outcrop Shrubland Alliance	8	10	9	8	35
PJ-WOOD Two-needle Pinyon - Utah Juniper / Shrub Understory Colorado Plateau Woodland & Scrub Alliance	9	9	6	5	29
PJ-LMONTAN Two-needle Pinyon - Utah Juniper / Shrub Understory Foothill & Lower Montane Dry-Mesic Woodland Alliance	10	8	8	4	30

Table A-6. Top 3 alliance group for each region.

Region	Rank 1 Alliance	Rank 2 Alliance	Rank 3 Alliance
Escalante	TAMAR Tamarisk species Ruderal Riparian Scrub Alliance	SHSALT Shadscale Saltbush Scrub Alliance	TJFSHRUB Torrey's Joint-fir Shrubland Alliance
San Juan	TAMAR Tamarisk species Ruderal Riparian Scrub Alliance	SHSALT Shadscale Saltbush Scrub Alliance	TJFSHRUB Torrey's Joint-fir Shrubland Alliance
Upper	MORTEA Mormon-tea Colorado Plateau Shrubland Alliance	BLCKSHRUB Blackbrush Colorado Plateau Shrubland Alliance	SSAGE Sand Sagebrush Desert Sand Scrub Alliance
Lower	SHSALT Shadscale Saltbush Scrub Alliance	MORTEA Mormon-tea Colorado Plateau Shrubland Alliance	BLCKSHRUB Blackbrush Colorado Plateau Shrubland Alliance

Appendix B. Parkwide soil and ecosite maps

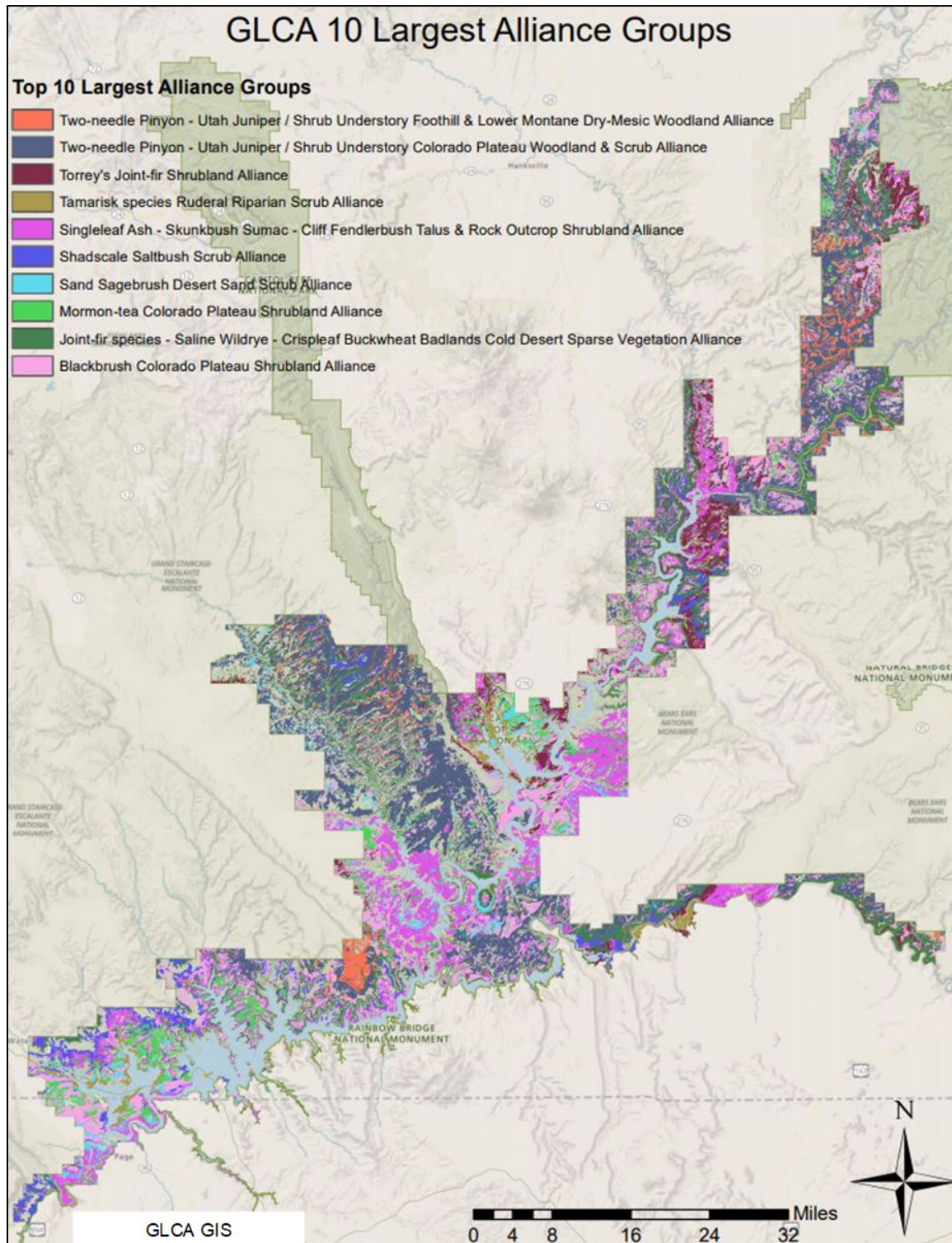


Figure B1. Map of GLCA 10 largest alliance groups.

Appendix C. Soil unit change maps

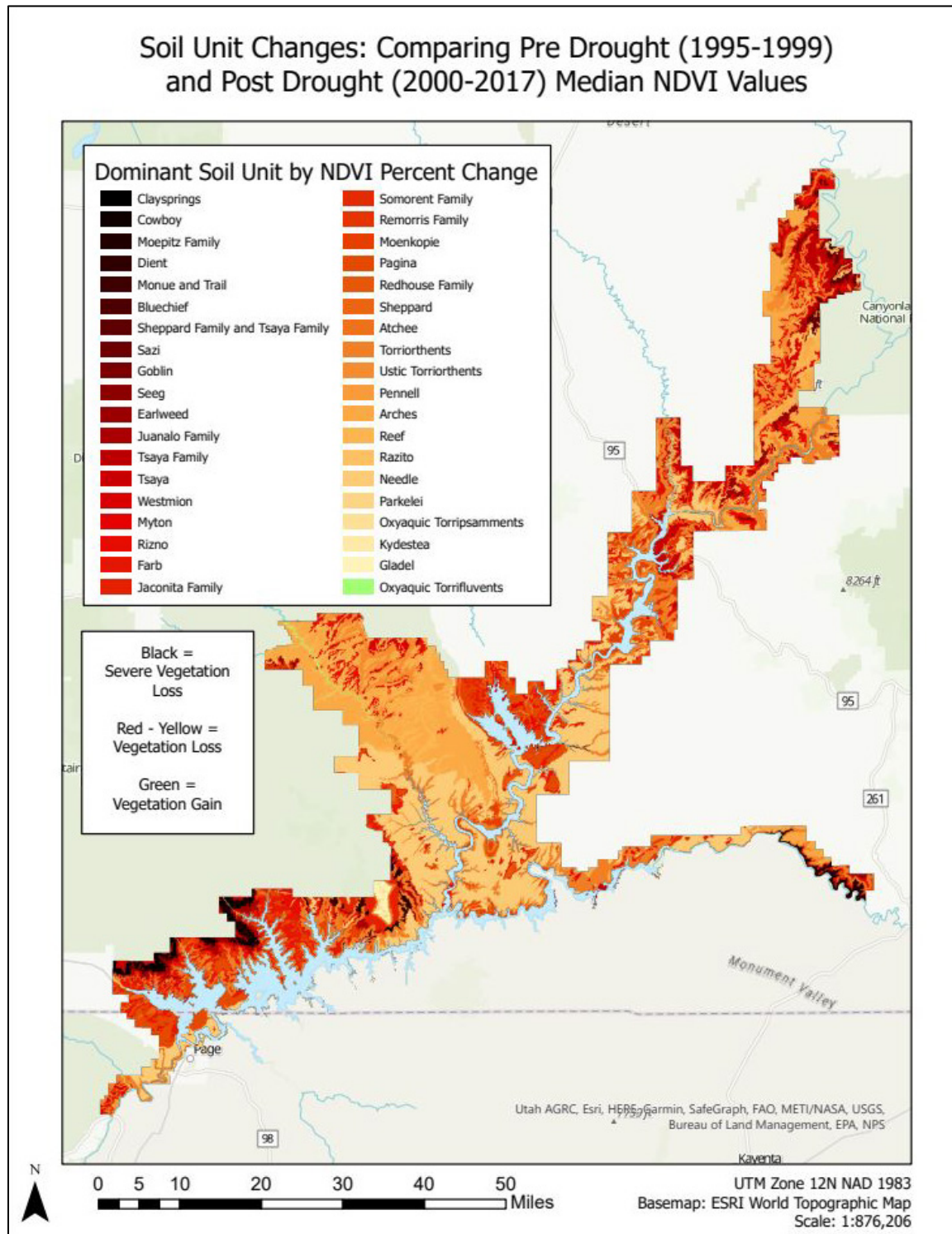


Figure C1. Map of soil unit changes. Comparing pre-drought (1995–1999) and post-drought (2000–2017) median NDVI values.

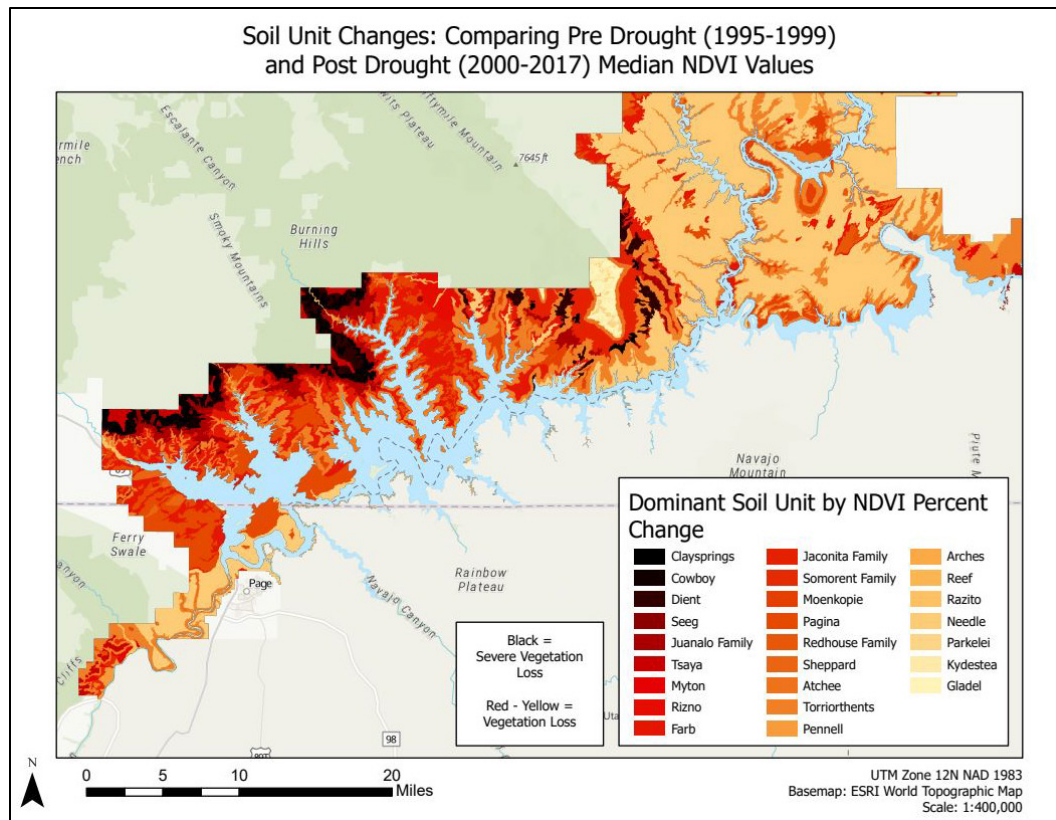


Figure C2. Map of soil unit changes. Comparing pre-drought and post-drought (2000–2017) median NDVI values.

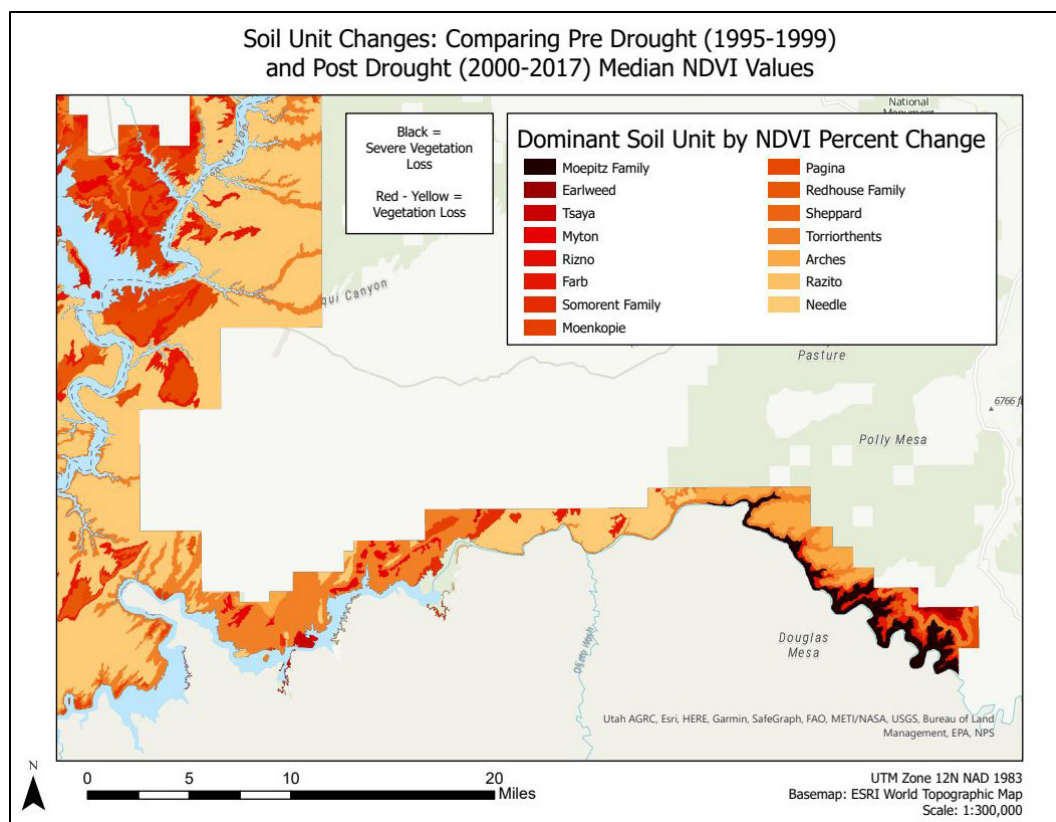


Figure C3. Map of soil unit changes. Comparing pre-drought (1995–1999) and post-drought (2000–2017) median NDVI values.

Soil Unit Changes: Comparing Pre Drought (1995-1999) and Post Drought (2000-2017) Median NDVI Values

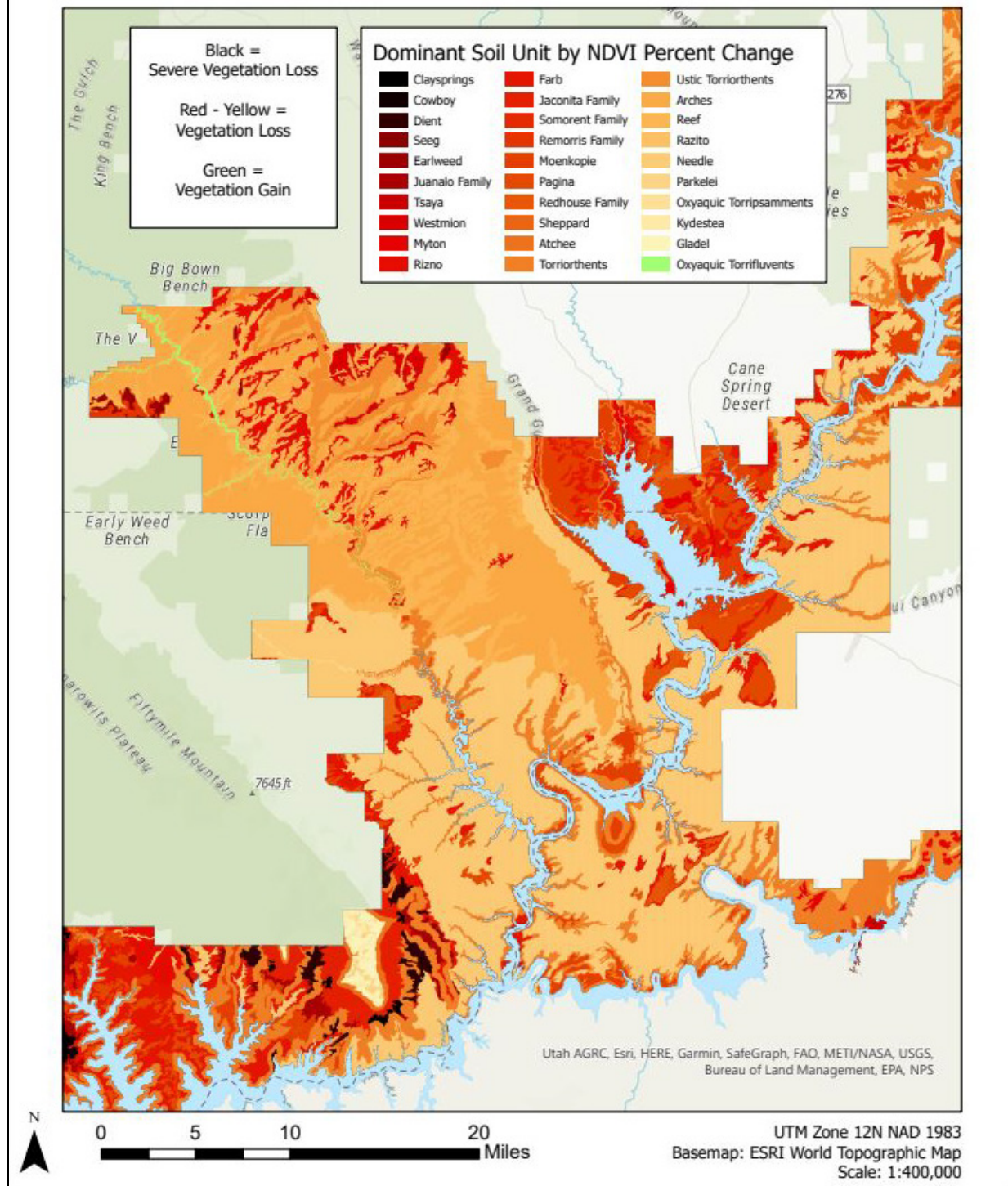


Figure C4. Map of soil unit changes. Comparing pre-drought (1995–1999) and post-drought (2000–2017) median NDVI values.

Soil Unit Changes: Comparing Pre Drought (1995-1999) and Post Drought (2000-2017) Median NDVI Values

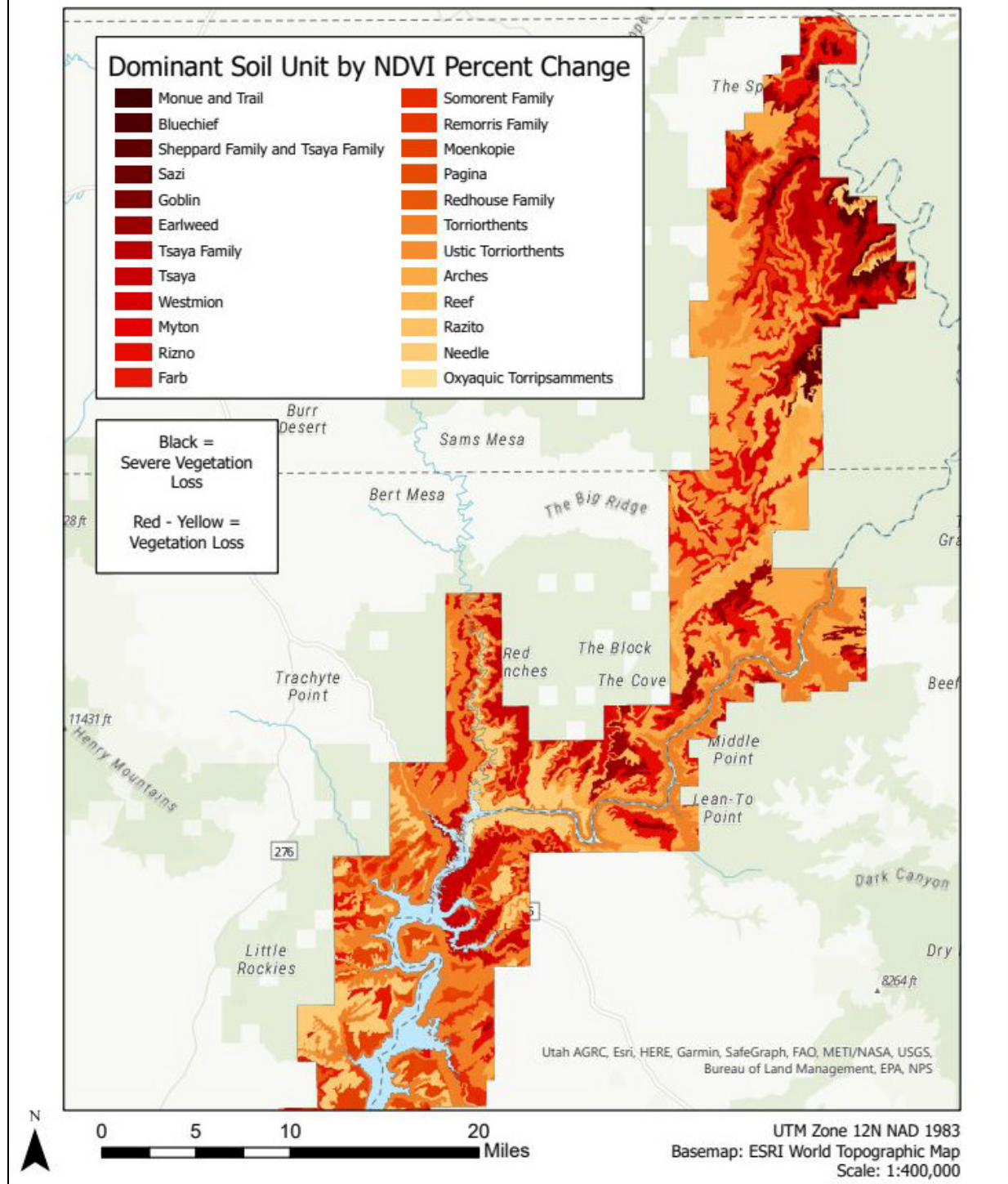


Figure C5. Map of soil unit changes. Comparing pre-drought (1995–1999) and post-drought (2000–2017) median NDVI values.

Appendix D. Ecological site change maps

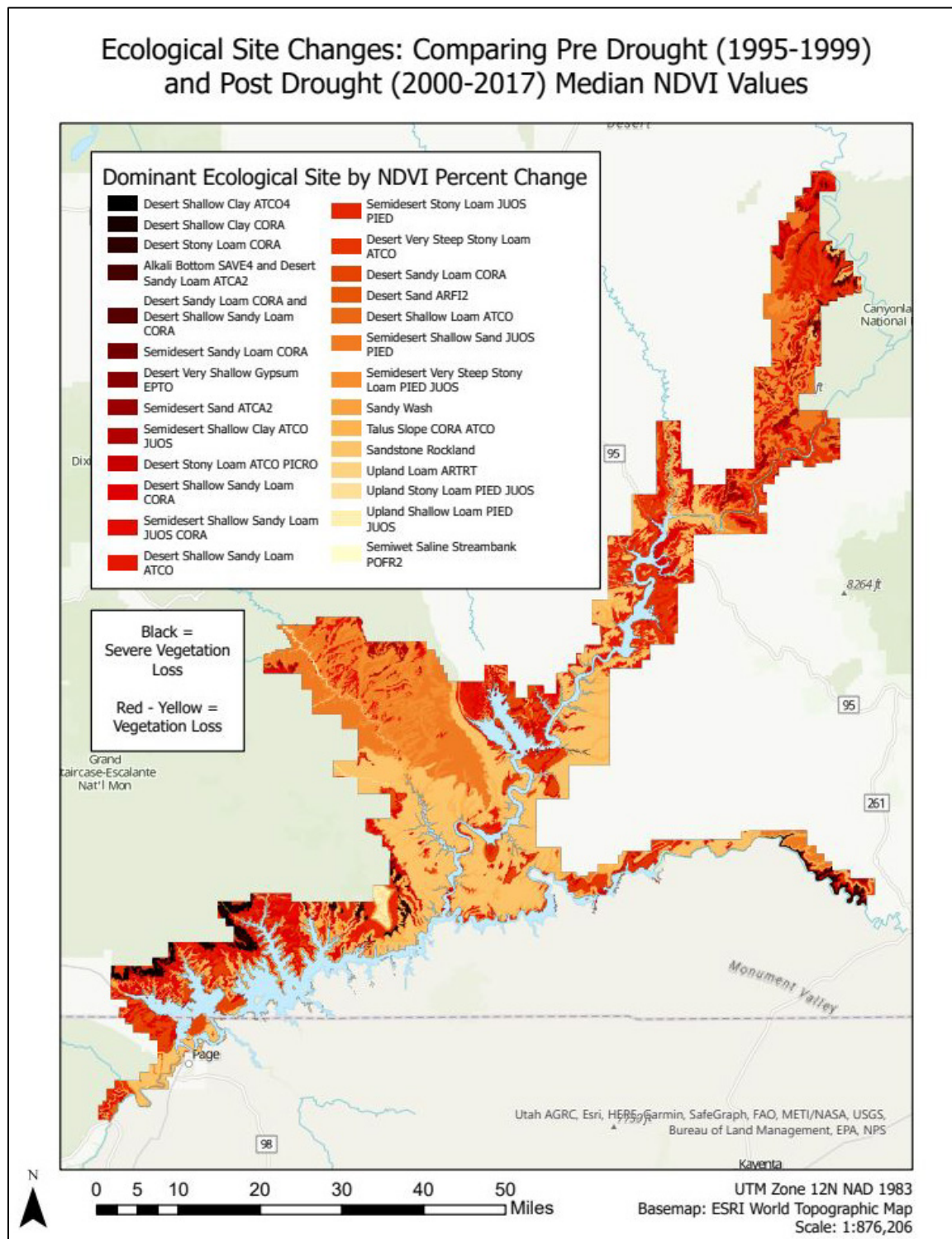


Figure D1. Map of ecological site changes. Comparing pre-drought (1995–1999) and post-drought (2000–2017) median NDVI values.

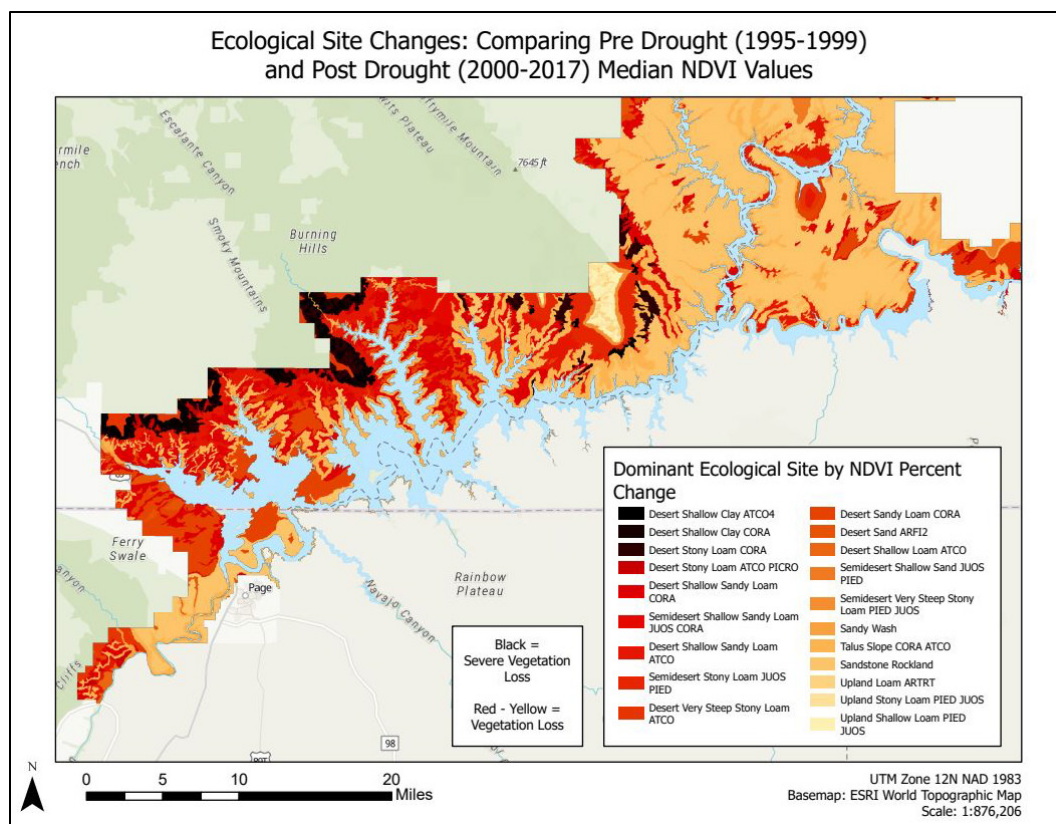


Figure D2. Map of ecological site changes. Comparing pre-drought (1995–1999) and post-drought (2000–2017) median NDVI values.

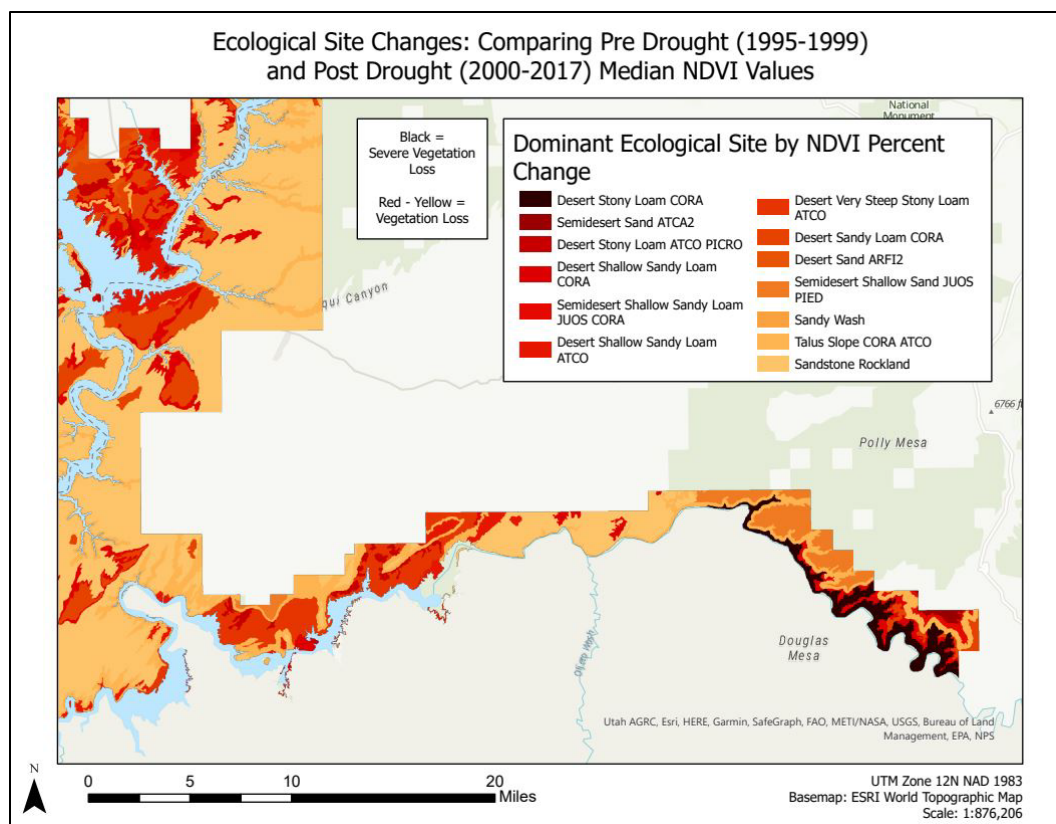


Figure D3. Map of ecological site changes. Comparing pre-drought (1995–1999) and post-drought (2000–2017) median NDVI values.

Ecological Site Changes: Comparing Pre Drought (1995-1999) and Post Drought (2000-2017) Median NDVI Values

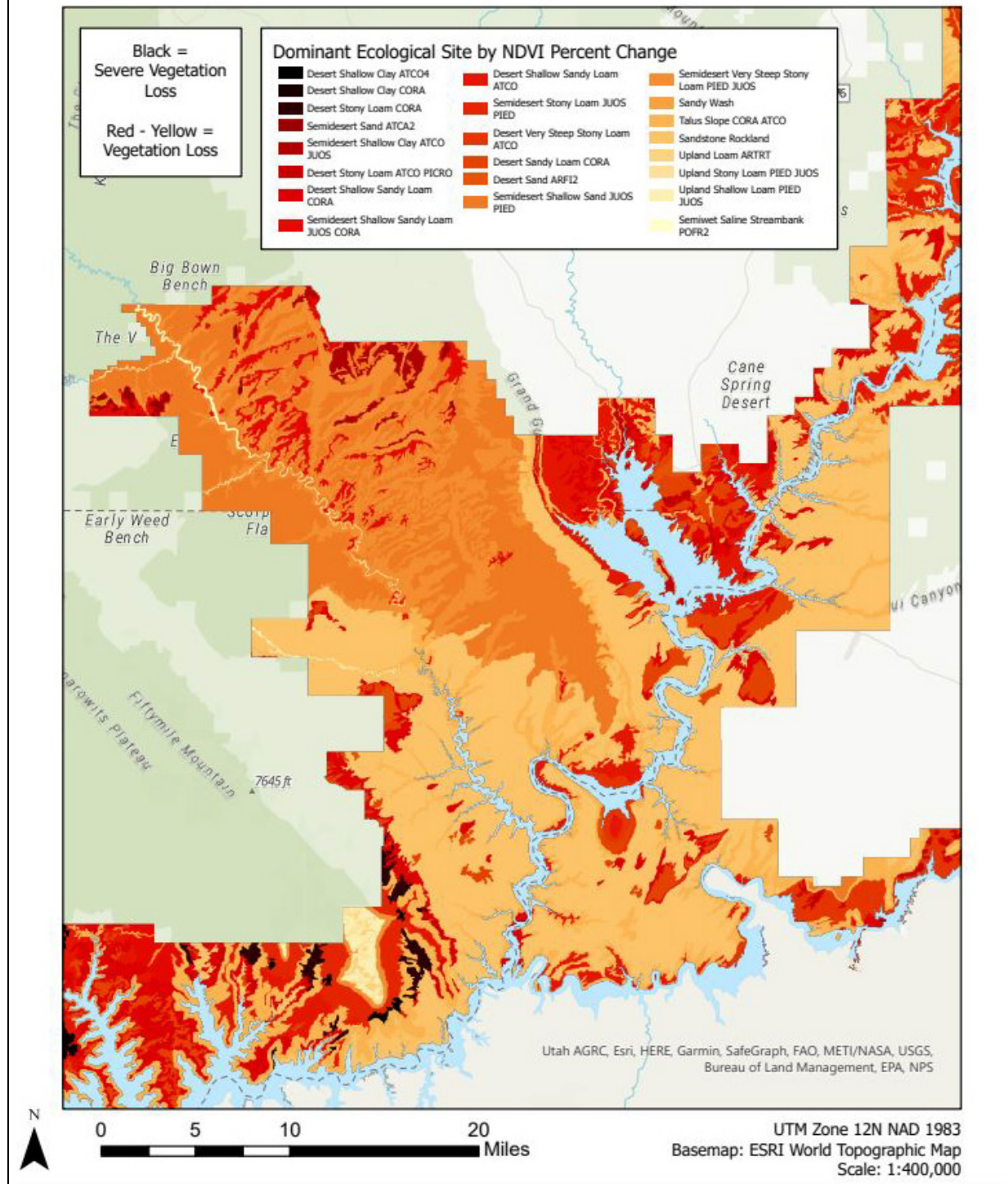


Figure D4. Map of ecological site changes. Comparing pre-drought (1995–1999) and post-drought (2000–2017) median NDVI values.

Ecological Site Changes: Comparing Pre Drought (1995-1999) and Post Drought (2000-2017) Median NDVI Values

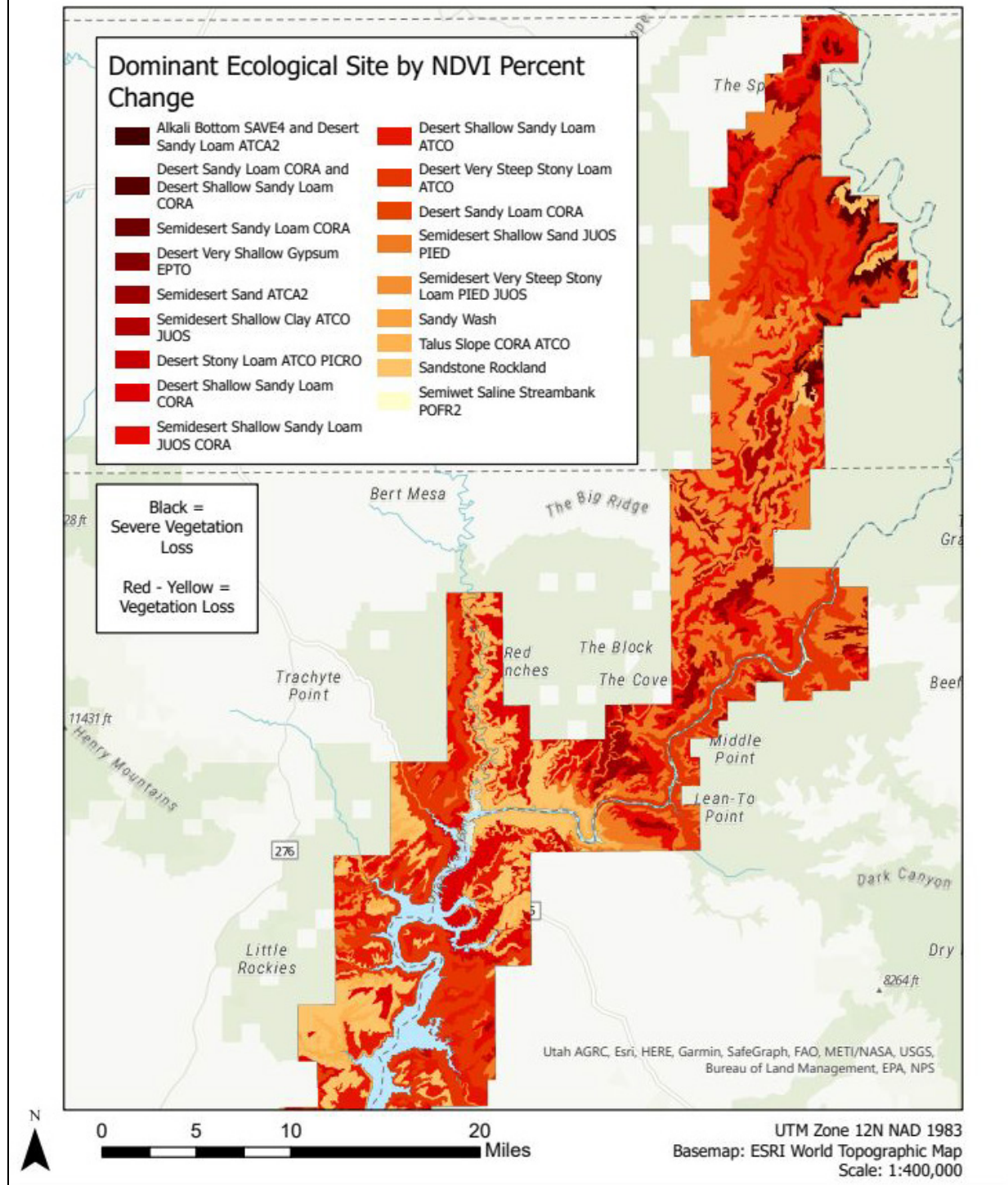


Figure D5. Map of ecological site changes. Comparing pre-drought (1995–1999) and post-drought (2000–2017) median NDVI values.

Appendix E. Alliance NDVI percent change maps

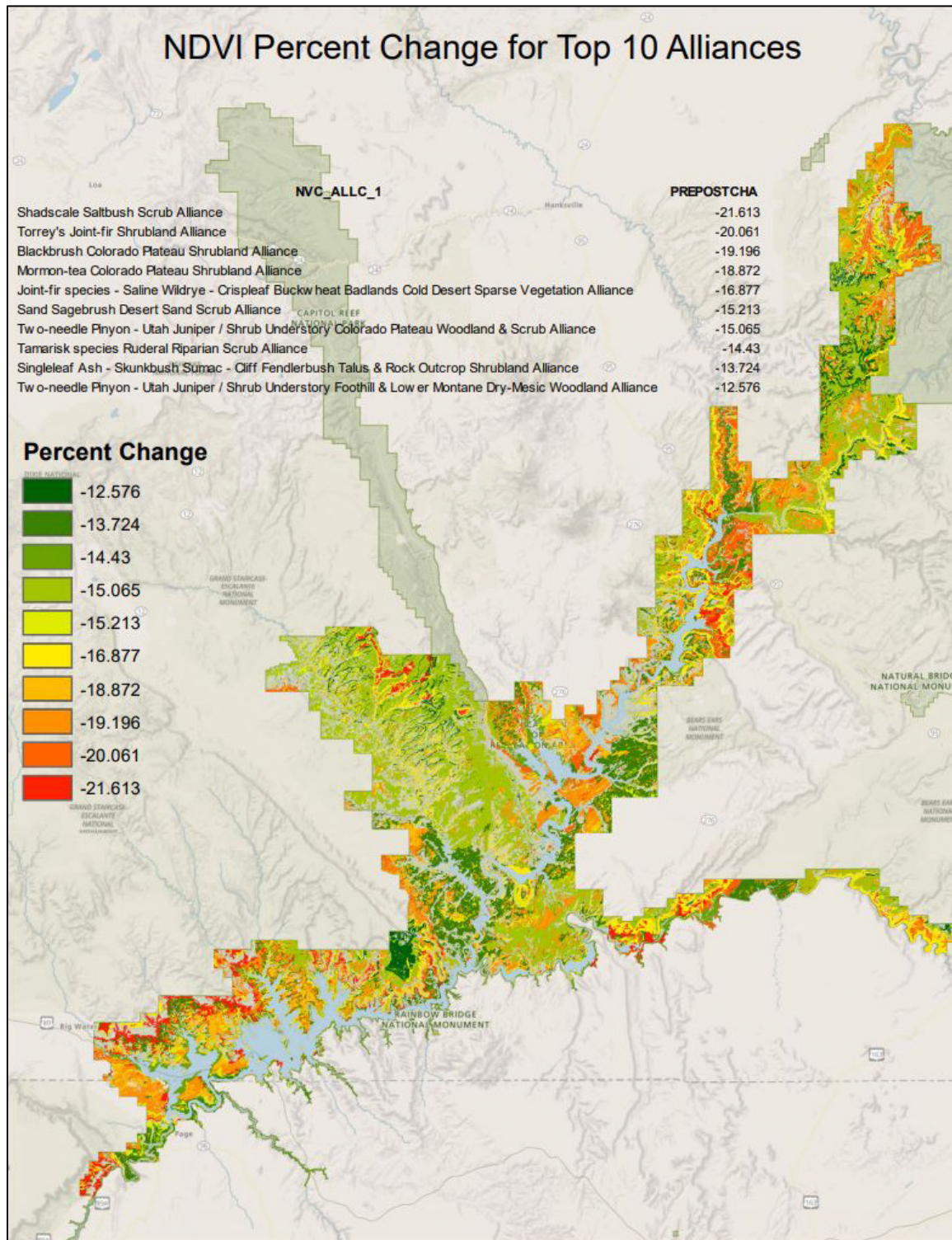


Figure E1. Map of NDVI percent change for top 10 alliances.

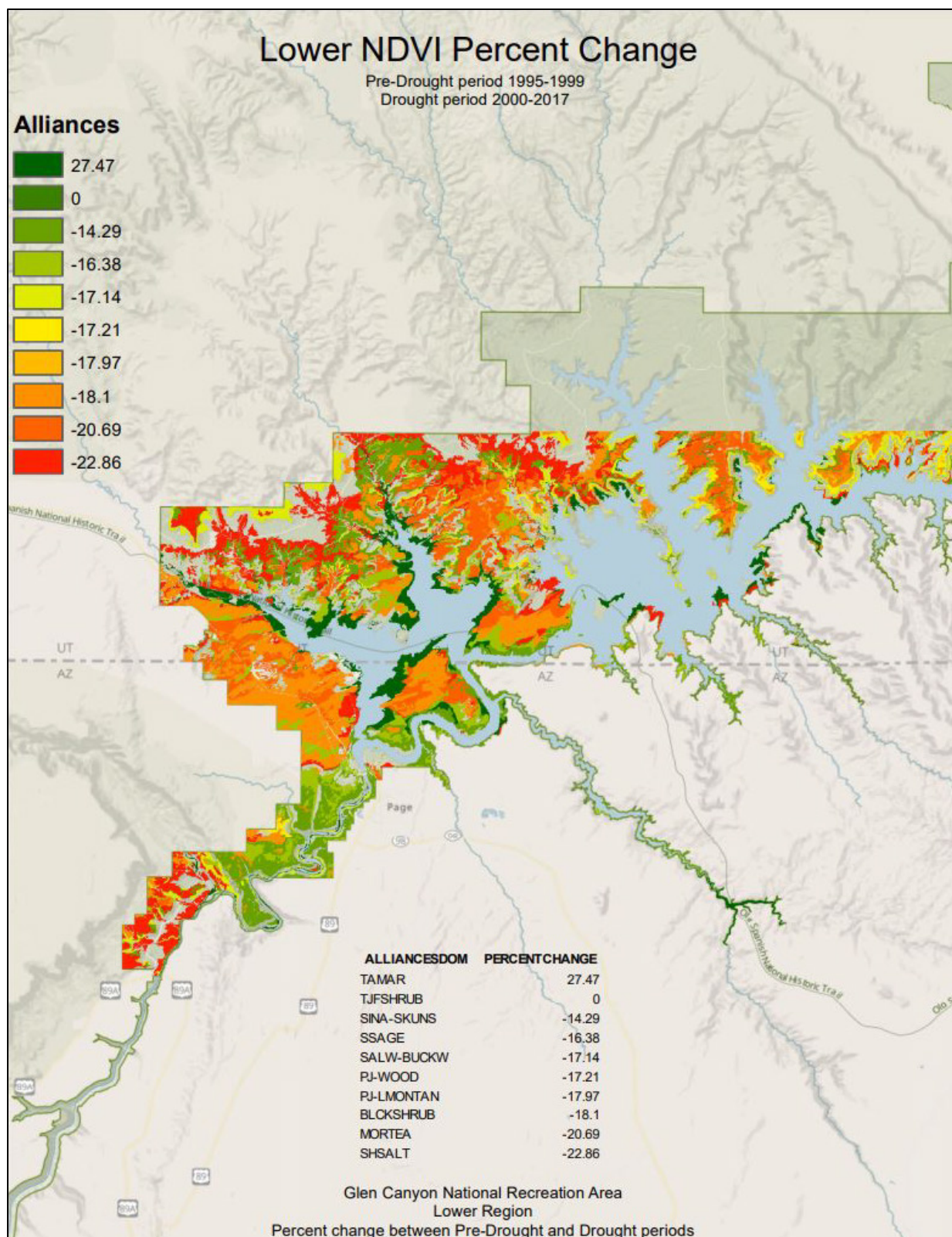


Figure E2. Map of lower NDVI percent change. Pre-drought period (1995–1999) and drought period (2000–2017).

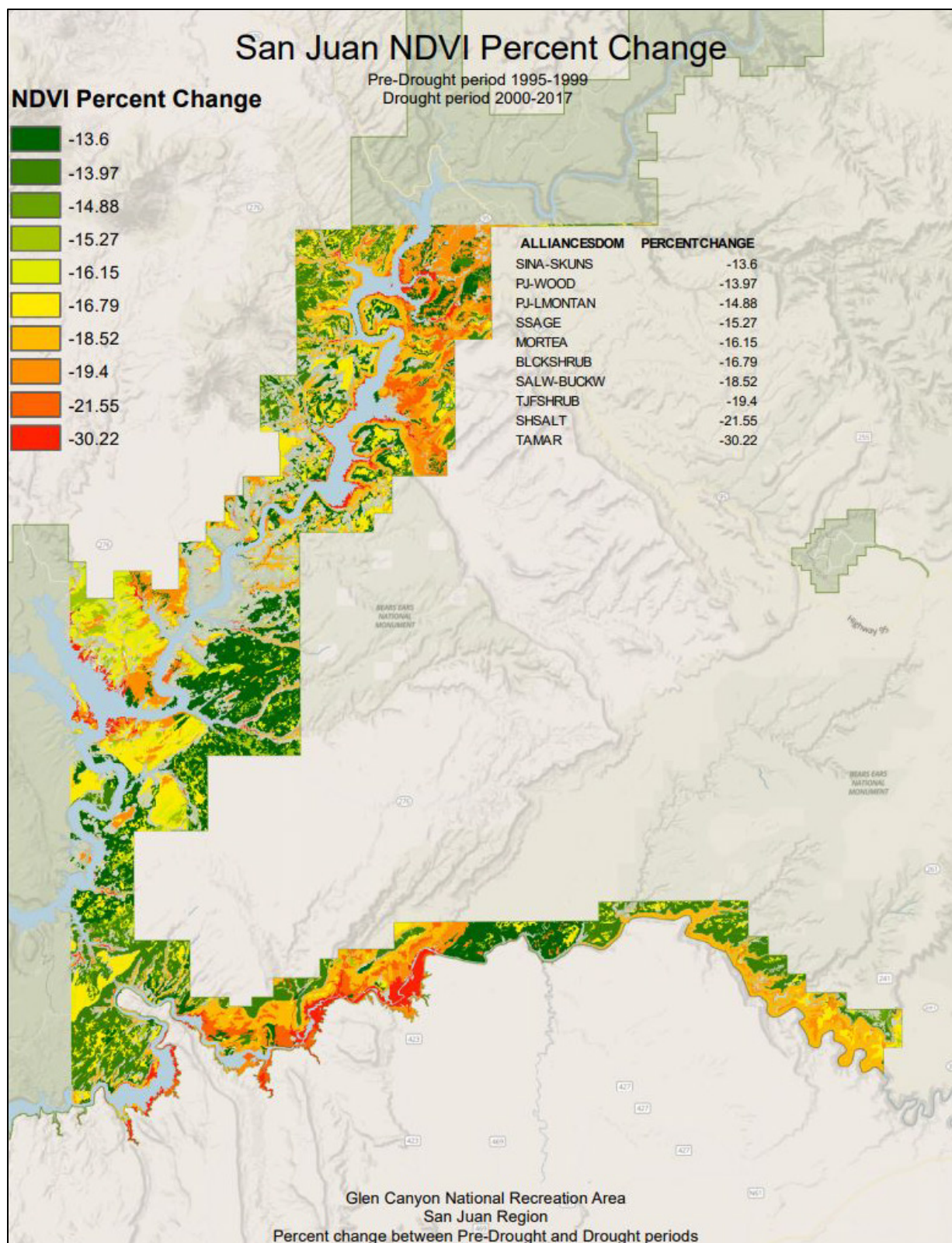


Figure E3. Map San Juan NDVI percent change. Pre-drought period (1995–1999) and drought period (2000–2017).

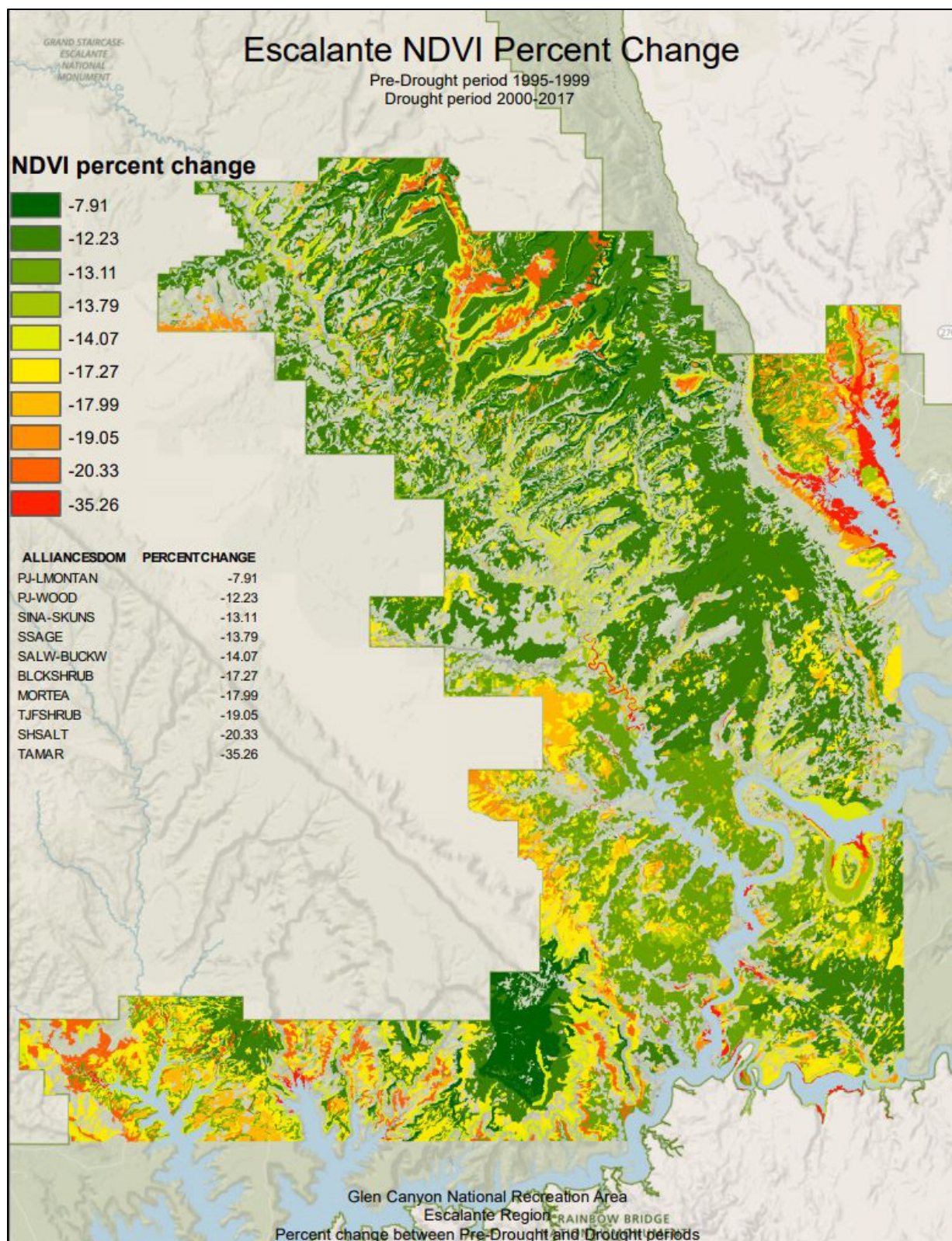


Figure E4. Map Escalante NDVI percent change. Pre-drought period (1995–1999) and drought period (2000–2017).

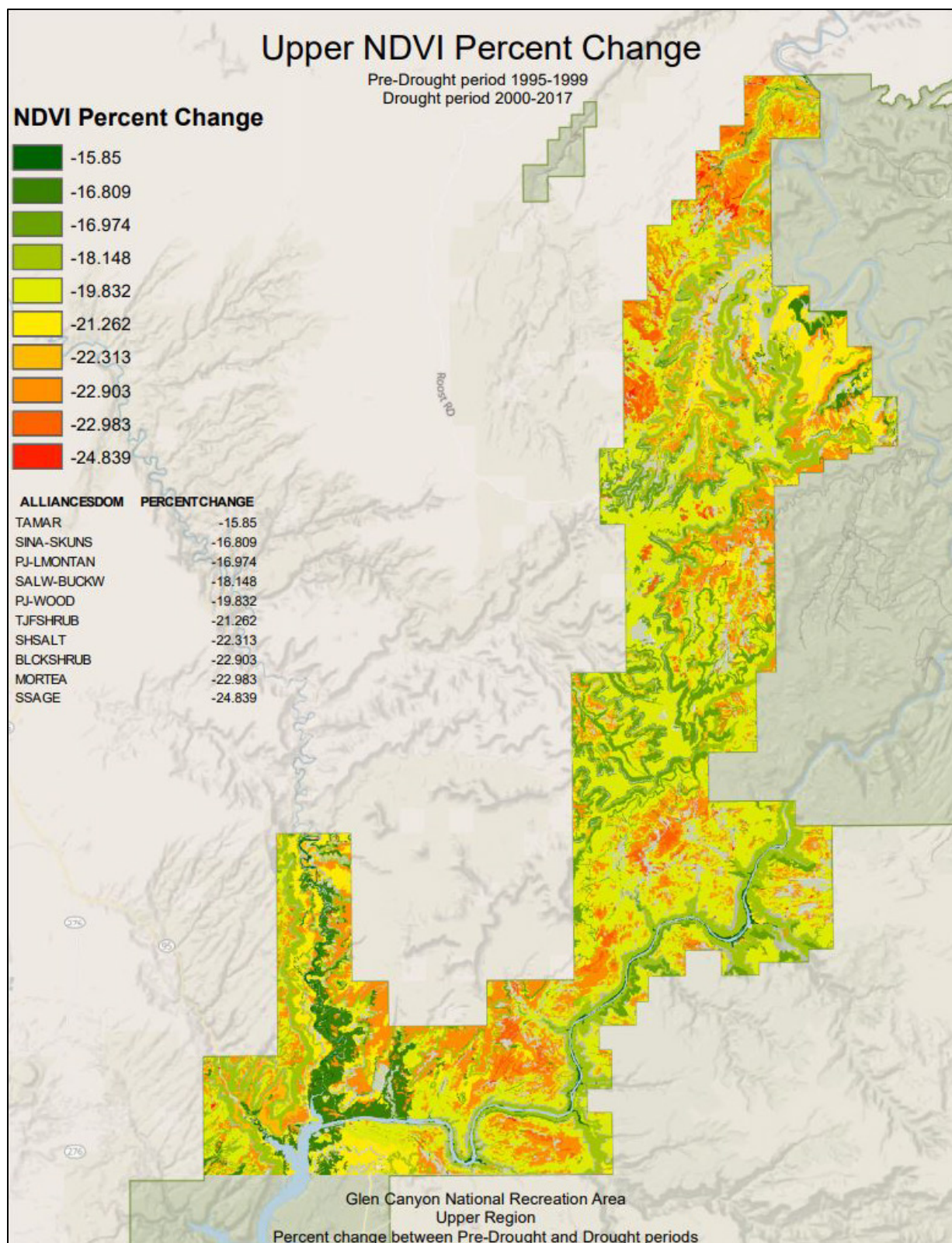


Figure E5. Map Upper NDVI percent change. Pre-drought period (1995–1999) and drought period (2000–2017).

Appendix F. GIS Methodology and Workflows

Overview

Satellite imagery can be used to better understand the health of specific vegetation types within Glen Canyon National Recreation Area which consists of over 1.25 million acres. The Normalized Difference Vegetation Index (NDVI) is a derived calculation from Landsat imagery that is used to indicate the presence of vegetation. The value of NDVI ranges from -1 to 1 where a value closer to 1, indicates a location with high chlorophyll readings, or denser vegetation. To understand a park wide NDVI analysis, this was paired with vegetation and soil type maps within the park. Together, the analysis has determined specific NDVI values that fall within certain vegetation regions, thereby indicating the health of a vegetation type.

Foundational Project: 2017–2018

In 2017–2018, the NASA DEVELOP Team in partnership with GLCA, used NASA earth observations to prioritize locations for further management of cultural resources by identifying areas that are at risk for vegetation loss, a proxy for areas that are threatened by erosion. The DEVELOP Team created multiple raw NDVI datasets and identified various markers for overall vegetation health for the previous 21 years. For full project background and methodology, see NASA DEVELOP LaRC Summer 2018 “Vegetation Change Mapping Standard Operating Procedure” by William Patrick Frier, Robert Cecil Byles, Robert Maxwell Stewart.

Foundational Project: Summer 2019

In 2019, GLCA’s Geoscientist-in-the-Parks Intern, Grace Bridget Cushing, worked with John Spence to build on the NASA DEVELOP products to further evaluate soil erosion at the park. Two NDVI datasets were used as median values for specific time-periods. The two time-periods that were of interest were the “Pre-Drought” period (years 1995–1999) and “Post-Drought” period (years 2000–2017; except for 2012 where data was not available). By looking at two periods that experienced significantly different climatic events, the analysis can show the change in NDVI values for each vegetation type between these two periods. These steps included:

Step 1: Identify areas with post-drought vegetation loss.

- 1) Obtained 22 Normalized Difference Vegetation Index (NDVI) and Modified Soil Adjusted Vegetation Index (MSAVI) layers from a project conducted by the NASA DEVELOP Glen Canyon Eco Team during summer 2018.
 - a) NASA DEVELOP pre-processed (masked, composited, mosaicked, and clipped) data downloaded from Earth Explorer from July, August, and September of each year from 1995–2017 (excluding 2012 due to a sensor failure of Landsat 7 that resulted in unusable data) to produce a total of 63 raster datasets for GLCA.
 - b) NASA DEVELOP then used the Raster Calculator Tool in ArcMap to produce NDVI and MSAVI images for each of the 63 rasters.
 - i)
$$NDVI = Float\left(\frac{(Band\ 4) - (Band\ 3)}{(Band\ 4) + (Band\ 3)}\right)$$

- ii)
$$MSAVI = Float\left(\frac{2(Band\ 4)+1-\sqrt{2(Band\ 4)^2-8(Band\ 4-Band\ 3)}}{2}\right)$$
- c) The Eco Team then used the Cell Statistics Tool in ArcMap to determine the maximum NDVI and maximum MSAVI for each year from 1995–2017, excluding 2012, by calculating the maximum from the three NDVI or MSAVI images for July, August, and September of each year.
- 2) When going through the NDVI_AnnualMax for each year, noticed that Max_NDVI_2015 shows an entirely black layer, with 1.#INFe+000 for max and mean. Did not include this layer in the raster calculator.
- When opened as an FGDBR, max & mean = infinity
 - Opens fine as TIFF but cannot do any processing without it creating infinity value
 - Requested individual unprocessed Summer 2015 rasters from NASA DEVELOP and created map “2015_Max_NDVI” to work in.
 - Created model and clipped, masked (cloud mask), composited bands, mosaicked, performed NDVI, and found MAX NDVI for 2015.
 - 36, 33
 - 36, 34
 - 37, 34

Pre-Process NDVI Layers:

- Created model “Re-Project Max NDVI.” (Figure F-1).
 - Create file geodatabase “Projected NDVI.gdb.”
 - Copy all NDVIs to new geodatabase and name it “Original_NDVI_AnnualMax.gdb.”
 - Use “NDVI_AnnualMax_Copy.gdb” as input into Iterate Rasters (keep default parameters).
 - Use output from Iterate Rasters as input to Project Raster tool to re-project each NDVI to *NAD_1983_UTM_Zone_12N* coordinate system and *D_North_American_1983* datum and save output as “Project_%name%” within Projected NDVI geodatabase.

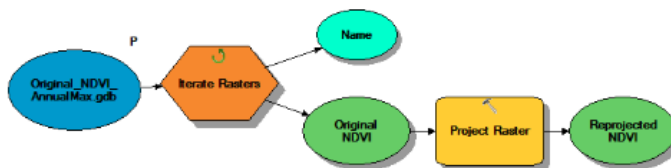
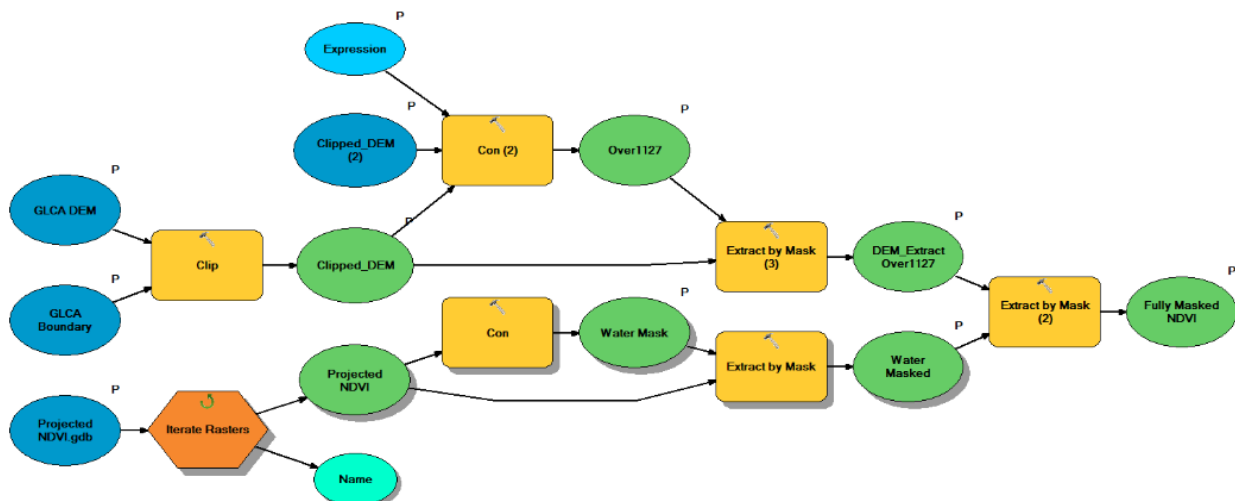


Figure F-1. Workflow used to reproject maximum NDVI

- Created “Full NDVI Masks” model (Figure F-2).
 - Use Clip tool with input raster of the “GLCA_TOPO_Elevation_ra” and output extent of “BND GLCA Boundary (2008)” (check Maintain Feature Geometry) and save output as “Clipped_DEM” in NDVI_Masks.gdb.

- b) Use Con tool with input conditional raster as “Clipped_DEM” and write query “Value > 1127” with input true raster as “Clipped_DEM” and save output as “Over1127.”
- c) Use Extract by Mask with input raster as “Clipped_DEM” and input raster mask as “Over1127” and save output as “DEM_ExtractOver1127” in the NDVI_Masks.gdb.
- d) Create NDVI_Masks.gdb.
- e) Use “Project NDVI.gdb” as input to Iterate Raster and use outputs as the input to the Con tool with the expression Value >= 0 and save output rasters as “WM_%name%” – this removes all values from the NDVI that are below 0 (which indicate water).
- f) Use Extract by Mask tool with WM_%name% as input raster or feature mask data and use the Project_%name% as input raster and save output as “WaterMasked_%name%” – this creates a raster for each year that does not include any water.
- g) Use Extract by Mask tool with “DEM_ExtractOver1127” as input raster or feature mask data and “WaterMasked_%name%” as input raster and save output as “FullMask_%name%” to the NDVI_Masks.gdb – this creates a raster for each year that does not include any values below 1127 meters OR water values.



3

Figure F-2. Workflow used for the full NDVI masks modeling.

Run Analyzes:

- 1) Created “Avg NDVI Total” model (Figure F-3).
 - a) Created “NDVI Analyses.gdb.”
 - b) Use NDVI_Masks.gdb as input to Iterate Rasters with Wildcard = FullMask_*.
 - c) Use Collect Values Tool and input the iterated rasters.
 - d) Use output values from Collect Values as the input to Cell Statistics with Overlay Statistics of MEAN (do not check Ignore NoData) and save output as “NDVI_Avg_Total” within the NDVI Analyses geodatabase.

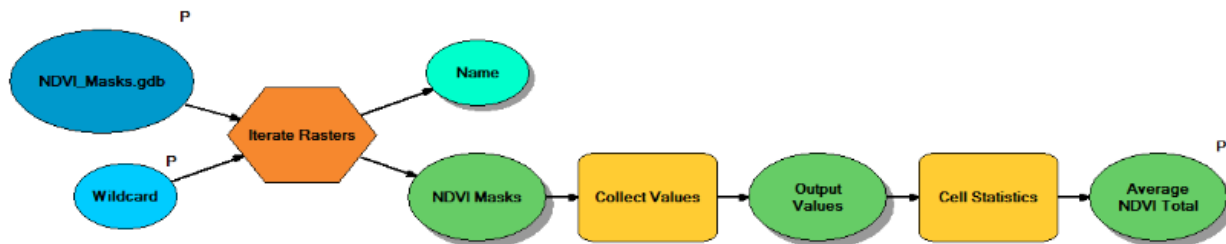


Figure F-3. Workflow used to create the average NVDI total model.

2) Created model “Pre Drought Median” (Figure F-4).

- a) Use NDVI_Masks.gdb as input to Iterate Rasters tool with Wildcard = FullMask_Project_Max_NDVI_1995* or FullMask_Project_Max_NDVI_1996* or FullMask_Project_Max_NDVI_1997* or FullMask_Project_Max_NDVI_1998*.
- b) Input the iterated rasters to Collect Values tool and then use Output Values as input for Cell Statistics with Overlay Statistics as MEDIAN (do not check “Ignore NoData”) and save output as “Median_PreDrought” in the NDVI Analyses geodatabase.

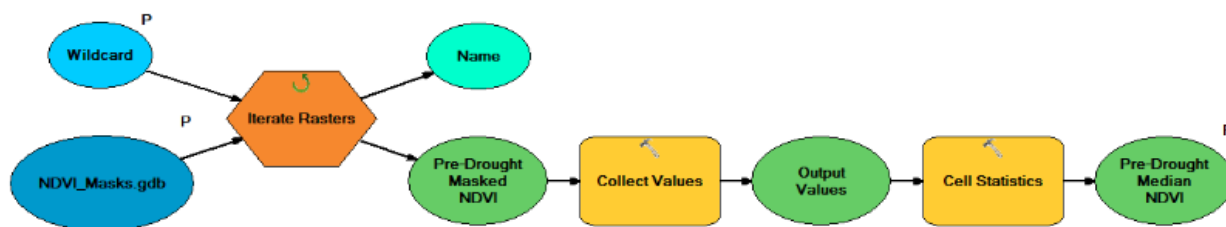


Figure F-4. Workflow used to create the pre-drought median model.

3) Created model “Post Drought Median” (Figure F-5).

- a) Use NDVI_Masks.gdb as input to Iterate Rasters tool with Wildcard = FullMask_Project_Max_NDVI_1999* or FullMask_Project_Max_NDVI_2000* or FullMask_Project_Max_NDVI_2001* or FullMask_Project_Max_NDVI_2002* or FullMask_Project_Max_NDVI_2003* or FullMask_Project_Max_NDVI_2004* or FullMask_Project_Max_NDVI_2005* or FullMask_Project_Max_NDVI_2006* or FullMask_Project_Max_NDVI_2007* or FullMask_Project_Max_NDVI_2008* or FullMask_Project_Max_NDVI_2009* or FullMask_Project_Max_NDVI_2010* or FullMask_Project_Max_NDVI_2011* or FullMask_Project_Max_NDVI_2013* or FullMask_Project_Max_NDVI_2014* or FullMask_Project_Max_NDVI_2015* or FullMask_Project_Max_NDVI_2016* or FullMask_Project_Max_NDVI_2017*.
- b) Input the iterated rasters to Collect Values tool and then use Output Values as input for Cell Statistics with Overlay Statistics as MEDIAN (do not check “Ignore NoData”) and save output as “Median_PostDrought” in the NDVI Analyses geodatabase.
- c) Run same process but remove 1999 NDVI and save output as “Median_PostDrought_No99.”

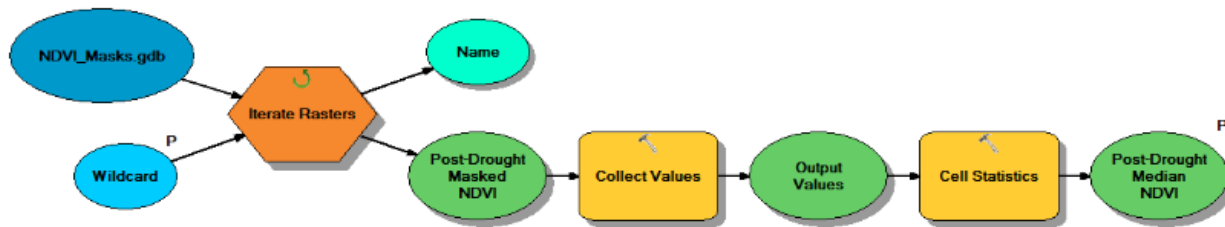


Figure F-5. Workflow used to create the post-drought median model.

Step 2: Identify high, medium, and low erosion potential areas based on NDVI change.

- 1) Created model “Post-PreDrought Change” to identify areas of high vegetation loss when comparing the pre-drought median and post-drought median (Figure F-6).
 - a) Used Minus tool to perform Median_PostDrought_No99 – Median_PreDrought and saved as “Minus_Post_PreAvg.”
 - b) Reclassified and saved as “Reclass_Minus_PostPreAvg.”
 - i) $-10.320583 - -0.035 = 1$, Red (Veg Loss)
 - ii) $-0.035 - -0.005 = 2$, Yellow (No Change)
 - iii) $-0.005 - 0.780941 = 3$, Green (Veg Gain)
 - c) Extract by Attributes with Value = 1 and save output as “Post_Pre_HighErosion.”

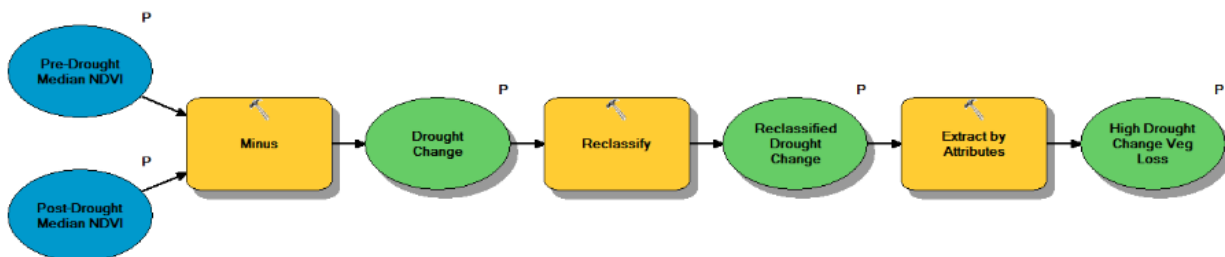


Figure F-6. Workflow used to create the post and pre-drought change model.

Step 3: Identify high medium, and low archeological site density areas.

Step 4: Identify areas of archeological interest and refine by soil type.

Step 5: Stratify by four general vegetation classes (woodland, shrub, grass, no veg).

Step 6: Overlay ORV and Accessible Shoreline Routes.

Step 7: Created associated metadata.

Step 8: Created maps to highlight Clearwater Canyon and Grand Bench.

Steps 3–8 are described in further detail in the SOP specific to that project but are not detailed here as they are less relevant for the current project’s methodology.

Current Project Process: Fall 2020

Building on the previous efforts, NPS GIS Intern Austin Breunig and GIP Intern Caleb Mathias with John Spence’s guidance focused on expanding the analyses as described in this FCA. Breunig focused on vegetation alliances and Mathias focused on soil/ecosite workflows.

Two NDVI datasets were used as median values for specific time-periods. The two time-periods that were of interest were the “Pre-Drought” period (years 1995–1999) and “Post-Drought” period (years 2000–2017; except for 2012 where data was not available). By looking at two periods that experienced significantly different climatic events, the analysis can show the change in NDVI values for each vegetation type between these two periods. The initial steps in accomplishing this were to conduct a process called Zonal Statistics. This tool identifies the surface area of each vegetation type at a given location as a zone. Within each vegetation zone, there would be corresponding NDVI values that fall within it. The process was to calculate the aggregate mean value for each vegetation zone, thereby identifying the NDVI values of each vegetation type.

This process was repeated for soil types and was calculated for each of the two time periods. A percent change calculation was then used between the two time periods to show the underlying amount that the NDVI values changed. The resulting values gave an overview of vegetation types that could be experiencing the largest amount of loss and additionally where that was happening in the park. The NDVI values for each vegetation type represented a mean value across the entire park. This meant that a vegetation type living in the northern region as well as the lower region were given the same value. To better understand if regional differences were occurring, the park was segregated by four distinct regions (Upper, Lower, Escalante, San Juan). By reducing the scope to smaller areas within the park, we could see if regional factors played a role in the NDVI value of a vegetation type. NDVI values were accounted for in their respective region, and the Zonal Statistics were repeated for each of the four regions. The results showcased a significant amount of variance based on region, indicating that within the park, micro-climates could be influencing vegetation health. The scope of further analysis of these results can be paired with the Archeology Site Density Model (NPS, 2017) to better direct management decisions related to protecting cultural resources. Additionally, it can be paired with grazing allotments to better understand underlying causes of vegetation loss and related erosion impacts. The results should continue to further management’s efforts in mitigating the effects of climate change as well as preserving cultural (and in many cases paleontological) resources vital to Glen Canyon.

Detailed GIS steps and models included:

Step 1: Pre-Process NDVI Layers

- 1) Reprocessed models created by Grace Cushing using the \\inpgclar-aregis\Projects\NASA_Develop\Projected_NDVI_Max.gdb workspace in order to remove the water mask which created analysis issues. Create “NDVI_Median_NoMask.gdb.”
- 2) Create toolbox “GLCA_Tests.tbx” to save all models within.
- 3) Modified “Pre-Drought Median” model to “Pre-Drought Median_Modified” (Figure F-7).

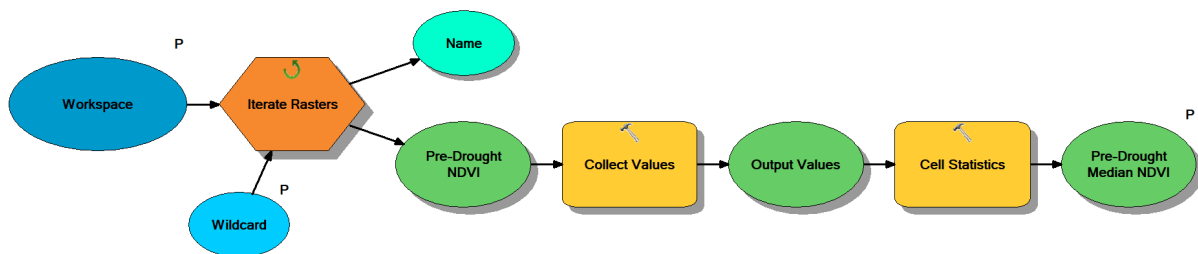


Figure F-7. Workflow used to modify the pre-drought to the pre-drought median model.

- a) Use “Projected_NDVI_Max.gdb” as input to Iterate Rasters tool with Wildcard = Project_Max_NDVI_1995* or Project_Max_NDVI_1996* or Project_Max_NDVI_1997* or Project_Max_NDVI_1998*.
 - b) Input the iterated rasters to Collect Values tool and then use Output Values as input for Cell Statistics with Overlay Statistics as MEDIAN (do not check “Ignore NoData”) and save output as “Median_PreDrought_NoMask” in the “NDVI_Median_NoMask.gdb.”
- 4) Modified “Post-Drought Median” model to “Post-Drought Median_Modified”.
- a) Use “Projected_NDVI_Max.gdb” as input to Iterate Rasters tool with Wildcard = Project_Max_NDVI_2000* or Project_Max_NDVI_2001* or Project_Max_NDVI_2002* or Project_Max_NDVI_2003* or Project_Max_NDVI_2004* or Project_Max_NDVI_2005* or Project_Max_NDVI_2006* or Project_Max_NDVI_2007* or Project_Max_NDVI_2008* or Project_Max_NDVI_2009* or Project_Max_NDVI_2010* or Project_Max_NDVI_2011* or Project_Max_NDVI_2013* or Project_Max_NDVI_2014* or Project_Max_NDVI_2015* or Project_Max_NDVI_2016* or Project_Max_NDVI_2017*.
 - b) Input the iterated rasters to Collect Values tool and then use Output Values as input for Cell Statistics with Overlay Statistics as MEDIAN (do not check “Ignore NoData”) and save output as “Median_PostDrought_NoMask” in the “NDVI_Median_NoMask.gdb.”

*** These NDVI datasets were utilized in both the soil and alliance analyses and resulting maps.

Here is where the workflows diverge between soil and alliances (Figure F-8). ***

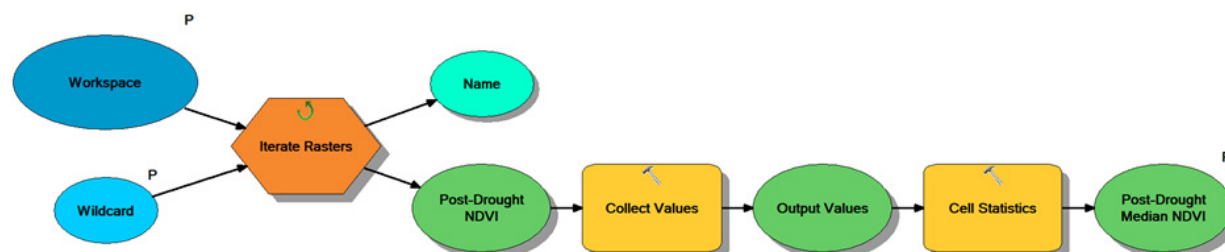


Figure F-8. Diagram showing where the workflows diverge between soil and alliance models.

Soils Step 2: Soils Data

Obtained feature class soil data from the GLCA Soil Survey published by the USDA NRCA in 2010 through the SSURGO database.

Soils Step 3: Convert Feature Class to Raster

Created “SSURGO Poly to Rast” model (Figure F-9).

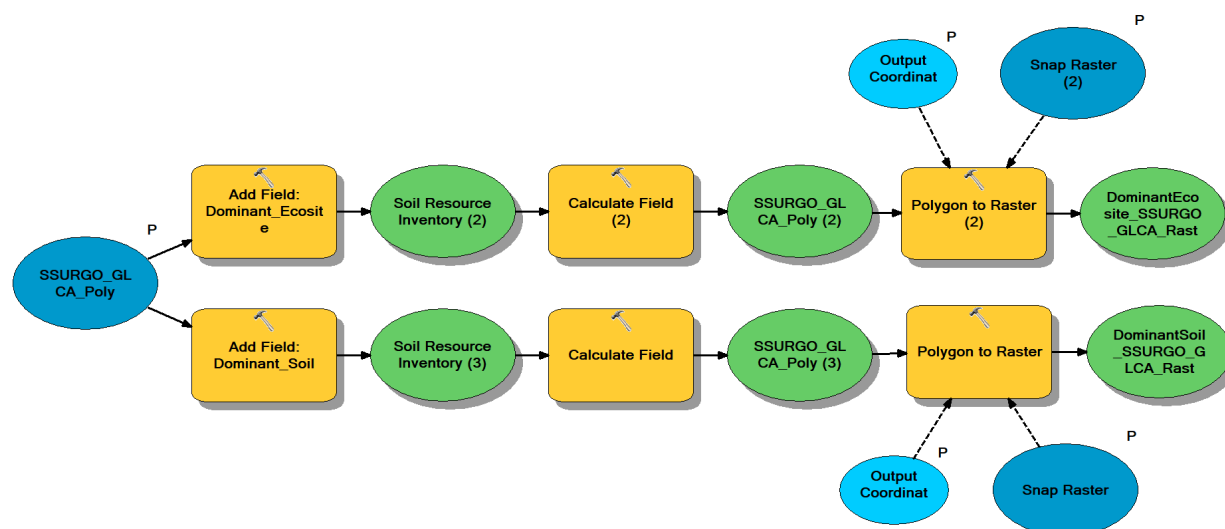


Figure F-9. Workflow used to create the SSurgo polygon to raster model.

- 1) Created “Drought_NDVI_Analysis.gdb.”
- 2) Use Add Field tool to add “Dominant_Ecosite” and “Dominant_Soil” fields to the feature class.
- 3) Use Calculate Field tool to calculate dominant ecological site and dominant soil associated with each “MUSYM” number and save to the output feature class dataset “SSURGO_GLCA_Poly” as “Dominant_Ecosite” and “Dominant_Soil” respectively.
 - a) Equations for calculating “Dominant_Ecosite”:

Expression:

Dominant_Ecosite = Reclass(!MUSYM!)

Code Block:

```
def Reclass(arg):  
    if arg is None:  
        pass  
    elif arg == "1":  
        arg = "Semidesert_Shallow_Sand_JUOS_PIED"  
    elif arg == "2":  
        arg = "Desert_Sandy_Loam_CORA"  
    elif arg == "3":  
        arg = "Desert_Shallow_Clay_ATCO4"  
    elif arg == "4":
```

```

        arg = "Desert_Shallow_Clay_CORA"
elif arg == "5":
        arg = "Desert_Stony_Loam_CORA"
elif arg == "6":
        arg = "Semidesert_Sand_ATCA2"
elif arg == "7":
        arg = "Desert_Shallow_Sandy_Loam_CORA"
elif arg == "8":
        arg = "Upland_Shallow_Loam_PIED_JUOS"
elif arg == "9":
        arg = "Desert_Very_Shallow_Gypsum_EPTO"
elif arg == "10":
        arg = "Semidesert_Stony_Loam_JUOS_PIED"
elif arg == "11":
        arg = "Desert_Shallow_Sandy_Loam_ATCO"
elif arg == "12":
        arg = "Upland_Stony_Loam_PIED_JUOS"
elif arg == "13":
        arg = "Desert_Shallow_Sandy_Loam_ATCO"
elif arg == "14":
        arg = "Desert_Stony_Loam_CORA"
elif arg == "15":
        arg = "Alkali_Bottom_SAVE4_and_Desert_Sandy_Loam_ATCA2"
elif arg == "16":
        arg = "Desert_Stony_Loam_ATCO_PICRO"
elif arg == "17":
        arg = "Sandstone_Rockland"
elif arg == "18":
        arg = "Semiwet_Saline_Streambank_POFR2"
elif arg == "19":
        arg = "Semiwet_Saline_Streambank_POFR2"
elif arg == "20":
        arg = "Desert_Sandy_Loam_CORA"
elif arg == "21":
        arg = "Upland_Loam_ARTRT"
elif arg == "22":
        arg = "Desert_Shallow_Loam_ATCO"
elif arg == "23":
        arg = "Sandy_Wash"
elif arg == "24":
        arg = "Desert_Sandy_Loam_CORA"
elif arg == "25":
        arg = "Semidesert_Shallow_Sandy_Loam_JUOS_CORA"
elif arg == "26":
        arg = "Semidesert_Very_Steep_Stony_Loam_PIED_JUOS"
elif arg == "27":
        arg = "Semidesert_Shallow_Sandy_Loam_JUOS_CORA"
elif arg == "28":
        arg = "Semidesert_Shallow_Sandy_Loam_JUOS_CORA"

```

```

elif arg == "29":
    arg = "Semidesert_Shallow_Sandy_Loam_JUOS_CORA"
elif arg == "30":
    arg = "Semidesert_Shallow_Sand_JUOS_PIED"
elif arg == "31":
    arg = "Semidesert_Very_Steep_Stony_Loam_PIED_JUOS"
elif arg == "32":
    arg = "Sandstone_Rockland"
elif arg == "33":
    arg = "Talus_Slope_CORA_ATCO"
elif arg == "34":
    arg = "Desert_Very_Steep_Stony_Loam_ATCO"
elif arg == "35":
    arg = "Semidesert_Sandy_Loam_CORA"
elif arg == "36":
    arg = "Desert_Stony_Loam_ATCO_PICRO"
elif arg == "37":
    arg = "Desert_Sand_ARFI2"
elif arg == "38":
    arg = "Desert_Sandy_Loam_CORA_and_Desert_Shallow_Sandy_Loam_CORA"
elif arg == "39":
    arg = "Desert_Shallow_Sandy_Loam_ATCO"
elif arg == "40":
    arg = "Desert_Very_Steep_Stony_Loam_ATCO"
elif arg == "41":
    arg = "Desert_Very_Steep_Stony_Loam_ATCO"
elif arg == "42":
    arg = "Desert_Shallow_Sandy_Loam_CORA"
elif arg == "43":
    arg = "Desert_Shallow_Sandy_Loam_ATCO"
elif arg == "44":
    arg = "Semidesert_Very_Steep_Stony_Loam_PIED_JUOS"
elif arg == "45":
    arg = "Water"
elif arg == "46":
    arg = "Semidesert_Shallow_Clay_ATCO_JUOS"
elif arg == "47":
    arg = "Rock_Outcrop"

return arg

```

b) Equations for calculating “Dominant_Soil”:

Expression:

Dominant_Soil = Reclass(!MUSYM!)

Code Block:

```

def Reclass(arg):
    if arg is None:
        pass

```

```

elif arg == "1":
    arg = "Arches"
elif arg == "2":
    arg = "Bluechief"
elif arg == "3":
    arg = "Claysprings"
elif arg == "4":
    arg = "Cowboy"
elif arg == "5":
    arg = "Dient"
elif arg == "6":
    arg = "Earlweed"
elif arg == "7":
    arg = "Farb"
elif arg == "8":
    arg = "Gladel"
elif arg == "9":
    arg = "Goblin"
elif arg == "10":
    arg = "Jaconita_family"
elif arg == "11":
    arg = "Juanalo_family"
elif arg == "12":
    arg = "Kydestea"
elif arg == "13":
    arg = "Moenkopie"
elif arg == "14":
    arg = "Moepitz_family"
elif arg == "15":
    arg = "Monue_and_Trail"
elif arg == "16":
    arg = "Myton"
elif arg == "17":
    arg = "Needle"
elif arg == "18":
    arg = "Oxyaquic_Torrifluvents"
elif arg == "19":
    arg = "Oxyaquic_Torripsamments"
elif arg == "20":
    arg = "Pagina"
elif arg == "21":
    arg = "Parkelei"
elif arg == "22":
    arg = "Pennell"
elif arg == "23":
    arg = "Razito"
elif arg == "24":
    arg = "Redhouse_family"
elif arg == "25":

```

```

        arg = "Reef"
    elif arg == "26":
        arg = "Reef"
    elif arg == "27":
        arg = "Remorris_family"
    elif arg == "28":
        arg = "Rizno"
    elif arg == "29":
        arg = "Rizno"
    elif arg == "30":
        arg = "Arches"
    elif arg == "31":
        arg = "Atchee"
    elif arg == "32":
        arg = "Needle"
    elif arg == "33":
        arg = "Torriorthents"
    elif arg == "34":
        arg = "Tsaya"
    elif arg == "35":
        arg = "Sazi"
    elif arg == "36":
        arg = "Seeg"
    elif arg == "37":
        arg = "Sheppard"
    elif arg == "38":
        arg = "Sheppard_family_and_Tsaya_family"
    elif arg == "39":
        arg = "Somorent_family"
    elif arg == "40":
        arg = "Torriorthents"
    elif arg == "41":
        arg = "Torriorthents"
    elif arg == "42":
        arg = "Tsaya"
    elif arg == "43":
        arg = "Tsaya_family"
    elif arg == "44":
        arg = "Ustic_Torriorthents"
    elif arg == "45":
        arg = "Water"
    elif arg == "46":
        arg = "Westmion"
    elif arg == "47":
        arg = "Nalcase"

    return arg

```

- c) Use Polygon to Raster tool with input polygon of “SSURGO_GLCA_Poly” and save Output Raster Dataset as “DominantEcosite/DominantSoil_SSURGO_Rast” to “Drought_NDVI_Analysis.gdb” with Value field set to “MUSYM”, Cell Size set to 30m, Output Coordinate System set to “NAD_1983_UTM_Zone_12N”, and Snap Raster set to either “PreDrought_Median_NoMask” or “PostDrought_Median_NoMask.”

Soils Step 4: Run Analysis on Soil And Ecological Site Types

- 1) Created “NDVI Zonal Statistics” model (Figure F10).

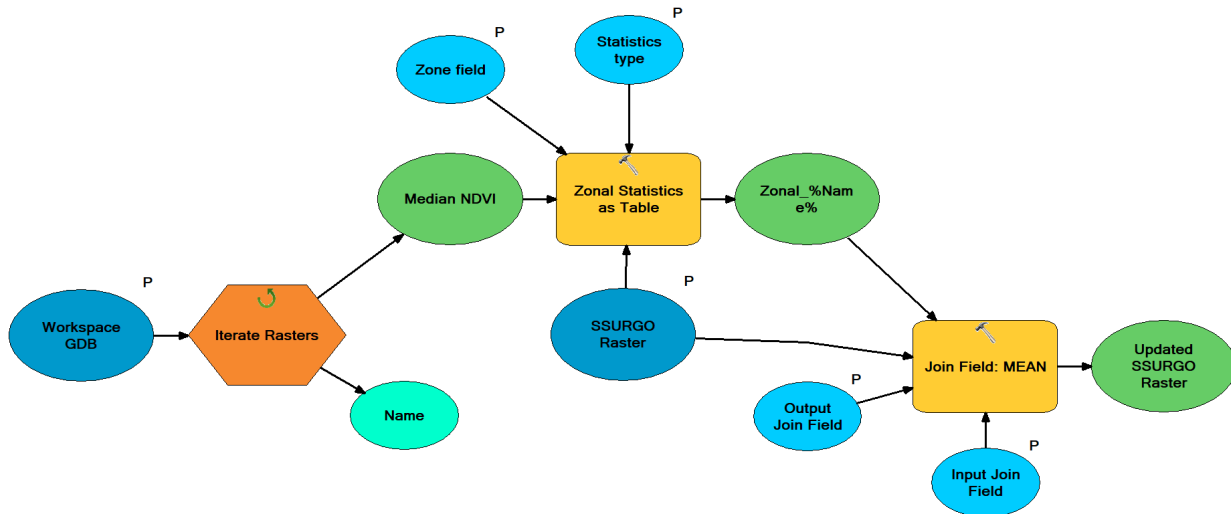


Figure F-10. Workflow used to create the NDVI zonal statistics model.

- a) Use “NDVI_Median_NoMask.gdb” as input Workspace to the Iterate Rasters tool.
 - b) Input the iterated rasters as values to the Zonal Statistics as Table tool with “DominantEcosite/DominantSoil_SSURGO_GLCA_Rast” as the input raster, Zone field set to “Dominant_Ecosite/Dominant_Soil” respectively, Statistics type set to “MIN_MAX_MEAN”, and Ignore NoData in calculations checked.
 - c) Input the Zonal Statistics as the Joint Table into the Join Field tool with “Dominant_Ecosite/Dominant_Soil” respectively set as the Input Join Field and Join Table Field, “OBJECTID” and “MEAN” checked in Transfer Fields, “DominantEcosite/DominantSoil_SSURGO_GLCA_Rast” set as the Input Table. This updates each “DominantEcosite/DominantSoil_SSURGO_GLCA_Rast” attribute table with mean NDVI statistics for each soil and ecological site type.
- 2) Created “Add Fields” model (Figure F-11).

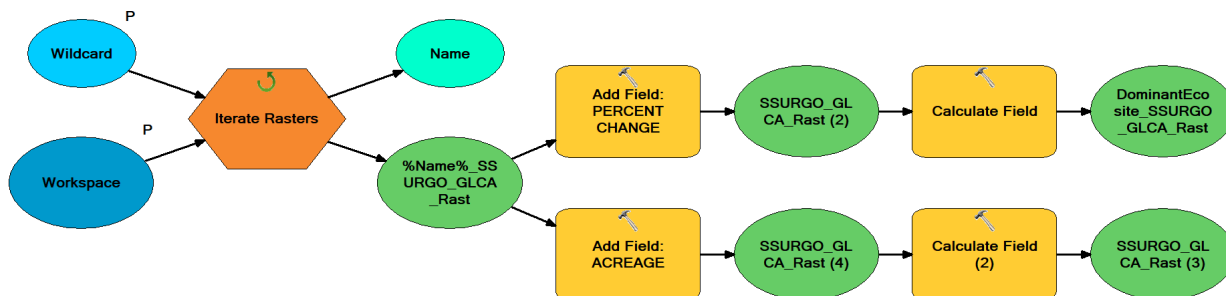


Figure F-11. Workflow used to create an all fields model.

- Use “Drought_NDVI_Analysis.gdb” as input Workspace to the Iterate Rasters tool with Wildcard = Dominant*.
- Input “DominantEcosite/DominantSoil_SSURGO_GLCA_Rast” to Add Field tools which adds field “ACREAGE” to each respective raster. Use Calculate Field tool to calculate acreage and store within attribute tables with the equation:

$$!Count! * 30 * 30 * 0.000247105$$
- Input “DominantEcosite/DominantSoil_SSURGO_GLCA_Rast” to Add Field tool which adds field “PERCENT_CHANGE” to each respective raster. Use Calculate Field tool to calculate percent change of mean NDVI values and store within attribute tables with the equation:

$$((!MEAN_1! - !MEAN!) / !MEAN!) * 100$$
- Export each “DominantEcosite/DominantSoil_SSURGO_GLCA_Rast” attribute table to save within a single Microsoft Excel spreadsheet as “NDVI_Zonal_Statistics”.

Soils Step 5: Spatially Represent the Analyses

Analyses are spatially represented by soil unit and ecological site to visualize which areas of the park are most adversely affected. They are sorted from highest to lowest NDVI percent change and labeled by the associated soil unit/ecological site.

Soils Step 6: Create Associated Metadata

Drought_NDVI_Analysis.gdb

- DominantEcosite_SSURGO_GLCA_Rast
- DominantSoil_SSURGO_GLCA_Rast
- SSURGO_GLCA_Poly

NDVI_Median_NoMask.gdb:

- Median_PostDrought_NoMask
- Median_PreDrought_NoMask

NASADevelop_Project.tbx

- Add Fields

- 2) NDVI Zonal Statistics
- 3) Post-Drought Median_Modified
- 4) Pre-Drought Median_Modified
- 5) SSURGO Poly to Rast

**** That is the conclusion of the soils steps and will now return to the alliances workflow. ****

Alliances Step 2: Pre-Process Alliance Map

The objective was to focus on the 10 largest Alliance groups within the park. Based on the cell count for each alliance in the “GLCA_Alliance_v2017” feature class, alliances were extracted with the additional removal of Water, Geology, and Non-Natural features. Final Raster Dataset: “all_large” (Figure F-12).

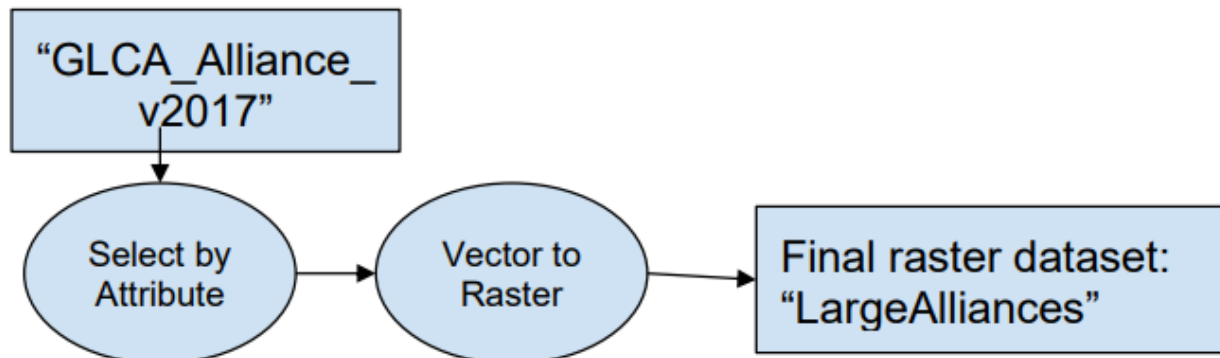


Figure F-12. Workflow used to generate the final raster dataset

Alliances Step 3: Zonal Statistics

The zonal statistics tool calculates desired statistics based on pixel values found in one layer which are found within user-defined zones of another layer. In this case, zones would be defined by the Alliance dataset and statistics would be calculated on NDVI values that were located within those zones. This was calculated for both Pre and Post Drought NDVI datasets. Mean values indicate NDVI values for each dataset. Derived dataset was created representing Percent Change between Pre and Post NDVI values (Figure F-13).

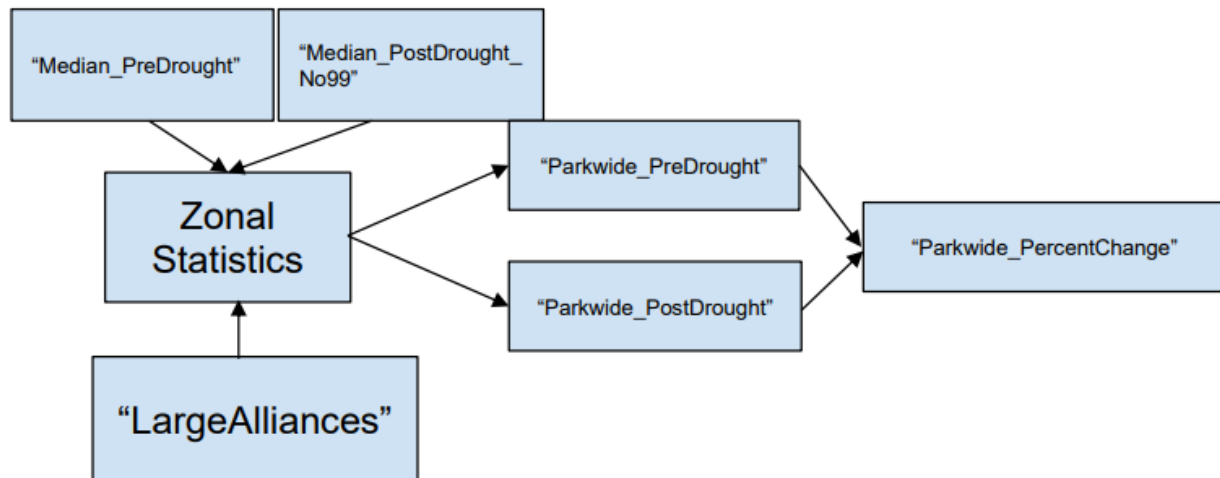


Figure F-13. Workflow used to generate the park-wide percent change between pre and post NDVI values.

Alliances Step 4: Regional Zones Feature Classes

Regions were calculated to differentiate climatic areas and their respective NDVI fluctuations. Regions were contrived areas and where some comprise significantly more surface area than others. The Zonal Statistics tool was used for each of the 4 regions for both Pre and Post NDVI datasets. The corresponding MEAN NDVI values were transferred to all regional datasets (Figure F-14). Tabular data includes Pre, Post, and PercentChange NDVI values for each region.

Tabular data includes Pre, Post, and PercentChange NDVI values for each region.

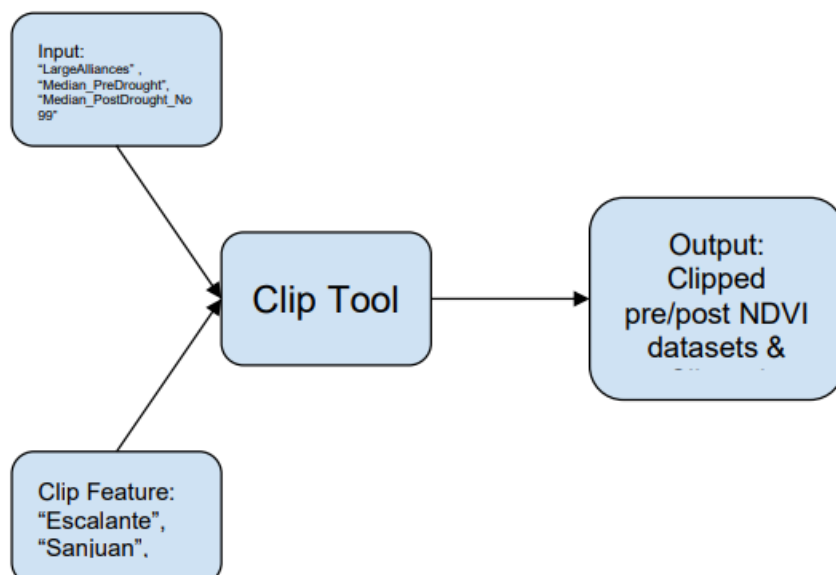


Figure F-14. The Zonal Statics workflow was conducted for each regional clipped NDVI/Alliance datasets.

Alliances Step 5: Spatially Represent the Analyses

Alliances Step 6: Create Associated Metadata

Figure F-15 shows a screenshot of the metadata created by Step 6.

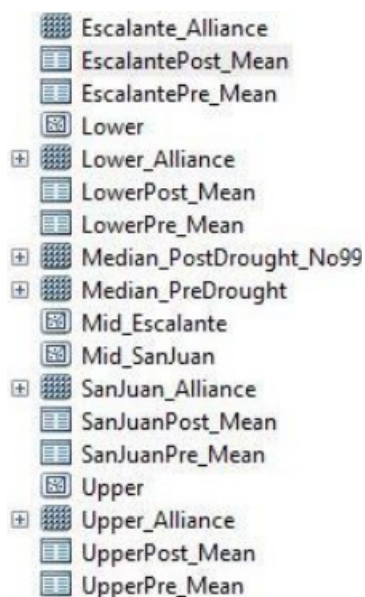


Figure F-15. Screenshot of the metadata fields generated.

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.

NPS 608/188586, June 2023

National Park Service
U.S. Department of the Interior



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