Drought Vulnerability Assessment to Inform Grazing Practices on Rangelands in Southeast Arizona and Southwest New Mexico's Major Land Resource Area 41

Major Land Resource Area (MLRA) 41-1 Loamy Upland ecological site in Arizona.

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Abstract

Increased climate variability, including more frequent and intense drought, is projected for the southwestern region of the United States. Increased temperatures and reduced precipitation lower soil water availability, resulting in decreased plant productivity and altered species composition, which may affect forage quality and quantity. Reduced forage quality and increased heat stress attributable to warmer temperatures could lead to decreased livestock performance in this system, which is extensively used for livestock grazing. Mitigating the effects of increasing drought is critical to social and ecological stability in the region. Reduced stocking rates and/or a change in livestock breeds and/or grazing practices are general recommendations that could be implemented to cope with increased climatic stress. Ecological Sites (ESs) and their associated state-and-transition models (STMs) are tools to help land managers implement and evaluate responses to disturbances. The projected change in climate will vary depending upon geographic location. Vulnerability assessments and adaptation strategies are necessary at the local level to inform local management decisions and help to ameliorate the effects of climate change on rangelands. The USDA Southwest Climate Hub and the Natural Resources Conservation Service (NRCS) worked together to produce this drought vulnerability assessment at the Major Land Resource Area (MLRA) level: it is based on ESs/STMs that will help landowners and government agencies to identify and develop adaptation options for drought on rangelands. The assessment illustrates how site-specific information can be used to help minimize the effects of drought on rangelands and to support informed decision-making for selecting management adaptations within MLRA 41.

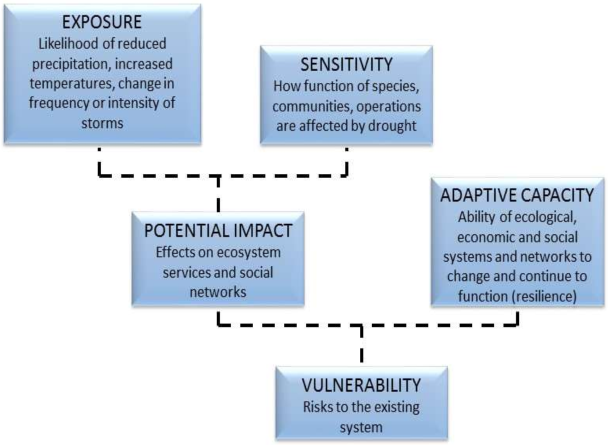
Keywords: drought, rangelands, grazing adaptation, MLRA 41, climate change, Arizona, New Mexico

Contents

Introduction

Increasing atmospheric concentrations of greenhouse gases (GHG) have elevated global surface temperatures by 0.8°C (National Research Council, 2012) over the past 100 years, and will likely exceed 1.5°C for the end of the 21st century (IPCC, 2013). Elevated levels of greenhouse gases cause greater climate variability, including more frequent and severe storms and drought in the southwestern United States where rangeland is the major land use. Rangelands represent diverse arid and semiarid systems defined by low plant productivity, high precipitation variability, and frequent drought (an extended period of relatively low precipitation). There are approximately 770 million acres of rangelands in the United States, comprising approximately 31 percent of the total land area in the U.S. and approximately 85 percent of the total land area in Arizona. Rangelands provide a multitude of goods and services including food, fiber, clean water, recreation opportunities, climate regulation, wildlife habitat, and water and nutrient cycling (Havstad et al., 2007; Maczko et al., 2011). Rangeland goods and services are necessary to meet society's current and future needs. A changing climate will have an effect on these services. Elevated carbon dioxide (CO_2) conditions may increase water use efficiency and plant production (Morgan et al., 2004), altering species composition and reducing forage quality (Milchunas et al., 2005; Morgan et al., 2004) and quantity in a system extensively used for livestock grazing. Productivity varies due to the high variability of soils, climate, and landforms across rangelands. Understanding the limitations of the land is necessary to conserve rangelands and the services they provide. Since projected changes in climate will vary depending upon geographic location, it is necessary to prepare vulnerability assessments and adaptation strategies at the local level to minimize the detrimental effects of climate change on rangelands (Briske et al., 2015; Joyce et al., 2013).

The term "vulnerability" can have different interpretations. The Intergovernmental Panel on Climate Change (IPCC) defines *vulnerability* as the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change; and is a function of exposure, sensitivity, and adaptability (McCarthy et al., 2001). Determining the potential impact of drought on rangelands requires developing realistic estimates of exposure and sensitivity to prepare for drought, and adaptive capacity to understand ways to mitigate the effects of drought (Brown et al., 2016). This assessment will focus on *contextual vulnerability*, using a systematic approach to assess the vulnerability of ecological sites to drought and adaptive measures to mitigate the effects of drought. Contextual vulnerability incorporates the socioecological approach that includes the institutional, biophysical, socio-economic, and technological processes (Figure 1) (Joyce et al., 2013; O'Brien et al., 2007). Vulnerability is influenced by the changing biophysical conditions and social, economic, political, institutional, and technological structures and processes (O'Brien et al., 2007).


EXPOSURE
Likelihood of reduced precipitation, increased temperatures, change in frequency or intensity of storms

SENSITIVITY
How function of species, communities, operations are affected by drought

POTENTIAL IMPACT
Effects on ecosystem services and social networks

ADAPTIVE CAPACITY
Ability of ecological, economic and social systems and networks to change and continue to function (resilience)

VULNERABILITY
Risks to the existing system

Figure 1. A vulnerability assessment framework for rangeland drought (Joyce et al., 2013).

Ecological site descriptions (ESDs) developed by the USDA provide land owners with recommended management strategies based on site potential and can be used to help manage the effects of climate variability at the local level. Ecological site concepts are uniquely developed within individual Major Land Resource Areas (MLRA), which is a component of the soil Land Resource Hierarchy (LRH). The LRH was developed by the USDA-NRCS to identify geographical areas at different levels of resolution that have similar capabilities and potentials for management (Bailey, 2014). The LRH divides landscapes into resource areas so that management and conservation plans can be applied. The LRH is based on soil resources and does not include an ecological site component, which is based on both vegetation and the soils (Figure 2). Salley et al. (2016) proposed incorporating ecological site concepts into the hierarchy to aid in the development of ecological sites, and to provide spatial scaling links between the ecological scales of the LRH. Furthermore, including ecological sites into the LRH will aid in evaluating biotic and abiotic influences, as landscapes are organized at the local level (Figure 2) (Salley et al., 2016). This assessment will apply ecological site concepts in order to evaluate how site-specific information can reduce the effects of drought on rangelands, and also help to improve the decision-making process for selecting management adaptations within Major Land Resource Area (MLRA) 41 in southeastern Arizona and southwestern New Mexico. MLRAs are geographically associated landscape classification components based on similar geology, landscapes and landforms, climate, soils, vegetation, and land use. MLRAs were developed by the USDA-Natural Resources Conservation Service (NRCS) to assist with conservation planning on private lands.

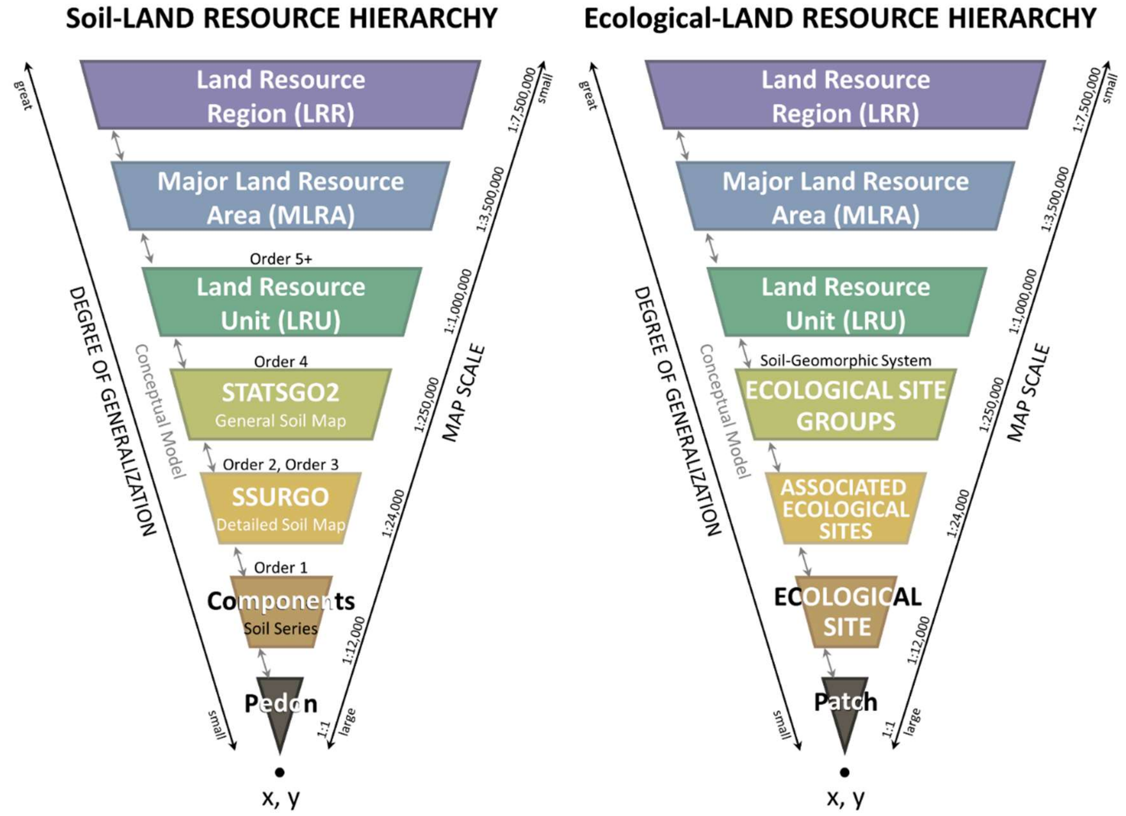


Figure 2. NRCS Land Resource Hierarchy of soil and ecological resources. (redrawn from Salley et al., 2016)

Major Land Resource Area 41 is located in the Basin and Range Province in southeastern Arizona and southwestern New Mexico (Figure 3). This MLRA covers approximately 10 million acres, 89 percent of which is located in southeastern Arizona and 11 percent in southwestern New Mexico. Major Land Resource Area 41 includes mountain ranges that trend from southeast to northwest, with broad, low-lying basins between the mountains. The eastern portion of the MLRA includes the Sonoran Desert in Arizona, and the southeastern boundary in New Mexico is the Continental Divide. Within this MLRA are three land resource units (LRUs) that differ in relief, vegetation, and soils (Table 1, Figure 3). Land resource units are unique areas within the MLRA that are based on specific properties that are important to use and management of the included lands. The majority of the runoff from the basins flows into the Gila River, which runs through the northern section of MLRA 41. Landforms include piedmonts, mountains, hills, ridges, escarpments, alluvial fans, swales, flood plains, terraces, and many others. The geology of MLRA 41 includes deep alluvium of silt, sand, and gravel deposited from adjacent mountains. The soil temperature regime is thermic and soil moisture regime is typic aridic or ustic aridic. The elevation ranges from 800 to 1,400 meters above sea level (MASL) in the basins and 1,500 to 1,800 MASL in the mountains. The mountains in this area make up the Madrean Sky Islands with the highest peak of 3,267 MASL. The mean annual precipitation (MAP) ranges from 230 to 510 millimeters (mm) across most of the MLRA, however, precipitation can be as high as 1,145 mm at higher elevations. Approximately 60 percent of the precipitation occurs during the five months of summer growing season (May-September), and 40 percent occurs during the winter growing season (October-April). The average length of the freeze-free period (temperatures less than 2.2 °C) is 245 days and ranges from 160 to 335 days, decreasing in length with increasing elevation. Mean annual air temperature is 8.0-20°C and summer temperatures may exceed 38°C at lower elevations. Winter temperatures may be less than 0°C at lower elevations and -18°C or lower at higher elevations where 2 - 6 cm of snow is common from December to March. Approximately 79 percent of the MLRA consists of grazing lands dominated by desert shrub-grassland, open grassland, and/or savanna ecosystems. Other land use includes forestland and agriculture land, and a majority of the land is privately owned. Major crops include cotton, corn, alfalfa, and small grains. Dominant soil orders include Aridisols, Entisols, and Mollisols. Major resource concerns related to soil are organic matter content, productivity of the soils, and water erosion. MLRA 41 contains 76 ecological sites, however, 13 sites have yet to be fully described and approved. For this report, 63 ecological sites have been combined into seven groups based on similar management and disturbance responses. An index of drought vulnerability will be developed based on site characteristics within the seven ES groups, which will define grazing management and/or adaptation strategies.

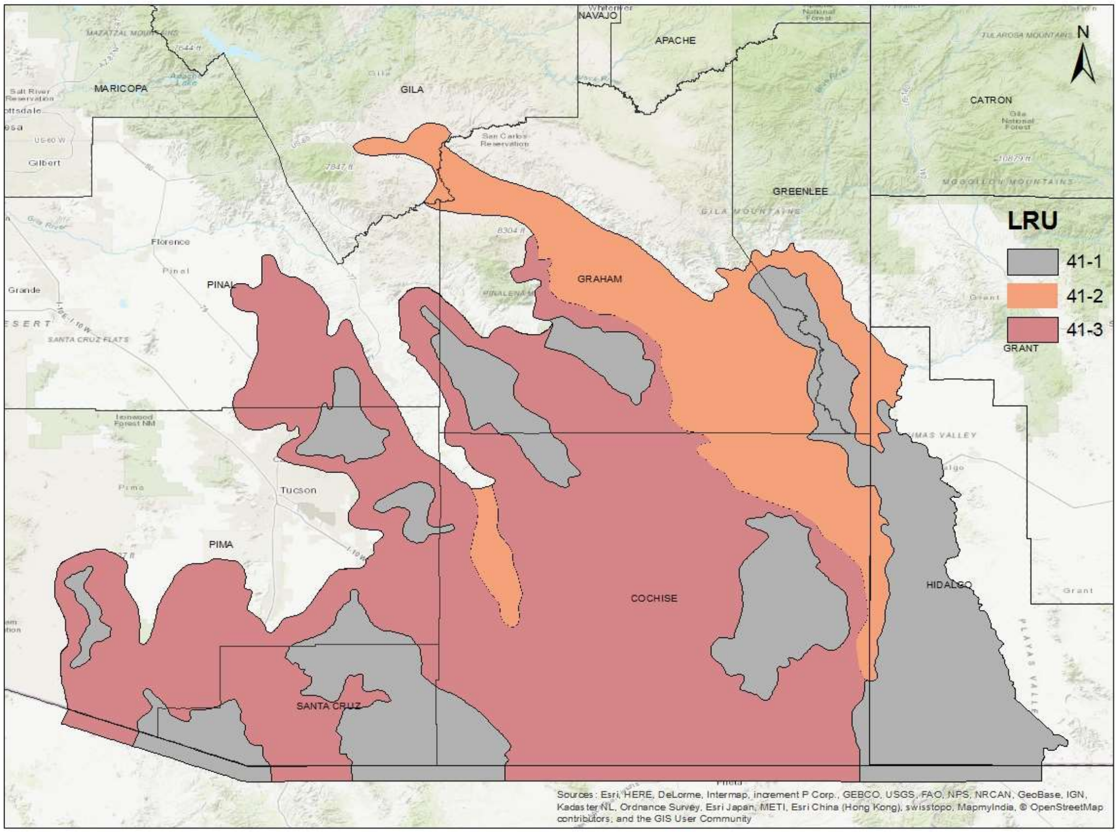


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Figure 3. Major Land Resource Area 41 and Land Resource Units located in the Southeastern Arizona Basin and Range province.

Table 1. MLRA 41 Land Resource Unit, Vegetation, Precipitation, and Elevation

LRU	**Name**	**Common Vegetation**	**Precipitation (mm)**	**Elevation (m)**
41-1	Madrean Oak Savanna	Grasses: gramas (*Bouteloua spp.*), plains lovegrass (*Eragrostis intermedia*), bullgrass (*Muhlenbergia emersleyi*), spiked crinkleawn (*Trachypogon spicatus*), cane beardgrass (*Bothriochloa barbinodis*) Shrubs: sacahuista (*Nolina microcarpa*), shrubby buckwheat (*Eriogonum spp.*), wait-a-bit (*Mimosa aculeaticarpa var. biuncifera*), velvetpod mimosa (*Mimosa dysocarpa*), false mesquite (*Calliandra eriophylla*) Trees: Arizona white oak (*Quercus arizonica*), Emory oak (*Quercus emoryi*), oneseed juniper (*Juniperus monosperma*) , mesquite (*Prosopis velutina* Wooton)	406 - 508	1,372 - 1,981
41-2	Chihuahuan Desert Shrub	Grasses: threeawns (*Aristida spp.*), tobosagrass (*Pleuraphis mutica*), dropseeds (Sporobolus cryptandrus and S. airoides), black grama (*Bouteloua eriopoda*), bush muhly (*Muhlenbergia porteri*) Shrubs: creosote bush (*Larrea tridentata*), whitethorn acacia (*Vachellia constricta and V. vernicosa*), burroweed (*Isocoma tenuisecta*), broom snakeweed (*Gutierrezia sarothrae*), soaptree yucca (*Yucca elata*), catclaw acacia (*Senegalia greggii*), American tarwort *(Flourensia cernua DC.)* and mariola *(Parthenium incanum Kunth)* Trees: mesquite *(Prosopis velutina and P. glandulosa)*	203- 305	792 - 1,219
41-3	Southern Arizona Semi-desert Grassland	Grasses: gramas, tobosa, tanglehead (*Heteropogon Pers*.), big sacaton (*Sporobolus wrightii*), Arizona cottontop (*Digitaria californica*), curly-mesquite (*Hilaria belangeri*) Shrubs: burroweed, snakeweed, false mesquite, ratany (*Krameria L.*), shrubby buckwheat, creosote bush, soaptree yucca Trees: mesquite *(P. velutina)*, netleaf hackberry *(Celtis laevigata var.)*	305 -406	975 - 1,524

Exposure

Both Arizona and New Mexico cover large geographic areas that have diverse climates and topography with a wide range of relief across the states. In Arizona, precipitation and temperatures vary in the higher elevations as the mountains run from the northwest to the southeast. The northeastern part of the state experiences cold winters and mild summers, while the deserts in the southern part are hot and dry. In 2014, Arizona experienced the hottest year on record when temperatures were 1.6°C above the long-term average; and since the beginning of the 21st century, the state has experienced an increase in the number of warm nights. Since 2000, the state has experienced an upward trend in both average daily maximum and minimum summer temperatures. Average annual temperatures have increased by 1.1°C since the early 20th century, and increasing temperatures and more frequent and extreme drought are projected for the future (Frankson et al., 2017a).

New Mexico temperature and precipitation events also vary widely across the state which includes mountain ranges, forests, grasslands, and deserts. Average annual temperature has increased by 1.1°C since the 1970s and the number of hot days and warm nights has increased. The number of extremely hot days (maximum temp above 37.7°C) has increased over the past 20 years, especially in the eastern plains. By the end of the 21st century, increased temperatures and heat wave intensity are projected to increase, posing a risk to human health. Higher temperatures and reduced spring moisture will impact reservoir levels and other water resources needed for irrigation during the hot summer months. Climate models project the average annual temperatures will increase by approximately 3.3 to 7.7°C for Arizona and 3.3 to 7.2°C for New Mexico by the end of the 21st century if GHGs continue to increase (Figure 4) (Frankson et al., 2017a, 2017b). In the next 20 years, the mean annual temperature is projected to increase by 1.28°C for MLRA 41 (Abatzoglou, 2017).

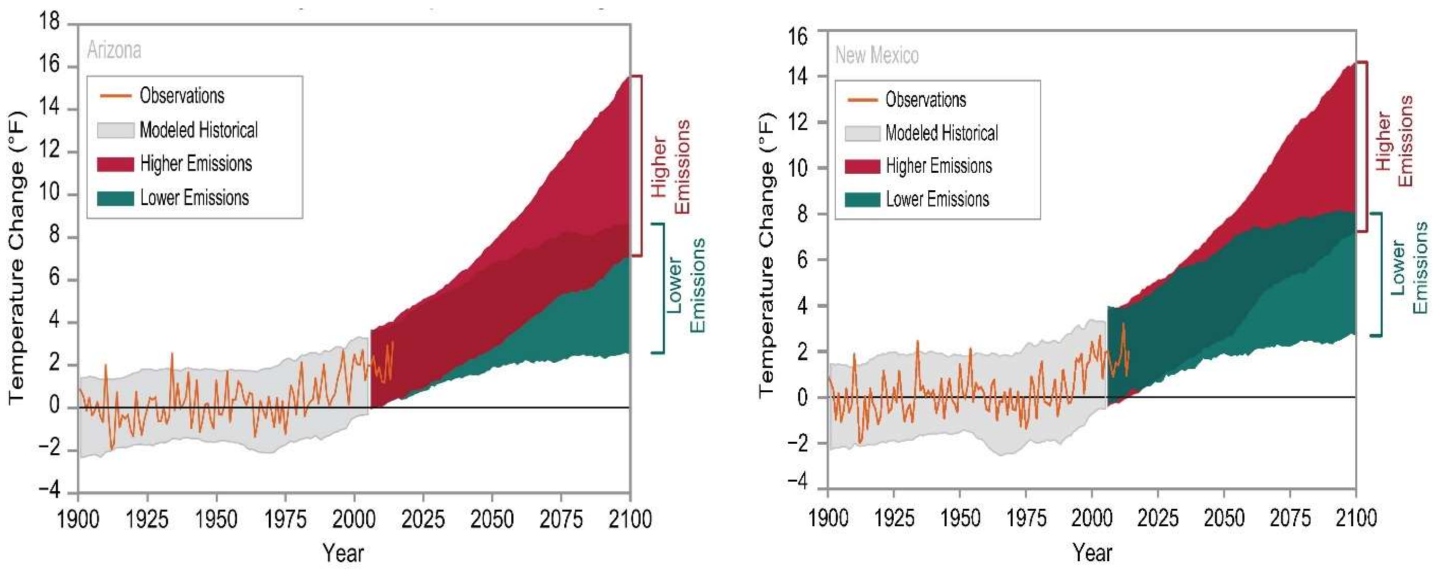

Figure 4. Observed and projected changes in near surface air temperature for Arizona and New Mexico (Frankson et al., 2017a, 2017b).

The complexity and interactions of the atmospheric processes make it difficult for global climate models to predict changes in future precipitation patterns (Knapp et al., 2008). Annual precipitation in Arizona varies widely, ranging from less than 73 mm in southwestern Arizona to around 1016 mm in the higher elevations (Figure 5), however, annual precipitation has been below average the last 20 years (Frankson et al., 2017a). In New Mexico, annual precipitation is highly variable (Figure 5) when multiyear periods of high and low precipitation result in large fluctuations in reservoir supplies for agriculture. Spring precipitation is projected to significantly decrease in New Mexico, affecting the mountain snowpack that flows into the reservoirs and river basins (Frankson et al., 2017b).

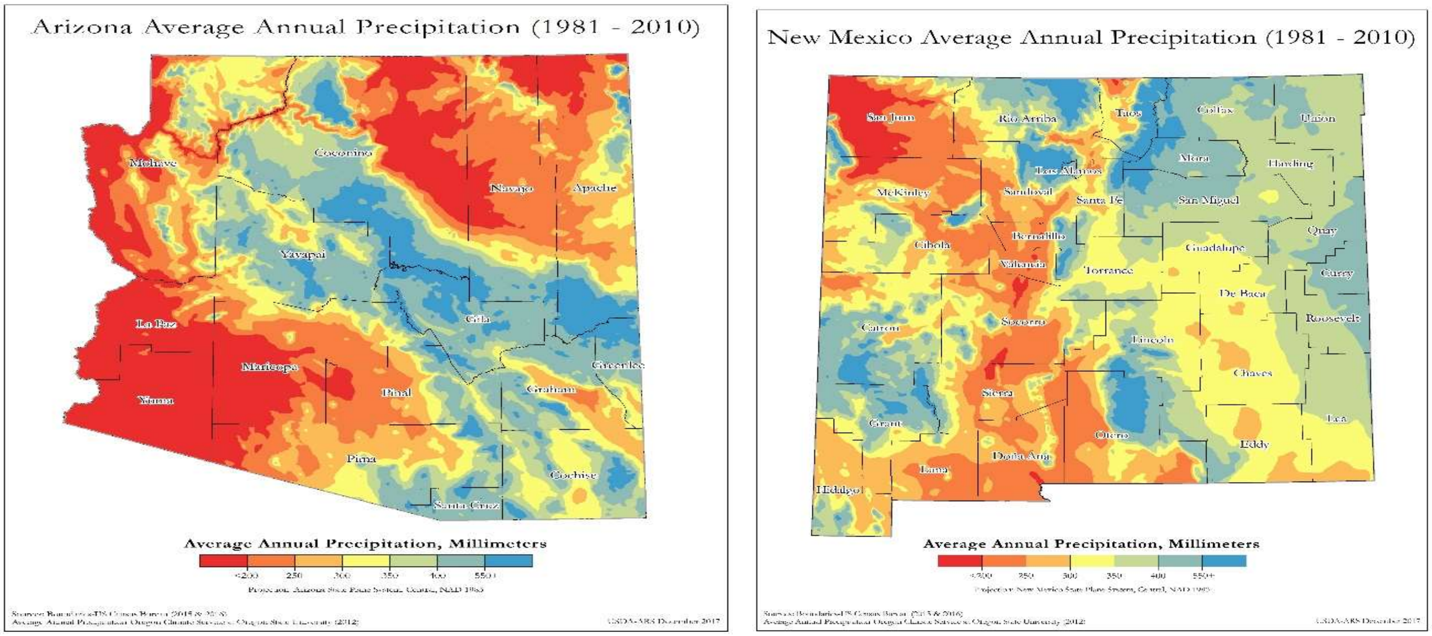

Figure 5. Arizona and New Mexico average annual precipitation from 1981-2010.

The North American monsoon season is highly variable, but typically results in large amounts of rainfall from early July to mid-September, and accounts for more than half of the annual precipitation in southern Arizona and New Mexico (Figure 6). The summer monsoons are critical to the Southwest as they suppress hot summer temperatures and replenish water resources that support forage production and the agricultural economy. Spring precipitation is predicted to decline, and there is high uncertainty regarding the summer monsoon season which provides relief to rangelands and agricultural enterprises.

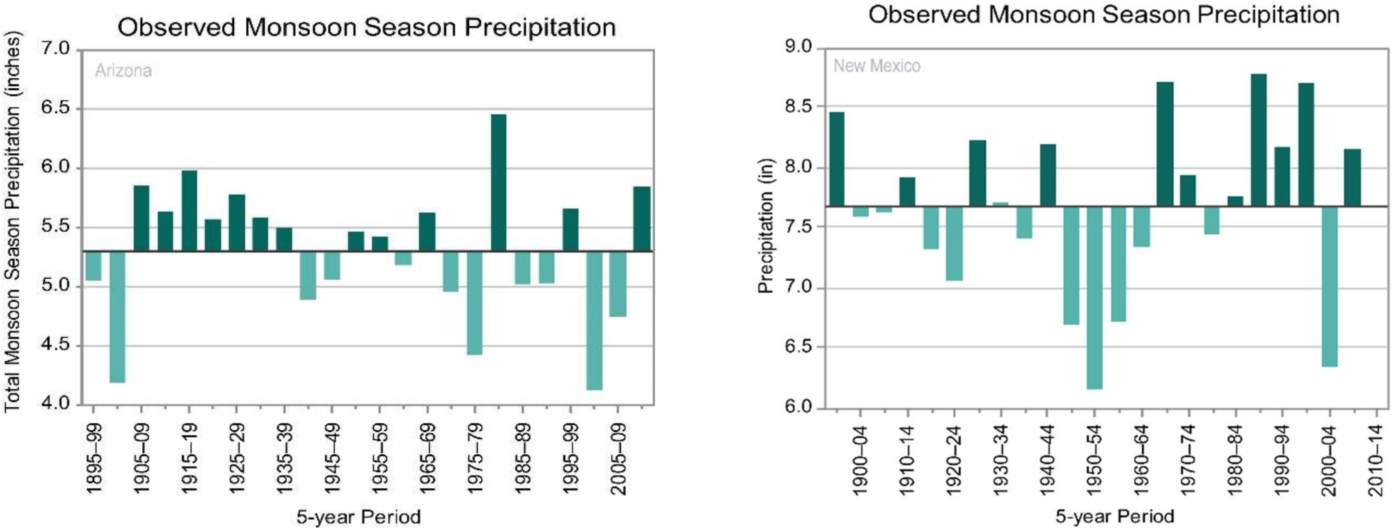

Figure 6. Observed monsoon season precipitation for Arizona and New Mexico (Frankson et al., 2017a, 2017b).

Decreased precipitation in the spring combined with warmer temperatures will reduce mountain snowpack that feeds water supply reservoirs, reducing valuable water resources. Increased temperatures and reduced spring precipitation will lead to higher evaporation rates and drought severity, further reducing streamflow, soil moisture, and water supplies. Multiple years with below-average precipitation affect reservoir supplies, such as Lake Mead, which is a critical water source for Arizona. Snowfall occurs in the higher elevations of the MLRA and is critical to the water supply for urban and agricultural areas in the valleys, as well as to provide groundwater recharge across both states. However, the projected temperature increases will result in earlier snowmelt, negatively affecting the valleys and river basins. Overall, both states are projected to experience increased temperatures, more frequent and extreme droughts, increased wildfire severity and occurrences, decreases in spring precipitation, and highly uncertain summer monsoon rainfall events. (Frankson et al., 2017b, 2017a).

The National Drought Mitigation Center (NDMC) defines drought as "*deficiency of precipitation over an extended period of time and its impacts vary from region to region*." There are four types of drought described by Henz et al. (2004) .

- Meteorological drought - expression of departure from normal precipitation over some period of time; and is the first indicator of drought.
- Agricultural drought - occurs when there is a lack of soil moisture availability that affects crop and/or rangeland production.
- Hydrological drought - refers to deficiencies in surface and subsurface water supplies and is measured as streamflow and as lake, reservoir, and groundwater levels.
- Socioeconomic drought - occurs when water shortages start to affect people and is associated with supply and demand.

Key variables in assessing drought are precipitation, snowpack, storage, and streamflow. Determining the impacts of drought can be described by evaluating the following drought characteristics (Henz et al., 2004):

- Magnitude (size of water deficits compared to historic average)
- Duration (length of time the drought persists)
- Severity (combination of the magnitude and duration) (Appendix – Table A1)
- Spatial extent (what area is impacted by the drought)

There are several types of indicators or indices used to help track droughts and provide information before, during, and after droughts to aid with decision making and formulation of drought management plans as a means of reducing potential impacts (Appendix – Table A2, A3).

Two types of drought defining magnitude and pattern, are expected to increase over the next century with each having different effects on ecosystem properties and processes. Press droughts occur when long-term reduction in precipitation (e.g. 10 percent decrease in MAP) and soil moisture coincide with increased temperatures and potential evapotranspiration. Pulse droughts are short in duration, but more extreme in magnitude (e.g. less than 5th percentile of annual rainfall) (Hoover and Rogers, 2016; IPCC, 2013). Pulse droughts affect carbon storage and cycling, as gross primary production has greater sensitivity to drought than to ecosystem respiration. Rangelands are more resistant to press droughts than to pulse droughts, as more carbon is lost during extreme pulse droughts (Hoover and Rogers, 2016).

Most of the moisture received in MLRA 41 is received during the summer monsoon season (July-September) with less than half of the annual moisture received during winter (Dec-March). The average annual precipitation ranges from 230 to 510 mm across most of the MLRA but can be as high as 1,145 mm at the higher elevations. More than half of the precipitation occurs as high-intensity, convective thunderstorms during July, August, and September with additional winter moisture received from December through March (Figure 7). Climate models predict a slight increase in mean annual precipitation for MLRA 41; however, increasing mean annual temperatures and potential evapotranspiration will lead to drier conditions for the area (Table 2.) Warmer temperatures result in more days above freezing, leading to a longer growing season (Abatzoglou, 2017) and greater abundance of warm-season plants.

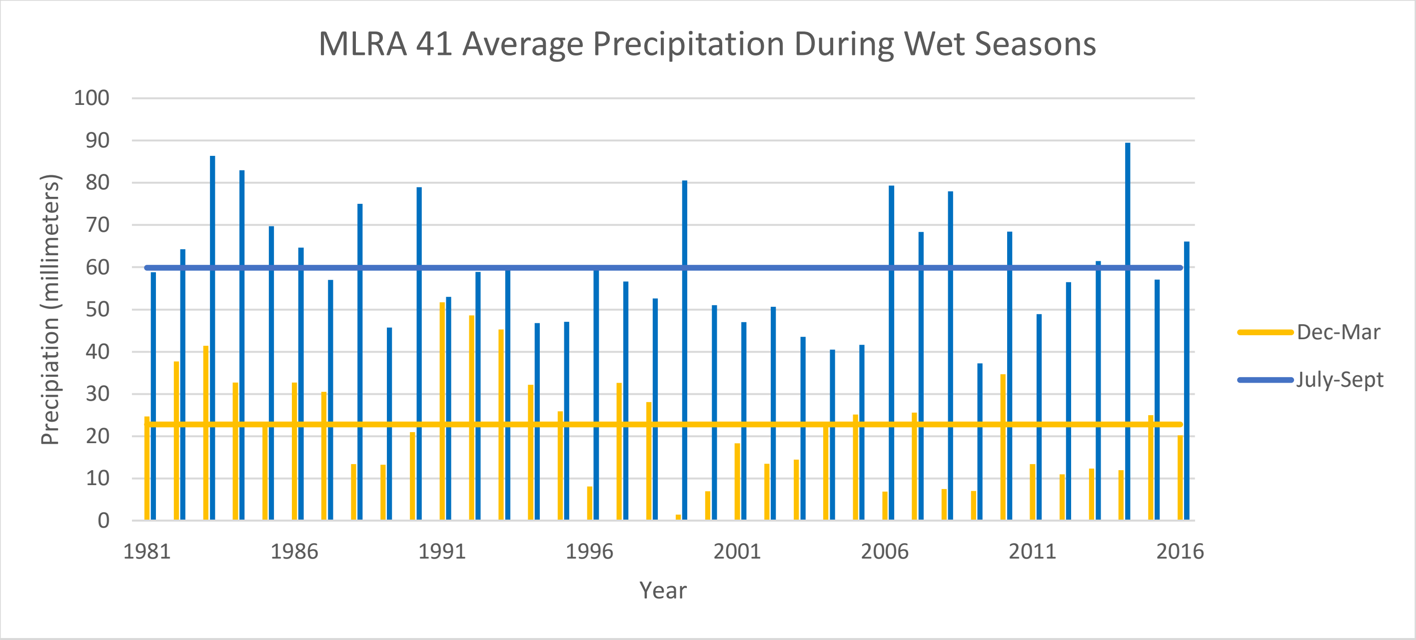

Figure 7. Average precipitation during the two growing seasons for MLRA 41 (horizontal lines indicate long-term average).

Table 2. MLRA 41 Historic and Future Climate Projections

Low/High Emissions and Year	Mean Annual Precip. (mm)	Mean Annual PET (mm)	Mean Annual Summer Min. Temp. (C)	Mean Annual Summer Max. Temp (C)	Mean Annual Winter Min. Temp. (C)	Mean Annual Winter Max. Temp. (C)	Mean Annual Freeze-Free Days
1971-2000	324.4	1815.9	17.0	34.3	-1.1	16.5	200
RCP4.5 2010-2039	328.1	1902.2	18.4	35.7	-0.2	17.8	222
RCP8.5 2010-2039	337.8	1909.6	18.5	35.9	-0.1	18.1	224
RCP4.5 2040-2069	334.3	1955.8	19.3	36.7	-0.6	18.8	233
RCP8.5 2040-2069	333.8	2003.3	20.1	37.5	1.2	19.6	243

*Northwest Climate Toolbox, University of Idaho.

The American Southwest experienced prolonged droughts in 2002, 2003, 2007, and 2009, when the average precipitation across several states, including Arizona and New Mexico, was less than 25 percent of the 20th century average (Guido, 2011). Droughts are common to MLRA 41 (Figure 8), however, temperatures are warmer than they were during historical droughts (Guido, 2012). Increased temperatures cause higher evapotranspiration, exacerbating the effects of drought, such as the 2011-2012 drought. A long-term drought with high temperatures in the Southwest may result in major shortages on the Colorado River, the Rio Grande, and other rivers that are heavily depended upon for water supplies. Furthermore, a long-term drought can have devastating impacts on the landscape. The severe drought of 2011-2012 resulted in widespread tree mortality and desert plants drying, and these circumstances exacerbated the conditions for record-breaking wildfires. Paleoclimatology data indicates that some droughts prior to 1600 were longer in duration and covered a larger area than the more recent droughts of the twentieth century

(Woodhouse and Overpeck, 1998). However, increased drought severity and duration today or in the future could have greater impacts due to the expanding metropolitan area and large-scale crop and livestock production.

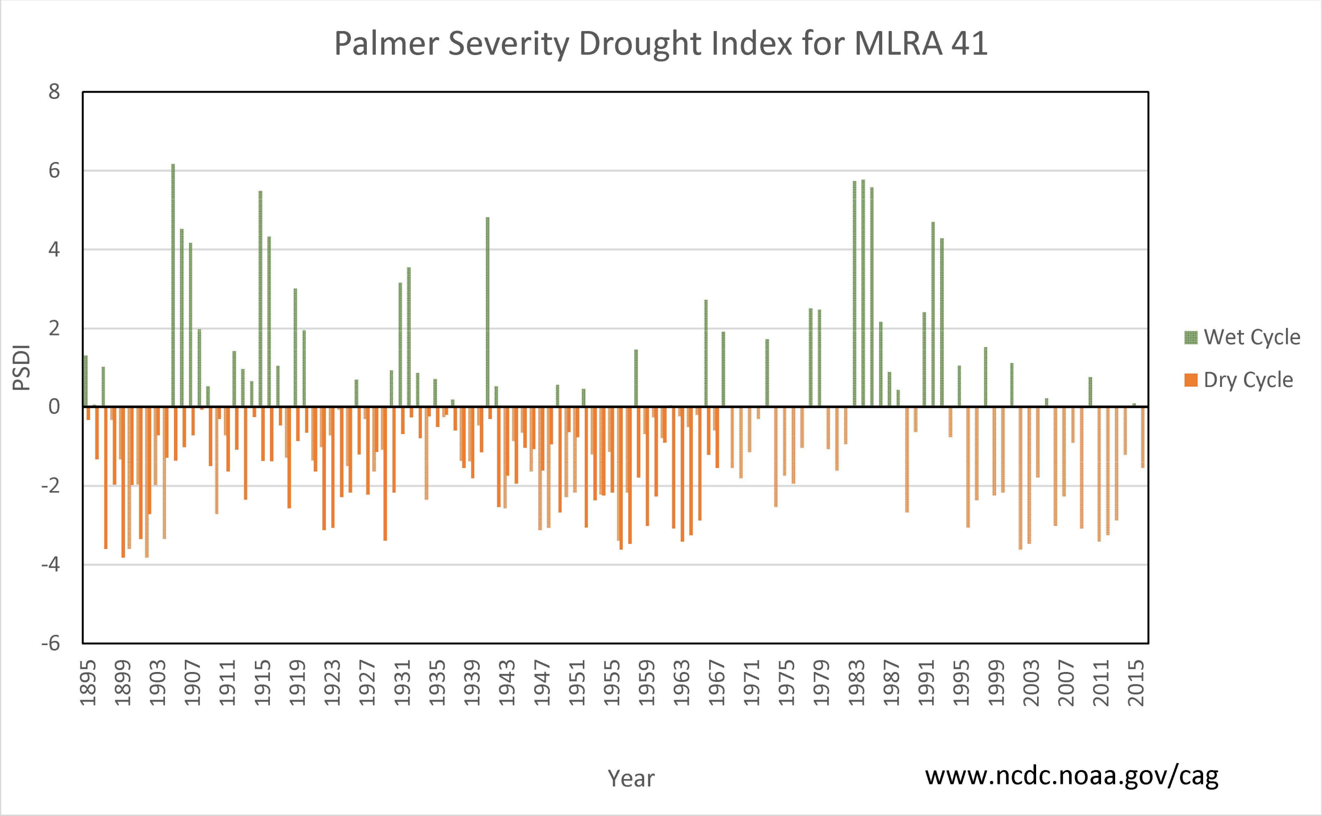

Figure 8. Southeastern Arizona (Climate Division 7) Palmer Drought Severity Index.

Climate change is expected to have diverse consequences on U.S. rangelands (Polley et al., 2013), as weather patterns will influence grazing practices and the livelihoods of millions of people (Briske et al., 2015). Rising temperatures and increased drought severity will lead to decreased livestock performance and production due to heat stress, reduced forage quantity and quality, and limited water and soil nutrient availability (Briske et al., 2015; Brown-Brandl et al., 2006; Gill et al., 2002; Polley et al., 2013).

Sensitivity

Knowledge of factors that drive and regulate ecological systems are needed in order to understand and predict response to drought. Applying the vulnerability assessment framework within the context of an Ecological Site State–and-Transition Model (STM) helps us to better understand potential impacts and preferred management strategies for each ecological site. There are 63 ecological sites within MLRA 41 (Figures 9A, 9B, 9C) that differ in production, response to disturbance (e.g. climate variability), management (e.g. prescribed grazing and/or fire), and ability to recover post-disturbance. The ecological sites are grouped based on landform position: Breaks, Soft Breaks, Sandy Upland, Saline Upland, Loamy Upland, Lowland, and Depressions (Schoeneberger and Wysocki, 2012). The vulnerability classes derived in this study (*low, moderate*, or *high*) are primarily based on landform position, production, rooting depth, soil depth, salt content, and land use. Secondary variables that were considered include soil texture, available water capacity (AWC), rock or other fragments, and aspect (Table 3). We evaluated the primary and secondary variables for each ecological site and determined that the variables either increased or decreased ES vulnerability to drought. Furthermore, to determine the vulnerability to drought for each site, we integrated local knowledge of soil scientists, ecological site specialists, and rangeland specialists. The vulnerability classes will allow land managers to evaluate how sensitive each class is to drought and support the development of adaptation strategies for conservation planning and implementation.

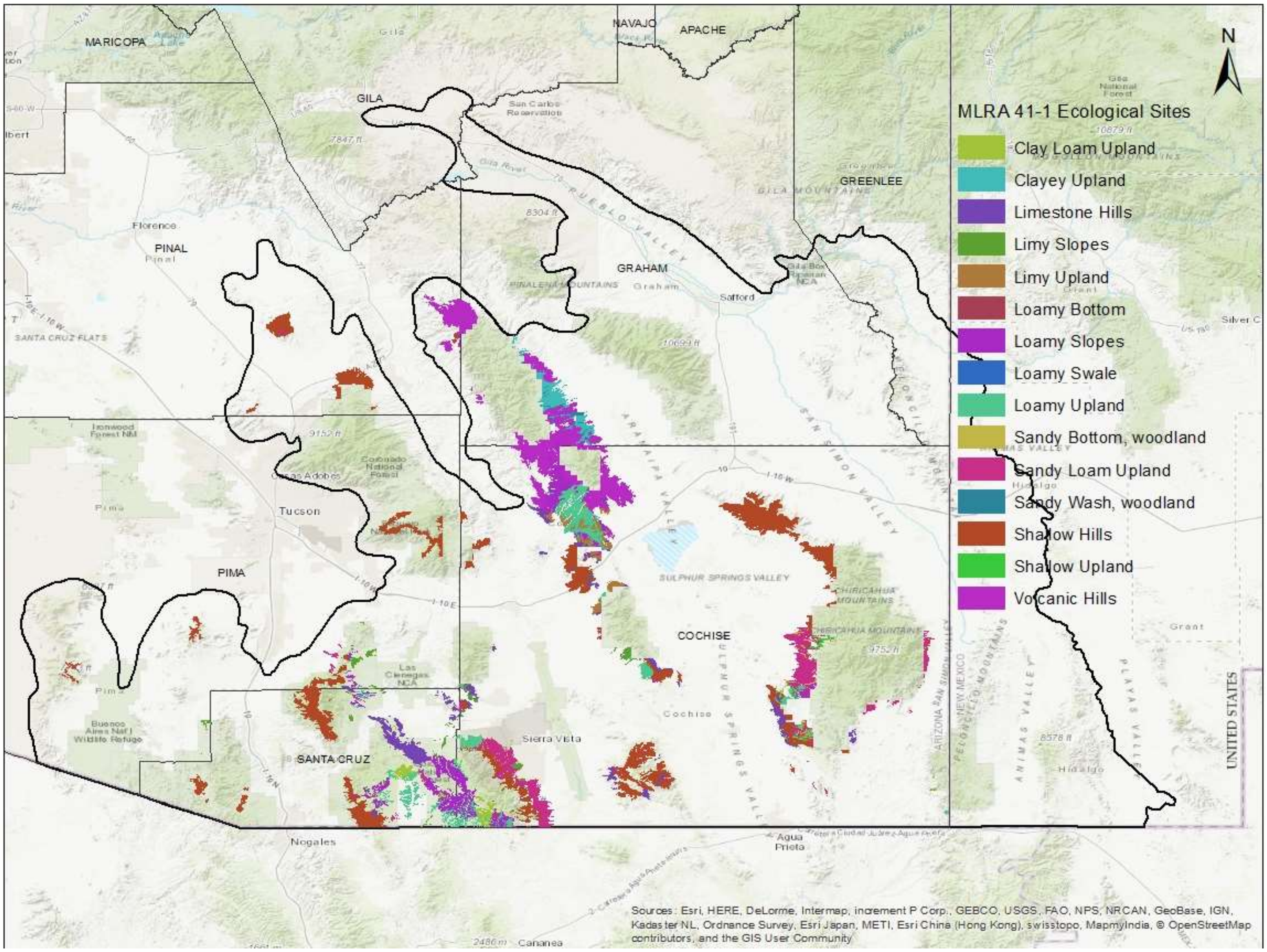

Figure 9A. MLRA 41 LRU 1 ecological site extent map.

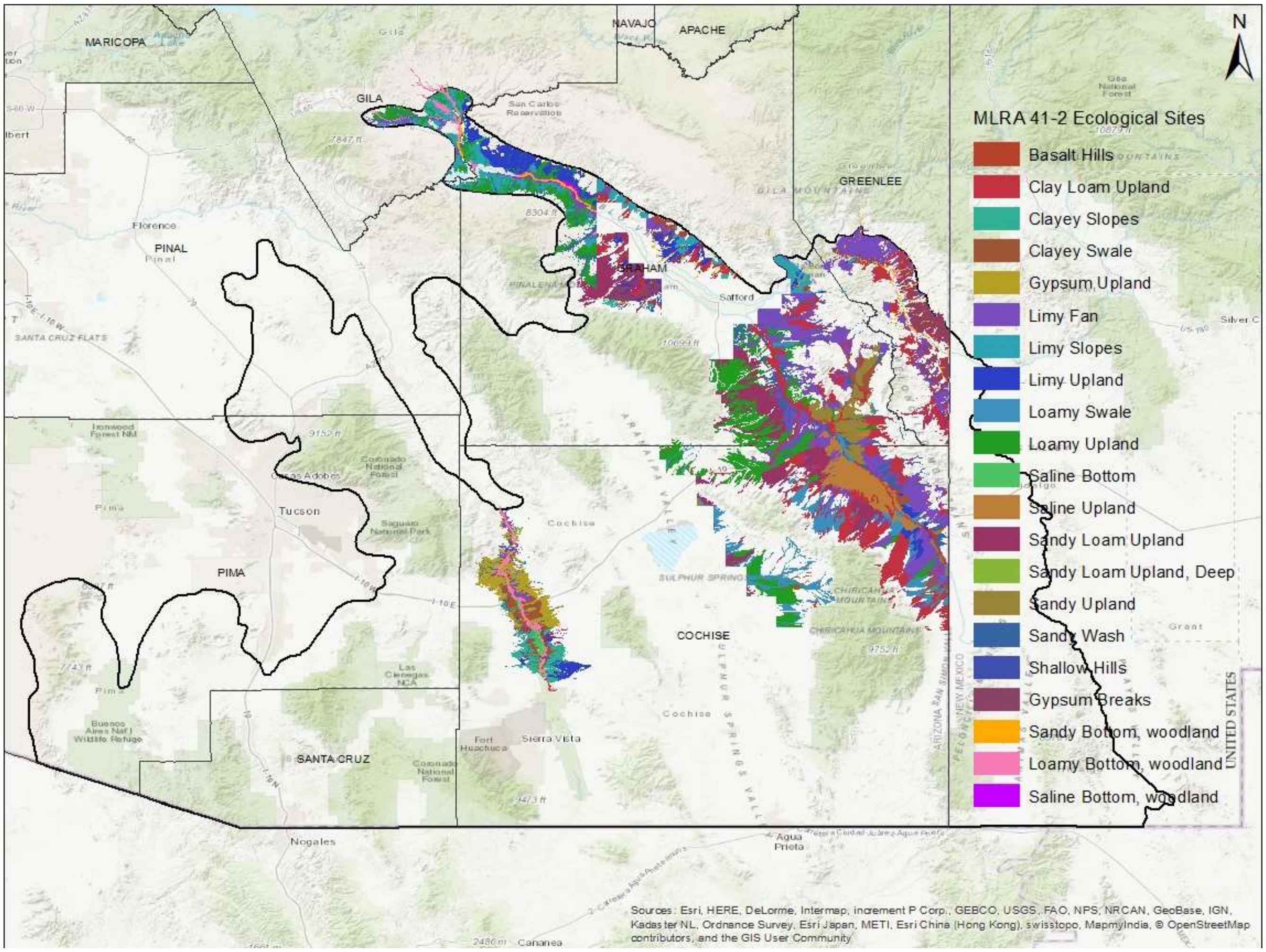

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Figure 9B. MLRA 41 LRU 2 ecological site extent map.

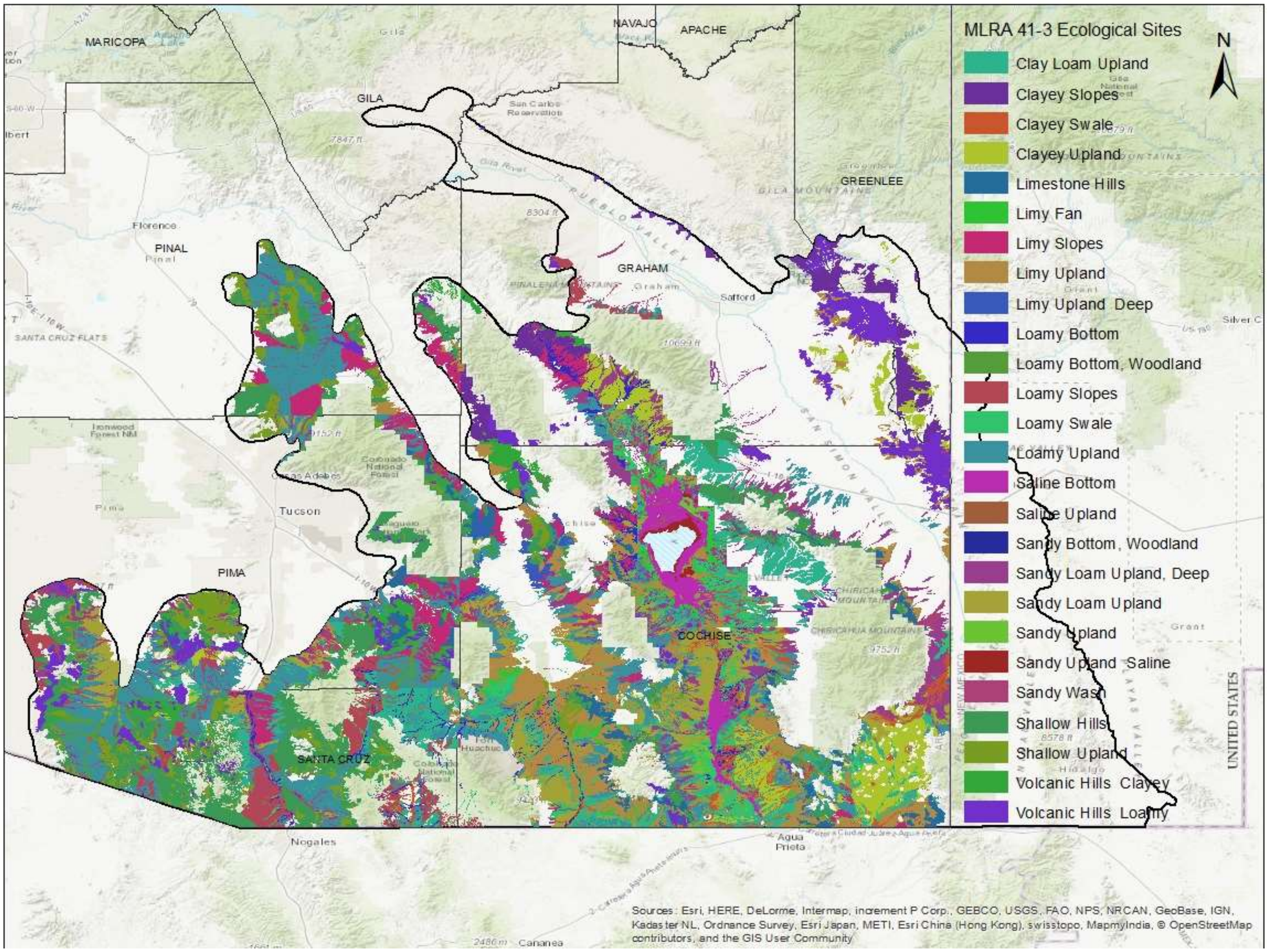

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Figure 9C. MLRA 41 LRU 3 ecological site extent map.

Table 3. MLRA 41 Ecological Site Drought Vulnerability Criteria

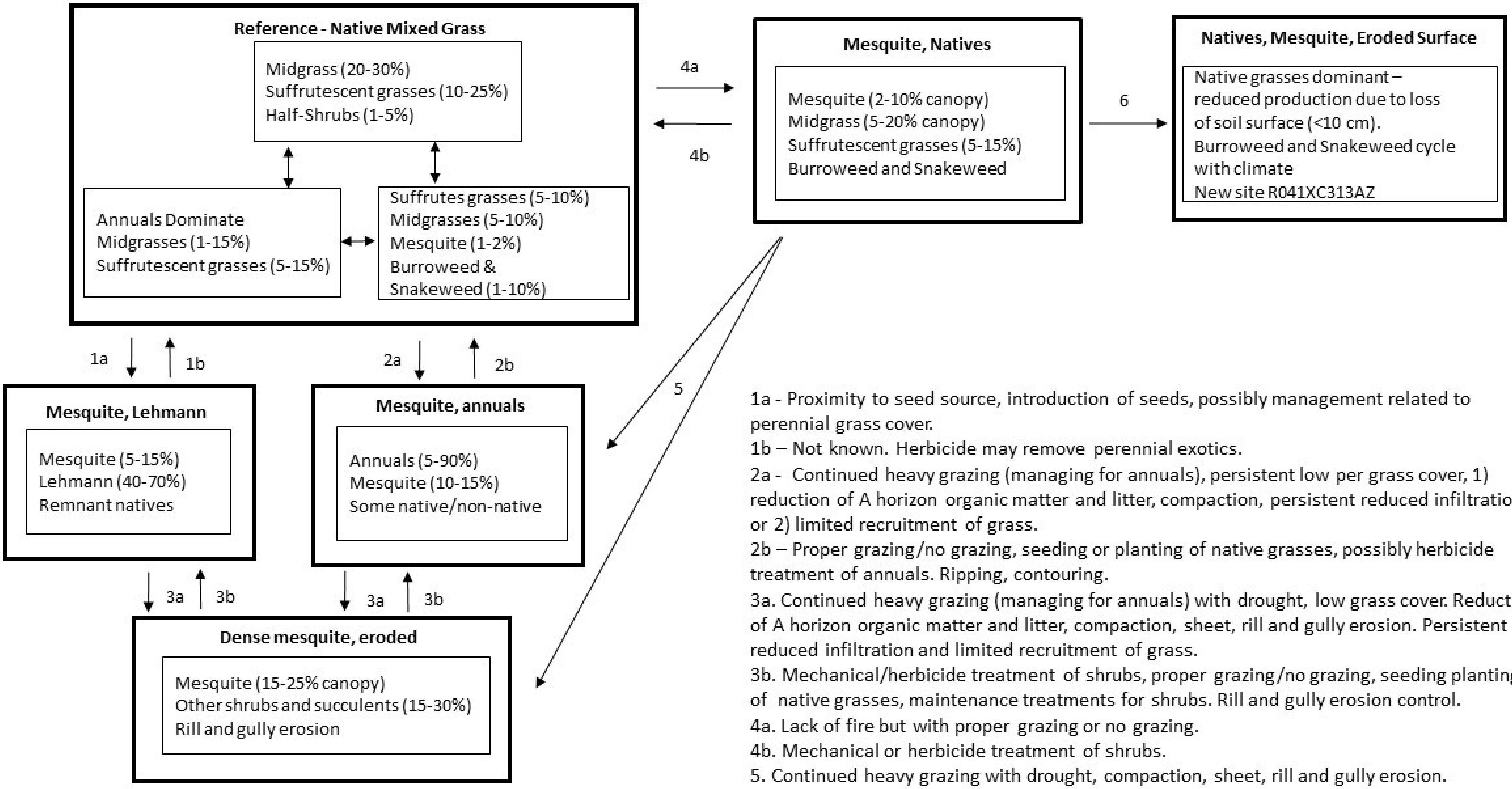
CRITERIA	DESCRIPTION
Primary Variables	
Landform Position	Is the site protected from weather fluctuations (e.g. bottomland vs. breaks)? Is there a hazard of water/wind erosion?
Production	Is productivity high enough to mitigate the impacts from drought (e.g. minimal bare ground)?
Vegetation Rooting Depth	Does the dominant vegetation have greater access to soil water deeper in profile (pinyon-juniper vs. mid-/tallgrasses vs. shortgrasses)?
Soil Depth	Is the site dominated by deep soils (i.e. 102 cm) or shallow soils (i.e. 51 cm)?
Salts	Will concentrations of salt in the soil profile impact uptake of water by plants?
Land Use	Is the site extensively grazed, tilled, or eroded?
Secondary Variables	
Soil Texture	Is the site dominated by loam, clay loam soils, or sandy soils?
Available Water Capacity	Does the site have a high water-holding capacity?
Fragments	Does the site have surface and/or subsurface fragments? Surface fragments reduce soil temperature and evaporation. Subsurface fragments help to stabilize the site from wind erosion.
Aspect	South-facing vs. north-facing slopes

Major Land Resource Area 41 includes a broad range of precipitation and relief that supports a diverse plant community and the associated ecological sites. To evaluate ecological site vulnerability, we have divided the ecological sites by the respective LRU (Table 1).

For this assessment, we estimated drought sensitivity based on the Reference State. For example, the Sandy Loam Upland (Figure 10) STM (Figure 11) shows that a site occupied by the Reference Native Mixed Grass State will likely transition to the Mesquite-Lehmann State in the absence of fire (Transition 1a). The lack of fire will result in shrub invasion and increase, and seed dispersal from adjacent sites will increase the distribution of non-native grasses (e.g. Lehmann lovegrass *(Eragrostis lehmanniana)*. The Mesquite-Lehmann State may return to the Reference State if mortality is induced by herbicide (Transition 1b). The Reference–Native Mixed Grass State can also transition to the Mesquite-Annual-Dominated State in the absence of fire (Transition 2a). It can return to the Reference–Native Mixed Grass State via herbicide or fire treatment (Transition 2b), reducing shrubs and non-native grasses and allowing for the reestablishment of native warm-season grasses. Depending upon land use and management, other states can occur within this ES state-and-transition model. Each ecological site was assigned a low, moderate, or high drought vulnerability classification for each LRU (Tables 4, 12, 20). The drought vulnerability classifications can be used as guides for conservationists and landowners when determining management practices.

Figure 10. MLRA 41-3 Sandy Loam Upland (R041XC319AZ) ecological site, Graham County, AZ – a)Reference Community, b)Mesquite-Native State, c)Reference Community (annuals-dominant) and d) Dense Mesquite Eroded State. Photos courtesy of Wilma Renken, NRCS-Arizona.

Figure 11. Rangeland State-and-Transition Model for Sandy Loam Upland ecological site (R041XC319AZ) in MLRA 41-3.



1a - Proximity to seed source, introduction of seeds, possibly management related to perennial grass cover.

1b – Not known. Herbicide may remove perennial exotics.

2a - Continued heavy grazing (managing for annuals), persistent low per grass cover, 1) reduction of A horizon organic matter and litter, compaction, persistent reduced infiltration or 2) limited recruitment of grass.

2b – Proper grazing/no grazing, seeding or planting of native grasses, possibly herbicide treatment of annuals. Ripping, contouring.

3a. Continued heavy grazing (managing for annuals) with drought, low grass cover. Reduction of A horizon organic matter and litter, compaction, sheet, rill and gully erosion. Persistent reduced infiltration and limited recruitment of grass.

3b. Mechanical/herbicide treatment of shrubs, proper grazing/no grazing, seeding planting of native grasses, maintenance treatments for shrubs. Rill and gully erosion control.

4a. Lack of fire but with proper grazing or no grazing.

4b. Mechanical or herbicide treatment of shrubs.

5. Continued heavy grazing with drought, compaction, sheet, rill and gully erosion.

6. Continued heavy grazing, severe soil surface erosion (sheet) resulting in loss of A horizon to less than 10 cm thick. Site #R041XC313AZ.

Madrean Oak Savanna – Land Resource Unit 41-1

For this assessment we have developed six ecological site groups to evaluate the 15 ecological sites within LRU 41-1 (Table 4). This LRU consists of approximately 1,236,954 acres, which makes up 17 percent of MLRA 41. Approximately 68 percent is rangeland and 31 percent is forestland. Land resource area 41-1 is a Madrean Oak Savanna ecoregion dominated by blue grama (*Bouteloua gracilis*), side-oats grama (*Bouteloua curtipendula*), plains lovegrass, Arizona white oak, Emory oak, and Mexican blue oak *(Quercus oblongifolia)*. This LRU receives 406-508 mm of annual precipitation, with about 60 percent of the moisture received in May-September and the remaining 40 percent was received as light rain or snow in October-April. Most of the grassland sites undergo drought as a natural reoccurrence. Within MLRA 41-1, periodic drought can occur and cause significant grass mortality. Droughts in the early 30s, mid-50s, 1975-76, 1988-89, 1995-96, and 2002 resulted in the loss of much of the grass cover. However, the sites were able to recover because of the amount of precipitation received within this LRU.

Table 4 MLRA 41-1 Ecological Site Drought Vulnerability Classes (based on the Reference Community)

Ecological Site Class	MLRA 41-1 Ecological Sites		
Bottomland	🟩 Loamy Bottom	🟩 Loamy Swale	
Bottomland, Woodland	🟩 Sandy Bottom, Woodland	🟩 Sandy Wash, Woodland	
Saline Upland	🟥 Limy Upland		
Sandy Upland	🟥 Shallow Upland	🟨 Sandy Loam Upland	
Loamy Upland	🟨 Loamy Upland	🟥 Clay Loam Upland	🟥 Clayey Upland
Hills	🟥 Volcanic Hills	🟥 Shallow Hills	🟥 Limestone Hills
Slopes	🟨 Limy Slopes	🟨 Loamy Slopes	

low 🟩 moderate 🟨 high 🟥

1. Bottomland Ecological Site Group (41-1)

The Bottomland Ecological Site group includes the Loamy Bottom and Loamy Swale ecological sites, both of which have low vulnerability to drought (Table 5). These ecological sites occur on flood plains, swales, and alluvial fans, and are gently sloping with 0-5 percent slopes. This group receives additional run-on moisture from adjacent areas, and the Loamy Bottom site is influenced by a shallow water table. However, during an extended drought the water tables may decline rapidly below the rooting depth, making these sites more vulnerable to drought. The soils for this group are very deep (greater than 152 cm), and surface textures vary greatly from sandy loam to clay loam with minimal surface fragments. Sites that have a sandy surface are subject to a hazard of wind erosion. However, wind erosion is minimal due to the landform position and production amounts. The Loamy Swale site is commonly grazed, which may increase site vulnerability to drought if not managed properly. The landform position, productivity, vegetation rooting and soil depth, and available water sources give these sites a low vulnerability to drought when in the Reference Community.

Table 5. MLRA 41-1 Bottomland Ecological Site Group Variable Index

CRITERIA	BOTTOMLAND ECOLOGICAL SITE GROUP – VARIABLE INFLUENCE ON DROUGHT VULNERABILITY		
Primary Variables	**Loamy Bottom**	**Loamy Swale**	**Description**
Landform Position	Decreases	Decreases	On gentle slopes, receives additional moisture from adjacent areas. Shallow water table present at some sites mitigates the effects of drought.
Production	Decreases	Decreases	High plant production and species diversity mitigate the effects of drought.
Vegetation Rooting Depth	Decreases	Decreases	Deep plant roots access water deeper in profile to mitigate the effects of drought.
Soil Depth	Decreases	Decreases	Deep soils with available water deeper in profile mitigates the effects of drought.
Salts	n/a	n/a	Has minimal salt content that influences site vulnerability.
Land Use	Decreases	Decreases	Light, moderate, or heavy grazing may influence how a site responds to drought.
Secondary Variables			
Soil Surface Texture	Decreases	Decreases	Has well drained soils with minimal water loss due to evaporation; coarse soils subject to wind erosion; surface texture is highly variable within sites due to landform position.
Available water-Holding Capacity	Decreases	Decreases	Has greater available water capacity in finer textured soils; however, it is highly variable within sites due to landform position. Higher available water-holding capacity in coarse soils would lower resistance to drought.
Fragments	n/a	n/a	Surface and subsurface fragments reduce evaporation and soil temperature, and stabilize site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	Sites occur on all aspects; aspect has no influence on site vulnerability.
Drought Vulnerability Rating	**low**	**low**	

2. Bottomland, Woodland Ecological Site Group (41-1)

The Bottomland Ecological Site group includes the Sandy Bottom, Woodland and Sandy Wash, Woodland ecological sites, both of which have a low vulnerability to drought (Table 6). These ecological sites occur on flood plains, stream terraces, and alluvial fans, and are gently sloping with a 0-3 percent slope. This group receives additional moisture from adjacent areas, and the Sandy Bottom, Woodland site is influenced by a shallow water table. However, during an extended drought, the water tables may decline rapidly below the rooting depth, making these sites more vulnerable to drought. The soils for this group are very deep (greater than 152 cm), and surface textures vary greatly from very cobbly sand to coarse loamy, and some sites contain surface fragments. Sites with sandy surface are subject to the hazard of wind erosion. However, wind erosion is minimal due to the landform position, production amounts, and surface fragments. The Sandy Bottom, Woodland site is commonly grazed which may increase site vulnerability to drought. The landform position, productivity, vegetation rooting and soil depth and available water sources give these sites a low vulnerability to drought when in the reference community.

Table 6. MLRA 41-1 Bottomland-Woodland Ecological Site Group Variable Index

CRITERIA	**BOTTOMLAND ECOLOGICAL SITE GROUP – VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**		
Primary Variables	**Sandy Bottom, Woodland**	**Sandy Wash, Woodland**	**Description**
Landform Position	Decreases	Decreases	On gentle slopes, receives additional moisture from adjacent areas, and shallow water table present at some sites mitigates the effects of drought.
Production	Decreases	Decreases	High plant production and species diversity mitigate the effects of drought.
Vegetation Rooting Depth	Decreases	Decreases	Deep plant roots access water deeper in the profile and mitigate the effects of drought.
Soil Depth	Decreases	Decreases	Deep soils with plant available water deeper in the profile mitigates the effects of drought.
Salts	n/a	n/a	Minimal salt content to influence site vulnerability.
Land Use	Increases	Increases	Light, moderate, or heavy grazing may influence how a site responds to drought.
Secondary Variables			
Soil Surface Texture	Decreases	Decreases	Has well drained soils with minimal water loss due to evaporation; coarse soils are subject to wind erosion; the surface texture is highly variable within these sites due to landform position.
Available Water Capacity	Increases	Increases	Finer textured soils have greater available water capacity; however, it is highly variable within sites due to landform position. A higher available water-holding capacity in coarse soils would lower resistance to drought.
Fragments	Decreases	Decreases	Surface and subsurface fragments reduce evaporation and soil temperature, and stabilize the site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	The sites occur on all aspects; aspect has no influence on site vulnerability.
Drought Vulnerability Rating	**low**	**low**	

3. Saline Upland Ecological Site Group (41-1)

The Saline Upland group includes the Limy Upland ecological site. This site occurs on ballenas, ridges, and fan piedmonts on slopes of less than 15 percent. The soils are shallow (51 cm) to lime cemented pans and are calcareous throughout.

The soil surface texture is gravelly loam or gravelly sandy loam with up to 55percent surface fragments. Approximately 80 percent of the total annual production is of grasses; however, when available, moisture will drain through the shallow, gravelly soil into the fractured pan layer, providing moisture to deep-rooted shrubs. High amounts of calcium carbonate occur within the soil profile, making these sites more vulnerable to drought. Soils high in salts affect the soil and root structure and the uptake of water by plants, leading to decreased productivity. Reduced plant productivity will increase during drought and can lead to increased bare ground. Soil depth, salts, landforms, and production make this site highly vulnerable to drought (Table 7).

Table 7. MLRA 41-1 Saline Upland Ecological Site Group Variable Drought Sensitivity

CRITERIA	**SALINE UPLAND ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**	
Primary Variables	**Limy Upland**	**Description**
Landform Position	Increases	Landform position, moderately steep slopes, higher potential for erosion and greater exposure to wind and sun make this site more vulnerable to drought.
Production	Increases	Low plant productivity, species diversity, and cover result in increased bare ground and evaporation.
Vegetation Rooting Depth	Decreases	Deep plant roots penetrate deeper into a fractured pan, accessing water deeper in the profile.
Soil Depth	Increases	Ranges from shallow soil to cemented pans.
Salts	Increases	High salt content affects the soil and root structure, and the uptake of water by plants.
Land Use	Increases	Moderately grazed by livestock.
Secondary Variables		
Soil Surface Texture	Decreases	Well drained soils with minimal water loss due to evaporation.
Available Water Capacity	Increases	Low available water capacity due to coarser textured soils.
Fragments	Decreases	Surface and subsurface fragments reduce evaporation and soil temperature and stabilize the site from erosion, thus reducing the effects of drought.
Aspect	n/a	The sites occur on all aspects; aspect has no influence on site vulnerability.
Drought Vulnerability Rating	**high**	

4. Sandy Upland Ecological Site Group (41-1)

The Sandy Upland Ecological Site group includes the Shallow Upland and Sandy Loam Upland ecological sites, both of which occur on fan piedmonts, terraces, and mountain valleys and plains (Table 8). These sites do not receive additional moisture from adjacent sites and are more exposed to weather extremes (e.g. sun and wind). The Shallow Upland ecological sites occur on soils less than 51 cm deep, with slopes ranging from 1-15 percent. The surface fragments will stabilize the site and mitigate the potential for erosion and runoff. When available, moisture will infiltrate through the shallow, gravelly soil into the underlying fractured pan, providing some relief to the deep-rooted shrubs. However, the dominant vegetation exhibits high plant mortality during short-term droughts. Landform position, productivity, soil depth, available water capacity, and land use make this site highly vulnerable to drought. The Sandy Loam Upland site occurs on soils deeper than 152 cm with slopes of less than 10 percent, and is highly productive; however, the dominant vegetation exhibits high mortality during short-term droughts. The landform position, vegetation rooting depth, land use, and available water capacity make this site moderately vulnerable to drought.

Table 8. MLRA 41-1 Sandy Upland Ecological Site Group Variable Index

CRITERIA	**SANDY UPLAND ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**		
Primary Variables	**Shallow Upland**	**Sandy Loam Upland**	**Description**
Landform Position	Increases	Increases	This is a runoff site with high potential for erosion. Greater climatic exposure makes this site more vulnerable to drought.
Production	Increases	Decreases	low plant productivity, species diversity or cover result in increased bare ground and evaporation on some sites; some sites have high production, but exhibit high plant mortality with short-term drought
Vegetation Rooting Depth	Increases	Increases	shallow to moderate rooting depth limits access to water and nutrients; reduced stability
Soil Depth	Increases	Decreases	Shallow soils are more vulnerable to drought due to landform position, have greater potential for erosion, less developed soils, and reduced available water.
Salts	n/a	n/a	Minimal content of salts to influence site vulnerability.
Land Use	Increases	Increases	Light to moderate grazing by livestock.
Secondary Variables			
Soil Surface Texture	Decreases	Decreases	The site has well drained soils with minimal water loss due to evaporation, and coarse soils subject to a hazard of wind erosion in areas with bare ground.
Available Water Capacity	Increases	Decreases	Lower available water capacity due to coarser textured soils in some sites.
Fragments	Decreases	n/a	Surface and subsurface fragments reduce evaporation and soil temperature and stabilize site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	The sites occur on all aspects; aspect has no influence on site vulnerability.
Drought Vulnerability Rating	**high**	**moderate**	

5. Loamy Upland Ecological Site Group (41-1)

The Loamy Upland group includes the Loamy Upland, Clay Loam Upland, and Clayey Upland ecological sites (Table 9). These sites can be found on fan piedmonts, plains, and alluvial fans. The soil depth ranges from moderately deep (51 - 120 cm) to deep (152 cm), and the soil surface texture is highly variable from sandy loam to clay. These sites are located in an upland landform position where they are not sheltered from weather extremes (e.g. sun and wind) and do not receive any additional moisture from adjacent sites.

The shortgrass-dominated state, landform position, and land use may result in a greater vulnerability to drought for the Loamy Upland site. However, the production, soil depth, soil surface texture, and presence of surface fragments mitigate the effects of drought. Furthermore, the surface fragments and LRU precipitation zone allow this site to recover rapidly from drought. The Clay Loam Upland and Clayey Upland sites are more vulnerable to drought because of the landform position, production of vegetation, and specifically the soil texture. The soils are high in clay, exhibiting high shrink-swell characteristics, which results in reduced infiltration and increased evaporation.

Table 9. MLRA 41-1 Loamy Upland Ecological Site Group Variable Index

CRITERIA	**LOAMY UPLAND ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**			
Primary Variables	**Loamy Upland**	**Clay Loam Upland**	**Clayey Upland**	**Description**
Landform Position	Increases	Increases	Increases	Slopes are less than 15 percent, but sites do not receive any additional moisture from adjacent sites and are exposed to extreme weather conditions (e.g. sun and wind).
Production	Decreases	Increases	Increases	Some sites have low plant productivity, species diversity, and cover, which results in increased bare ground and evaporation; sites with greater cover and productivity have greater resistance to drought.
Vegetation Rooting Depth	Increases	Increases	Increases	Shallow to moderate rooting depth limits access to water and nutrients and reduces stability.
Soil Depth	Decreases	Decreases	Decreases	Moderately deep to deep soils have available water deeper in the profile to mitigate the effects of drought.
Salts	n/a	n/a	n/a	Has minimal content of salts to influence site vulnerability.
Land Use	Increases	Decreases	Decreases	Light to moderate grazing by livestock depending upon the site.
Secondary Variables				
Soil Surface Texture	Decreases	Increases	Increases	Sites that have coarse textured soils over an argillic horizon will have good infiltration and minimal moisture loss due to evaporation; heavy clay soils minimize infiltration, increasing runoff and evaporation potential on some sites.
Available Water Capacity	Increases	Decreases	Decreases	Sites with higher clay content typically are less vulnerable to drought due to the higher available water capacity.

Fragments	Decreases	Decreases	n/a	Surface and subsurface fragments reduce evaporation and soil temperature and stabilize the site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	n/a	The sites occur on all aspects; aspect has no influence on site vulnerability.
Drought Vulnerability Rating	**moderate**	**high**	**high**	

6. Hills Ecological Site Group (41-1)

The Hills Ecological Site group includes the Shallow Hills, Limestone Hills, and Volcanic Hills ecological sites, all of which have a high vulnerability to drought (Table 10). These ecological sites occur on hills, ridges, saddles, pediments, and mountains with slopes ranging from 15-65 percent. The Hills sites consist of shallow soils and the landform position creates greater climatic exposure; however, the presence of surface fragments will mitigate some of the potential for erosion as the site stability is increased. Maintaining minimal grazing on these sites due to the slopes will help to reduce the effects of drought, as will sustaining high plant diversity. The herbaceous component of these sites is more vulnerable to short-term drought, and the half-shrubs and shrubs are more vulnerable to a long-term drought. The dominant plant community is vulnerable to drought, and sites with salts may influence available moisture. The landform position, steep slopes, vegetation rooting depths, and shallow soils make these sites highly vulnerable to drought.

Table 10. MLRA 41-1 Hills Ecological Site Group Variable Index

CRITERIA	**HILLS ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**			
Primary Variables	**Shallow Hills**	**Limestone Hills**	**Volcanic Hills**	**Description**
Landform Position	Increases	Increases	Increases	Landform position, steep slopes, higher potential for erosion, and greater climatic exposure make this site more vulnerable to drought.
Production	Decreases	Decreases	Decreases	High plant productivity and species diversity mitigates the effects of drought.
Vegetation Rooting Depth	Increases	Increases	Increases	The dominant plant community consists of shallow to moderate rooting depths that limit access to water and nutrients and reduces stability.
Soil Depth	Increases	Increases	Increases	Shallow soils are more vulnerable to drought due to landform position, greater erosion potential, less developed soils, and reduced available water.
Salts	n/a	Increases	n/a	This site has minimal content of salts to influence site vulnerability.
Land Use	Increases	Decreases	Decreases	This site has minimal to moderate grazing effects due to the slope.
Secondary Variables				
Soil Surface Texture	Decreases	Decreases	Decreases	The site has well drained soils with minimal water loss from evaporation or runoff.
Available Water	Increases	Increases	Increases	Lower available water capacity due to the coarser textured soils.

Capacity				
Fragments	Decreases	Decreases	Decreases	Surface and subsurface fragments reduce evaporation and soil temperature and stabilize the site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	n/a	The site can occur on all aspects; however, vulnerability to drought is increased on south-facing slopes.
Drought Vulnerability Rating	**high**	**high**	**high**	

7. Slopes Ecological Site Group (41-1)

The Slopes Ecological Site Group includes the Loamy and Limy Slopes ecological sites, all of which have moderate vulnerability to drought (Table 11). These ecological sites occur on hills, ridges, and saddles with slopes ranging from 8-45 percent. The steep slopes increase the runoff potential, but the deep, coarse soils and fragments should minimize the effects of water loss and drought on these sites. The Limy Slopes ecological site includes salts; however, the concentration is not high enough to influence the dominant plant community or production. This may be a result of the well-drained deep soils and the amount of precipitation received at this site during normal years.

Table 11. MLRA 41-1 Slopes Ecological Site Group Variable Index

CRITERIA	**SLOPES ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**		
Primary Variables	**Loamy Slopes**	**Limy Slopes**	**Description**
Landform Position	Increases	Increases	The landform position, steep slopes, higher potential for erosion, and greater climatic exposure make this site more vulnerable to drought.
Production	Increases	Increases	Plant production and species diversity is minimal due to the landform position.
Vegetation Rooting Depth	Increases	Increases	The dominant plant community consists of shallow to moderate rooting depth that limits access to water and nutrients; reduced stability.
Soil Depth	Decreases	Decreases	Moderately deep to deep soils have available water deeper in profile mitigate the effects of drought.
Salts	n/a	Increases	The content of salts is none to moderate to influence site vulnerability.
Land Use	Increases	Decreases	Minimal to moderate grazing effects due to the slope.
Secondary Variables			
Soil Surface Texture	Decreases	Decreases	This group has well drained soils with minimal water loss due to evaporation.
Available Water Capacity	Decreases	Increases	The sites with higher clay content typically are less vulnerable to drought due to the higher available water capacity.

Fragments	Decreases	Decreases	Surface and subsurface fragments reduce evaporation and soil temperature and stabilize site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	The site can occur on all aspects; however, vulnerability to drought is increased on south-facing slopes.
Drought Vulnerability Rating	**moderate**	**moderate**	

Chihuahuan Desert Shrub – Land Resource Unit 41-2

For this assessment we developed seven ecological site groups to evaluate the 22 ecological sites within LRU 41-2 (Table 12). Land resource area 41-2 is represented by the Chihuahuan Desert Shrub ecoregion, which has a mixture of shrubs, perennial grasses, and forbs. This LRU consists of approximately 1,329,092 acres, which makes up 19 percent of MLRA 41. Approximately 94 percent of this unit is used as rangeland, and the remaining is used for agriculture/farmland. This desert shrub-grassland receives approximately 8-12 inches (203 to 305 mm of annual precipitation, the majority of which is received during the months of July-September. Much of this LRU is located in the San Simon Valley, with smaller portions in the Gila, Animas, Playas, and San Pedro Valleys of southeastern Arizona and southwestern New Mexico.

Table 12. MLRA 41-2 Ecological Site Drought Vulnerability Classes (based on Reference Community)

Ecological Site Group	MLRA 41-2 Ecological Sites			
Bottomland	🟩 Sandy Wash	🟨 Saline Bottom	🟩 Loamy Swale	🟨 Clayey Swale
Bottomland, Woodland	🟩 Sandy Bottom, Woodland	🟩 Loamy Bottom, Woodland	🟩 Saline Bottom, Woodland	
Saline Upland	🟨 Saline Upland	🟨 Limy Fan	🟥 Gypsum Upland	🟥 Limy Upland
Sandy Upland	🟨 Sandy Upland	🟩 Sandy Loam Upland	🟩 Deep Sandy Loam Upland	
Loamy Upland	🟨 Loamy Upland	🟥 Clayey Upland	🟨 Clay Loam Upland	
Hills	🟥 Shallow Hills/ Granitic Hills	🟥 Basalt Hills		
Slopes	🟨 Limy Slopes	🟨 Clayey Slopes	🟥 Gypsum Breaks/Slopes	

low 🟩 moderate 🟨 high 🟥

1. Bottomland Ecological Site Group (41-2)

The Bottomland Ecological Site group includes the Sandy Wash, Saline Bottom, Loamy Swale, and Clayey Swale ecological sites, which occur on flood plains, alluvial fans, stream terraces, swales, and playas. These sites have deep soils, occur on slopes of less than 5 percent, and receive additional moisture from adjacent sites when available. The Sandy Wash and Loamy Swale sites are highly productive, and consist of well drained soils with surface fragments to mitigate soil temperature and moisture loss via evaporation. The landform position, high productivity, vegetation rooting depth, soil depth, and the surface texture and fragments on the Sandy Wash and Loamy Swale sites help to mitigate the effects of drought on these sites, resulting in a low vulnerability to drought (Table 13). The Saline Bottom and Clayey Swale sites have high clay soils that exhibit shrinking and swelling, resulting in low infiltration and greater potential for moisture loss via evaporation. These Bottomland sites also contain high concentrations of salts that may affect water uptake by plants and the soil and root structures. The landform position and the vegetation rooting and soil depths help to mitigate drought effects; however, the high contents of clay and salt on these sites make them moderately vulnerable to drought (Table 13).

Table 13. MLRA 41-2 Bottomland Ecological Site Group Variable Index

CRITERIA	BOTTOMLAND ECOLOGICAL SITE GROUP – VARIABLE INFLUENCE ON DROUGHT VULNERABILTY				
Primary Variables	**Sandy Wash**	**Saline Bottom**	**Loamy Swale**	**Clayey Swale**	**Description**
Landform Position	Decreases	Decreases	Decreases	Decreases	This site has gentle slopes and receives additional moisture from adjacent areas, and a shallow water table present at some sites mitigates the effects of drought.
Production	Decreases	Increases	Decreases	Increases	High plant production and species diversity mitigate the effects of drought.
Vegetation Rooting Depth	Decreases	Decreases	Decreases	Decreases	Moderate to deep plant roots access water deeper in the profile, mitigating the effects of drought.
Soil Depth	Decreases	Decreases	Decreases	Decreases	The site has deep soils with available water deeper in the profile, which helps to mitigate the effects of drought.
Salts	n/a	Increases	n/a	Increases	A high content of salts and sodium affect the soil and root structure, and the uptake of water by plants.
Land Use	Increases	Increases	Increases	Decreases	Light, moderate, or heavy grazing may influence how a site responds to drought.
Secondary Variables					
Soil Surface Texture	Decreases	Increases	Decreases	Increases	Has well drained soils with minimal water loss due to evaporation and coarse soils subject to wind erosion; the surface texture is highly variable within the sites due to landform position.
Available Water Capacity	Increases	Decreases	Decreases	Decreases	Has greater available water capacity in finer textured soils, however, it is highly variable within sites due to landform position. The available water-holding capacity in coarse soils lowers resistance to drought.
Fragments	Decreases	n/a	Decreases	n/a	Surface and subsurface fragments reduce evaporation and soil temperature, and stabilize the site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	n/a	n/a	Sites occur on all aspects; aspect has no influence on site vulnerability.
Drought Vulnerability Rating	**low**	**moderate**	**low**	**moderate**	

2. Bottomland, Woodland Ecological Site Group (41-2)

The Bottomland, Woodland Ecological Site Group includes the Sandy Bottom, Woodland; Loamy Bottom, Woodland; and Saline Bottom, Woodland ecological sites, all of which have low vulnerability to drought (Table 14). These ecological sites occur on flood plains, stream terraces, and alluvial fans, and are gently sloping with 0-3 percent slopes. They are forestland ecological sites dominated by deep-rooted trees that have access to a shallow water table. Because they occur on the stream terraces or drainages along the Gila and San Pedro Rivers, they often receive additional moisture from over-bank flooding or from valleyside drainages. The Saline Bottom, Woodland site includes some salts; however, the salt content is minimal and will be offset by the deep roots and soils, water table, landform position, and high production.

Table 14. MLRA 41-2 Bottomland, Woodland Ecological Site Group Variable Index

CRITERIA	**BOTTOMLAND, WOODLAND ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**			
Primary Variables	**Sandy Bottom, Woodland**	**Loamy Bottom, Woodland**	**Saline Bottom, Woodland**	**Description**
Landform Position	Decreases	Decreases	Decreases	This site has gentle slopes. Some sites receive additional moisture from adjacent areas, and the shallow water table present at some sites mitigates the effects of drought.
Production	Decreases	Decreases	Decreases	High plant production and species diversity mitigate the effects of drought.
Vegetation Rooting Depth	Decreases	Decreases	Decreases	Deep plant roots access water deeper in the profile to mitigate the effects of drought.
Soil Depth	Decreases	Decreases	Decreases	Deep soils with available water deeper in the profile mitigates the effects of drought.
Salts	n/a	n/a	Increases	High salts affect the soil and root structure, and the uptake of water by plants.
Land Use	Increases	Decreases	Increases	Light, moderate, or heavy grazing may influence how a site responds to drought.
Secondary Variables				
Soil Surface Texture	Decreases	Decreases	Decreases	The sites have well drained soils with minimal water loss due to evaporation; coarse soils subject to wind erosion; surface texture is highly variable within sites due to landform position.
Available Water Capacity	Increases	Decreases	Decreases	Finer textured soils have greater available water capacity; however, it is highly variable within sites due to landform position. A higher available water-holding capacity in coarse soils lowers resistance to drought.
Fragments	Decreases	n/a	n/a	Surface and subsurface fragments reduce evaporation and soil temperature, and stabilize the site from erosion, thus reducing effects of drought

Aspect	n/a	n/a	n/a	The sites occur on all aspects; aspect has no influence on site vulnerability.
Drought Vulnerability Rating	**low**	**low**	**low**	

3. Saline Upland Ecological Site Group (41-2)

The Saline Upland Ecological Site Group includes the Saline Upland, Limy Fan, Limy Upland, and Gypsum Upland ecological sites. These sites occur on alluvial flats, stream terraces, fan piedmont, fan remnants, and ridges. Most of these sites occur on slopes of less than 5 percent. The Limy Upland sites occur on fan piedmonts, fan remnants, and ridges with slopes of up to 15 percent. The ecological sites within this group have relatively low productivity and contain high amounts of calcium carbonate, sodium, and/or gypsum. The Saline Upland and Limy Fan sites consist of well drained deep soils with high available water capacity and salt-tolerant vegetation. However, these sites are moderately vulnerable to drought due to the landform position, salt content, low productivity, and increased areas of bare ground. The Gypsum Upland site includes moderately deep to deep (51-152 cm) soils that are highly erosional due to large amounts of gypsum and low plant production. The Limy Upland sites have shallow (51 cm) soils above a lime and/or silica cemented pan with low productivity and reduced infiltration. Both the Gypsum Upland and Limy Upland sites are highly vulnerable to drought due to landform position, the high content of salts, low productivity, and soil depth (Table 15).

Table 15. MLRA 41-2 Saline Upland Ecological Site Group Variable Index

CRITERIA	**SALINE UPLAND ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**				
Primary Variables	**Saline Upland**	**Limy Fan**	**Limy Upland**	**Gypsum Upland**	**Description**
Landform Position	Increases	Increases	Increases	Increases	The slopes are less than 15 percent, but these sites do not receive any additional moisture from adjacent sites and are exposed to extreme weather conditions (e.g. sun and wind).
Production	Increases	Increases	Increases	Increases	Low plant productivity and species diversity may result in increased bare ground, increasing the potential for erosion and runoff and reducing site resistance to drought.
Vegetation Rooting Depth	Decreases	Decreases	Increases	Decreases	The dominant vegetation consists of short-, mid-, or tall warm-season grasses depending upon the site.
Soil Depth	Decreases	Decreases	Increases	Decreases	Shallow soils are more vulnerable to drought due to landform position, have a greater potential of erosion, less developed soils, and reduced available water.
Salts	Increases	Increases	Increases	Increases	High salts and sodium affect the soil and root structure, and the uptake of water by plants.
Land Use	Decreases	Increases	Increases	Decreases	None to moderate to extensively grazed.

Secondary Variables					
Soil Surface Texture	Increases	Decreases	Decreases	Increases	The sites have well drained soils with minimal water loss due to evaporation, and coarse soils subject to wind erosion; greater potential for evaporation in finer textured soils.
Available Water Capacity	Decreases	Increases	Increases	Decreases	Sites with higher clay content typically are less vulnerable to drought due to a higher available water capacity.
Fragments	n/a	Decreases	Decreases	n/a	Surface and subsurface fragments reduce evaporation and soil temperature, and stabilize the site from erosion, thus reducing effects of drought.
Aspect	n/a	n/a	n/a	n/a	These sites occur on all aspects; aspect has no influence on site vulnerability.
Drought Vulnerability Rating	**moderate**	**moderate**	**high**	**high**	

4. The Sandy Upland Ecological Site Group (41-2)

The Sandy Upland Ecological Site group includes the Sandy, Deep Sandy Loam, and Sandy Loam Upland ecological sites, which occur on plains, fan piedmonts, dunes, valleys, flood plains, and terraces (Table 16). These sites do not receive additional moisture from adjacent sites and are more exposed to weather extremes (e.g. sun and wind). The Sandy Loam and Deep Sandy Loam Upland ecological sites occur on soils deeper than 102 cm with slopes typically less than 15 percent and low plant production. Both of these sites have surface fragments that will stabilize the site and mitigate the potential of erosion and runoff. Furthermore, the well-drained soils and surface fragments will reduce moisture loss via evaporation. These sites have a low vulnerability to drought due to the deep soils, landform position, surface fragments, and greater available water-holding capacity.

The Sandy Upland site occurs on soils deeper than 152 cm with slopes of less than 10 percent. Plant production is typically low, and the dominant vegetation exhibits high mortality during short-term droughts. This site has a high hazard of wind erosion due to decreased plant production, increased bare ground, and sandy soils. The landform position, high percentage of bare ground, low plant production, and available water capacity make this site moderately vulnerable to drought.

Table 16. MLRA 41-2 Sandy Upland Ecological Site Group Variable Index

CRITERIA	**SANDY UPLAND ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**			
Primary Variables	**Sandy Upland**	**Deep Sandy Loam Upland**	**Sandy Loam Upland**	**Description**
Landform Position	Increases	Decreases	Increases	These runoff sites have a high potential of erosion, and greater climatic exposure (e.g. wind and sun) make this site more vulnerable to drought.
Production	Increases	Increases	Increases	Low plant productivity and species diversity may result in increased bare ground, thus increasing the potential of erosion and reducing site resistance to drought.

Vegetation Rooting Depth	Decreases	Decreases	Decreases	Deep plant roots access water deeper in the profile.
Soil Depth	Decreases	Decreases	Decreases	The sites have deep soils with high plant available water deeper in profile.
Salts	n/a	n/a	n/a	The sites have no to minimal salt content to influence site vulnerability.
Land Use	Increases	Increases	Increases	low to moderate grazing due to accessibility
Secondary Variables				
Soil Surface Texture	Increases	Decreases	Decreases	well drained soils with minimal water loss due to evaporation; coarse soils subject to wind erosion in areas with bare ground
Available Water Capacity	Increases	Decreases	Decreases	Finer textured soils have greater available water capacity; limited available water-holding capacity in coarse soils lowers resistance to drought.
Fragments	n/a	Decreases	Decreases	Surface and subsurface fragments reduce evaporation and soil temperature and stabilize the sites from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	n/a	The sites occur on all aspects; aspect has no influence on site vulnerability.
Drought Vulnerability Rating	**moderate**	**low**	**low**	

5. The Loamy Upland Ecological Site Group

The Loamy Upland Ecological Site Group includes the Loamy Upland, Clay Loam Upland, and Clayey Upland ecological sites (Table 17). These sites occur on ridges, fan piedmonts, and mesas on slopes ranging from 1-15 percent. The soil is moderately deep, and the soil texture varies from sandy loam and clay loam to loam. These sites have surface fragments which will help to mitigate evaporative moisture loss and reduce soil temperature. Although the available water capacity increases as clay content increases with depth, the plant productivity is relatively low and dominated by sod-forming short-grasses that limit infiltration. The presence of salts, high clay content, low productivity, shallow rooting depth, and landform position make these sites moderately vulnerable to drought. The Clayey Upland ecological site consists of soils that have high shrink-swell properties, making it highly vulnerable to drought.

Table 17. MLRA 41-2 Loamy Upland Ecological Site Group Variable Index

CRITERIA	**LOAMY UPLAND ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**			
Primary Variables	**Loamy Upland**	**Clay Loam Upland**	**Clayey Upland**	**Description**
Landform Position	Increases	Increases	Increases	The slopes are less than 15 percent, but these sites do not receive any additional moisture from adjacent sites and are exposed to extreme weather conditions (e.g. sun and wind).

Production	Increases	Increases	Increases	Low plant productivity and species diversity may result in increased bare ground, which increases the potential for erosion and runoff and reduces site resistance to drought.
Vegetation Rooting Depth	Increases	Increases	Increases	The dominant vegetation consists of mid-season short-grasses; some of the dominant vegetation is sod-forming.
Soil Depth	Decreases	Decreases	Decreases	Shallow soils are more vulnerable to drought due to landform position, greater potential for erosion, less developed soils, and reduced available water.
Salts	Increases	n/a	Increases	A high content of salts may affect the soil and root structure, and the uptake of water by plants.
Land Use	Decreases	Decreases	Decreases	Minimally to moderately grazed by livestock.
Secondary Variables				
Soil Surface Texture	Decreases	Decreases	Increases	The sites have well drained soils with minimal water loss due to evaporation; coarse soils subject to wind erosion in areas with bare ground; and some sites have finer textured soils at surface, resulting in greater evaporation.
Available Water Capacity	Decreases	Decreases	Decreases	Sites with higher clay content are less vulnerable to drought due to a higher available water capacity.
Fragments	Decreases	Decreases	n/a	Surface and subsurface fragments reduce evaporation and soil temperature and stabilize site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	n/a	The sites occur on all aspects; aspect has no influence on site vulnerability.
Drought Vulnerability Rating	**moderate**	**moderate**	**high**	

6. Hills Ecological Site Group (41-2)

The Hills Ecological Site Group includes the Shallow and Basalt Hills ecological sites, both of which are highly vulnerable to drought (Table 18). These sites occur on hills, ridges, mesas, and escarpments with slopes of up to 65 percent. The very shallow to shallow (51 cm) soils, low productivity, and steep slopes would limit infiltration and result in greater runoff and potential for erosion. Although the presence of surface and subsurface fragments would help to stabilize the site and reduce soil temperatures, these sites are highly vulnerable to drought due to landform position, slope, low productivity, salt content, shallow soils and rooting depth, and low available water capacity.

Table 18. MLRA 41-2 Hills Ecological Site Group Variable Index

CRITERIA	**HILLS ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**		
Primary Variables	**Shallow Hills**	**Basalt Hills**	**Description**
Landform Position	Increases	Increases	Landform position, steep slopes, higher potential of erosion, and greater climatic exposure (e.g. sun and wind) make this site more vulnerable to drought.

Production	Increases	Increases	Low plant productivity and species diversity may result in increased bare ground, increasing the potential of erosion and runoff, and reducing resistance to drought.
Vegetation Rooting Depth	Increases	Increases	The dominant plant community consists of a shallow to moderate rooting depth that limits access to water and nutrients and reduces soil stability.
Soil Depth	Increases	Increases	Shallow soils are more vulnerable to drought due to landform position, greater erosion potential, less developed soils, and reduced available water.
Salts	n/a	Increases	The presence of salts affect the soil and root structure, and the uptake of water by plants.
Land Use	Decreases	Decreases	Minimal to moderate grazing effects due to slope.
Secondary Variables			
Soil Surface Texture	Decreases	Decreases	The sites have well drained soils with minimal water loss from evaporation or runoff.
Available Water Capacity	Increases	Increases	The sites have a lower available water capacity due to coarser textured soils.
Fragments	Decreases	Decreases	Surface and subsurface fragments reduce evaporation and soil temperature and stabilize site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	This site can occur on all aspects; however, vulnerability to drought is increased on south-facing slopes.
Drought Vulnerability Rating	**high**	**high**	

7. Slopes Ecological Site Group (41-2)

The Slopes Ecological Site Group includes the Clayey, Gypsum, and Limy Slopes ecological sites that occur on hills, fan remnants, and ridges with slopes up to 55 percent. The steep slopes increase runoff potential, but the deep, coarse soils and surface fragments should minimize the effects of water loss and drought on these sites. Areas of bare ground are common on the Limy Slopes site, and the high content of calcium carbonate in the soils may influence available water, making this site less resistant to drought.

The Gypsum Slopes ecological site includes gypsum, which makes this site highly erosional and highly vulnerable to drought. The dominant vegetation on the Limy and Gypsum Slopes sites include creosote bush, which inhibits growth of nearby vegetation due to the ability of creosote bushes to secure more water, which results in more interspaces and bare ground between plants. The high clay content and sod-forming vegetation will limit infiltration and increase evaporation on the Clayey Slopes site. The landform position, low productivity, steep slopes, and high content of salt make these sites moderately to highly vulnerable to drought (Table 19).

Table 19. MLRA 41-2 Slopes Ecological Site Group Variable Index

CRITERIA	**SLOPES ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**

Primary Variables	**Clayey Slopes**	**Gypsum Slopes**	**Limy Slopes**	**Description**
Landform Position	Increases	Increases	Increases	Landform position, steep slopes, higher potential for erosion, and greater climatic exposure make this site more vulnerable to drought.
Production	Increases	Increases	Increases	Low plant productivity and species diversity may result in increased bare ground, increasing the potential for erosion and runoff, and reducing site resistance to drought.
Vegetation Rooting Depth	Increases	Decreases	Decreases	Depending upon the site, the rooting depth ranges from moderate to deep, and is either sod-forming or limits access to water and nutrients to adjacent plants.
Soil Depth	Decreases	Decreases	Decreases	Moderately deep to deep soils have available water deeper in the soil profile to mitigate the effects of drought.
Salts	Increases	Increases	Increases	High content of salts affect the soil and root structure, and the uptake of water by plants; the presence of gypsum results in a high potential for erosion.
Land Use	Decreases	Decreases	Decreases	Minimal to moderate grazing effects due to the slope.
Secondary Variables				
Soil Surface Texture	Decreases	Decreases	Decreases	This site has well drained soils with minimal water loss due to evaporation.
Available Water Capacity	Decreases	Decreases	Increases	Sites with higher clay content typically are less vulnerable to drought due to the higher available water capacity.
Fragments	Decreases	n/a	Decreases	Surface and subsurface fragments reduce evaporation and soil temperature, and stabilize the site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	n/a	This site can occur on all aspects, however, vulnerability to drought is increased on south-facing slopes.
Drought Vulnerability Rating	**moderate**	**high**	**moderate**	

Southern Arizona Semidesert Grassland – Land Resource Unit 41-3

For this assessment we developed seven ecological site groups to evaluate the 26 ecological sites within LRU 41-3 (Table 20). This LRU consists of approximately 4,545,071 acres, which makes up 64 percent of MLRA 41. Approximately 89 percent is used as rangeland and 4 percent for agricultural land and forestland, with the remaining as barren or urban land. Land resource area 41-3 is a Semidesert Grassland ecoregion dominated by gramas, tobosagrass, big sacaton, cane beardgrass, curly-mesquite, burroweed, snakeweed, and mesquite. This LRU receives 305-406 mm of annual precipitation in the eastern part, and higher amounts in the higher elevations to the west. About 65 percent of the moisture is received during July-September, usually as brief, intense thunderstorms.

Table 20. MLRA 41-3 Ecological Site Drought Vulnerability Classes (based on Reference Community)

Ecological Site Group	MLRA 41-3 Ecological Sites				
Bottomland	🟨 Saline Bottom	🟩 Loamy Bottom	🟩 Sandy Wash	🟩 Loamy Swale	🟨 Clayey Swale
Bottomland, Woodland	🟩 Sandy Bottom, Woodland	🟩 Loamy Bottom, Woodland			
Saline Upland	🟨 Sandy Upland, Saline	🟨 Saline Upland	🟥 Limy Upland	🟨 Limy Upland, Deep	
Sandy Upland	🟥 Shallow Upland	🟩 Sandy Upland	🟩 Sandy Loam Upland	🟩 Sandy Loam Upland, Deep	
Loamy Upland	🟨 Loamy Upland	🟨 Clay Loam Upland	🟨 Clayey Upland	🟨 Limy Fan	
Hills	🟥 Limestone Hills	🟥 Shallow Hills	🟥 Volcanic Hills, Loamy	🟥 Volcanic Hills, Clayey	
Slopes	🟨 Loamy Slopes	🟨 Limy Slopes	🟨 Clayey Slopes		

low 🟩 moderate 🟨 high 🟥

1. Bottomland Ecological Site Group (41-3)

The Bottomland Ecological Site Group includes the Saline Bottom, Loamy Bottom, Sandy Wash, Loamy Swale, and Clayey Swale ecological sites. These sites occur on alluvial fans, flood plains, stream terraces, playas, and swales. All the sites have deep soils (102 – 152 cm), except the Saline Bottom ES, which has soils ranging in depth from 51 to 152 cm. These sites occur on less than 3 percent slopes and receive additional moisture from adjacent sites when available. The Loamy Bottom, Sandy Wash, and Loamy Swale sites are highly productive and consist of well drained soils with textures ranging from gravelly sand to silty clay loam. The landform position, high productivity, and soil texture and depth help to mitigate drought on these sites, resulting in a low drought vulnerability rating (Table 21). The Saline Bottom and Loamy Bottom sites have a shallow water table to help mitigate drought; however, the Saline Bottom ES consists of high clay content and salt/sodic conditions limiting available water to plants.

The Saline Bottom and Clayey Swale sites have soils with high content of clay that exhibit shrinking and swelling, resulting in low infiltration and greater potential for moisture loss via evaporation. These sites also contain high concentrations of salts that may affect plant water uptake and soil and root structure. The landform position, vegetation rooting, and high available water-holding capacity help to mitigate drought effects; however, the high content of clay and salt on these sites make them moderately vulnerable to drought (Table 21).

Table 21. MLRA 41-3 Bottomland Ecological Site Group Variable Index

CRITERIA	**BOTTOMLAND ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**					
Primary Variables	**Loamy Bottom**	**Loamy Swale**	**Clayey Swale**	**Saline Bottom**	**Sandy Wash**	**Description**
Landform Position	Decreases	Decreases	Decreases	Decreases	Decreases	On gentle slopes, some sites receive additional moisture from adjacent areas, and a shallow water table present at some sites mitigates the effects of drought.
Production	Decreases	Decreases	Decreases	Decreases	Decreases	High plant production and species diversity mitigate the effects of drought.

Vegetation Rooting Depth	Increases	Increases	Increases	Decreases	Decreases	Dominant vegetation consists of short-, mid-, or tall warm-season grasses depending upon the site; deeper plant roots access water deeper in the profile, mitigating the effects of drought.
Soil Depth	Decreases	Decreases	Decreases	Increases	Decreases	Highly variable due to landform position; typically, deep soils with available water deeper in the profile mitigate the effects of drought.
Salts	Decreases	Decreases	Decreases	Increases	Decreases	High content of salts and sodium affect the soil and root structure, and the uptake of water by plants.
Land Use	Increases	Increases	Increases	Increases	Increases	Light, moderate, or heavy grazing may influence how a site responds to drought.
Secondary Variables						
Soil Surface Texture	Decreases	Decreases	Increases	Decreases	Decreases	Well drained soils with minimal water loss due to evaporation; coarse soils subject to wind erosion; surface texture is highly variable within sites due to landform position; reduced infiltration and increased evaporation on finer textured soils.
Available Water Capacity	Decreases	Decreases	Decreases	Decreases	Increases	Finer textured soils have greater available water capacity, however, it is highly variable within sites due to landform position. Available water-holding capacity in coarse soils lowers resistance to drought.
Fragments	n/a	n/a	n/a	n/a	Decreases	Surface and subsurface fragments reduce evaporation and soil temperature, and stabilize the site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	n/a	n/a	n/a	The sites occur on all aspects; aspect has no influence on site vulnerability.
Drought Vulnerability Rating	**low**	**low**	**moderate**	**moderate**	**low**	

2. The Bottomland, Woodland Ecological Site Group (41-3)

The Bottomland, Woodland Ecological Site Group includes the Sandy Bottom, Woodland and Loamy Bottom, Woodland ecological sites, both of which have a low vulnerability to drought (Table 22). These ecological sites occur on flood plains and stream terraces and channels with slopes that are less than 3 percent. They are forestland ecological sites dominated by deep-rooted trees that have access to a shallow water table. These sites receive additional moisture from adjacent sites, have deep, well-drained soils, and are highly productive.

Table 22. MLRA 41-3 Bottomland, Woodland Ecological Site Group Variable Index

CRITERIA	**BOTTOMLAND, WOODLAND ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**		
Primary Variables	**Sandy Bottom, Woodland**	**Loamy Bottom, Woodland**	**Description**
Landform Position	Decreases	Decreases	On gentle slopes, some sites receive additional moisture from adjacent areas, and the presence of a shallow water table mitigates the effects of drought.
Production	Decreases	Decreases	High plant production and species diversity mitigate the effects of drought.
Vegetation Rooting Depth	Decreases	Decreases	Deep plant roots access water deeper in profile mitigate the effects of drought.
Soil Depth	Decreases	Decreases	Deep soils with plant available water deeper in profile mitigate drought effects
Salts	n/a	n/a	Salts have no to minimal influence on these sites.
Land Use	Increases	Increases	Light, moderate, or heavy grazing may influence how a site responds to drought.
Secondary Variables			
Soil Surface Texture	Decreases	Decreases	well drained soils with minimal water loss due to evaporation; coarse soils subject to wind erosion; surface texture is highly variable within sites due to landform position
Available Water Capacity	Increases	Decreases	Finer textured soils have greater available water capacity , however, it is highly variable within sites due to landform position. Limited available water-holding capacity in coarse soils lowers resistance to drought.
Fragments	n/a	n/a	Fragments have no influence on site vulnerability.
Aspect	n/a	n/a	The sites occur on all aspects; aspect has no influence on site vulnerability.
Drought Vulnerability Rating	**low**	**low**	

3. The Saline Upland Ecological Site Group (41-3)

The Saline Upland Ecological Site Group includes the Sandy Upland, Saline, and the Saline Upland, Limy Upland, and Limy Upland, Deep ecological site groups. These sites occur on pediments, alluvial flats, stream terraces, and fan piedmonts with highly variable slopes. The ecological sites within this group have relatively low productivity and contain high amounts of calcium carbonate and/or sodium. The Saline Upland, the Limy Upland, Deep, and the Sandy Upland, Saline sites consist of well drained soils ranging from 102-152 cm deep. Due to the landform position, high content of salts and sodium, low productivity, and vegetation rooting depth these sites are moderately vulnerable to drought (Table 23). The Limy Upland site has shallow soils above a lime cemented plan, low productivity, reduced infiltration, and steep slopes, which make this site highly vulnerable to drought. Although the dominant vegetation is salt-tolerant, the high content of sodium will affect available water and soil structure.

Table 23. MLRA 41-3 Saline Upland Ecological Site Group Variable Index

CRITERIA	**SALINE UPLAND ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**				
Primary Variables	**Sandy Upland, Saline**	**Saline Upland**	**Limy Upland**	**Limy Upland, Deep**	**Description**
Landform Position	Decreases	Decreases	Increases	Increases	Some sites do not receive any additional moisture from adjacent sites and are exposed to extreme weather conditions (e.g. sun and wind).
Production	Increases	Increases	Increases	Increases	Low plant productivity and species diversity may result in increased bare ground, increasing erosion and runoff potential, and reduced site resistance to drought.
Vegetation Rooting Depth	Decreases	Decreases	Increases	Decreases	The dominant vegetation consists of short-, mid-, or tall warm-season grasses depending upon site; deeper plant roots access water deeper in profile, mitigating the effects of drought.
Soil Depth	Decreases	Decreases	Increases	Decreases	Shallow soils are more vulnerable to drought due to landform position, greater erosion potential, less developed soils, and reduced available water.
Salts	Increases	Increases	Increases	Increases	High content of salts and sodium affect the soil and root structure, and the uptake of water by plants.
Land Use	Decreases	Decreases	Decreases	Decreases	Light, moderate, or heavy grazing may influence how a site responds to drought.
Secondary Variables					
Soil Surface Texture	Decreases	Decreases	Decreases	Decreases	Well drained soils with minimal water loss due to evaporation; coarse soils subject to wind erosion; greater potential for evaporation in finer textured soils.
Available Water Capacity	Increases	Decreases	Increases	Increases	Sites with higher clay content typically are less vulnerable to drought due to higher available water capacity.
Fragments	n/a	n/a	Decreases	Decreases	Surface and subsurface fragments reduce evaporation and soil temperature, and stabilize the site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	n/a	n/a	The sites occur on all aspects; aspect has no influence on site vulnerability.

Drought Vulnerability Rating	**moderate**	**moderate**	**high**	**moderate**	

4. The Sandy Upland Ecological Site Group (41-3)

The Sandy Upland Ecological Site Group includes the Shallow Upland, Sandy Upland, Sandy Loam Upland, and Sandy Loam Upland, Deep ecological sites. These sites occur on pediments, mountain valleys, stream terraces, sand sheets, and plains. Most sites have deep, well drained soils with slopes of less than 8 percent. The Sandy Upland, Sandy Loam Upland, and Sandy Loam Upland, Deep sites are less vulnerable to drought due to the low slopes, deep and well drained soils, and the vegetation rooting depth (Table 24). On some sites, the coarse surface texture and surface fragments will minimize evaporation rates; however, there is high potential for wind erosion.

The Shallow Upland site has well drained soils that are very shallow to shallow (less than 51 cm) with surface and subsurface fragments and slopes of up to 15 percent. Due to the landform position, shallow soils, shallow rooting depth, possible barren areas, and low available water-holding capacity and productivity, this site is highly vulnerable to drought (Table 24).

Table 24. MLRA 41-3 Sandy Upland Ecological Group Variable Index

CRITERIA	**SANDY UPLAND ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**				
Primary Variables	**Shallow Upland**	**Sandy Upland**	**Sandy Loam Upland**	**Sandy Loam Upland, Deep**	**Description**
Landform Position	Increases	Decreases	Increases	Decreases	The slopes are less than 15 percent, but sites do not receive any additional moisture from adjacent sites and are exposed to extreme weather conditions (e.g. sun and wind).
Production	Increases	Increases	Decreases	Decreases	The dominant vegetation consists of short-, mid-, or tall warm-season grasses and half-shrubs depending upon the site; deeper plant roots access water deeper in the profile, mitigating the effects of drought.
Vegetation Rooting Depth	Increases	Decreases	Decreases	Decreases	The dominant vegetation consists of short-, mid-, or tall warm-season grasses depending upon the site; deeper plant roots access water deeper in profile, mitigating the effects of drought.
Soil Depth	Increases	Decreases	Decreases	Decreases	Shallow soils are more vulnerable to drought due to landform position, greater potential for erosion, less developed soils, and reduced available water. l
Salts	n/a	n/a	n/a	n/a	The content of salt is none to minimal to influence site vulnerability.

Land Use	Increases	Decreases	Increases	Increases	Light, moderate, or heavy grazing may influence how a site responds to drought.
Secondary Variables					
Soil Surface Texture	Decreases	Decreases	Decreases	Decreases	Well drained soils with minimal water loss due to evaporation; coarse soils are subject to the hazard of wind erosion in areas with bare ground.
Available Water Capacity	Increases	Increases	Decreases	Increases	The site has greater available water capacity in finer textured soils; limited available water-holding capacity in coarse soils lower resistance to drought.
Fragments	Decreases	n/a	Decreases	Decreases	Surface and subsurface fragments reduce evaporation, soil temperature and stabilize site from erosion, thus reducing effects of drought.
Aspect	n/a	n/o	n/a	n/a	The sites occur on all aspects; aspect has no influence on site vulnerability.
Drought Vulnerability Rating	**High**	**low**	**low**	**low**	

5. The Loamy Upland Ecological Site Group (41-3)

The Loamy Upland group includes the Loamy Upland, Clay Loam Upland, Clayey Upland, and Limy Fan ecological sites (Table 25). All of the ecological sites within this group have a moderate drought vulnerability rating. These sites can be found on fan piedmonts, plains, alluvial fans, stream terraces, basin floors, and plains with slopes of less than 15 percent. The soils are deep (102-152 cm), and the soil surface texture is highly variable from fine sandy loam to clay loam. These sites are located in an upland landform position where they are not sheltered from weather extremes (e.g. sun and wind), and do not receive any additional moisture from adjacent sites.

The shortgrass-dominated plant community, landform position, and land use may result in an increased vulnerability to drought in the Loamy Upland site. However, the production, soil depth, soil surface texture, and surface fragments mitigate the effects of drought. Furthermore, the surface fragments and LRU precipitation zone allow this site to recover rapidly from drought. The Clay Loam Upland and Clayey Upland sites are more vulnerable to drought because of the landform position, production, and specifically the soil texture. These sites have soils that are high in clay, exhibiting high shrink-swell characteristics, which results in reduced infiltration and increased evaporation. The Limy Fan site contains high amounts of salts that may affect water uptake; however, the dominant vegetation is salt-tolerant and, with good plant production, this site may resist short-term drought.

Table 25. MLRA 41-3 Loamy Upland Ecological Site Group Variable Index

CRITERIA	**LOAMY UPLAND ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**				
Primary Variables	**Loamy Upland**	**Clay Loam Upland**	**Clayey Upland**	**Limy Fan**	**Description**
Landform Position	Increases	Increases	Increases	Increases	The slopes are less than 15 percent, but sites do not receive any additional moisture from adjacent sites and are exposed to

					extreme weather conditions (e.g. sun and wind).
Production	Decreases	Increases	Decreases	Decreases	Low plant productivity and species diversity may result in increased bare ground, increasing the potential of erosion and reducing site resistance to drought; high plant productivity and species diversity can mitigate the effects of drought.
Vegetation Rooting Depth	Decreases	Decreases	Decreases	Decreases	The dominant vegetation consists of -mid-season shortgrasses; some of the dominant vegetation is sod–forming, which can reduce infiltration.
Soil Depth	Decreases	Decreases	Decreases	Decreases	Deep soils with available water deeper in the profile mitigate the effects of drought.
Salts	n/a	n/a	n/a	Increases	A high content of salts may affect the soil and root structures, and the uptake of water by plants.
Land Use	Increases	Increases	Increases	Increases	Light, moderate, or heavy grazing may influence how a site responds to drought.
Secondary Variables					
Soil Surface Texture	Decreases	Decreases	Increases	Decreases	These sites have well drained soils with minimal water loss due to evaporation; coarse soils subject to wind erosion in areas with bare ground; some sites have finer textured soils at the surface, resulting in greater evaporation.
Available Water Capacity	Decreases	Decreases	Decreases	Increases	Sites with higher clay content typically are less vulnerable to drought due to the higher available water capacity.
Fragments	Decreases	Decreases	n/a	Decreases	Surface and subsurface fragments reduce evaporation and soil temperature, and stabilize the site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	n/a	n/a	The sites occur on all aspects; aspect has no influence on site vulnerability.
Drought Vulnerability Rating	**moderate**	**moderate**	**moderate**	**moderate**	

6. The Hills Ecological Site Group (41-3)

The Hills Ecological Site group includes the Limestone Hills, Shallow Hills, Volcanic Hills, Loamy, and Volcanic Hills, Clayey ecological sites, all of which are highly vulnerable to drought (Table 26). These ecological sites occur on hills, ridges, mountain slopes, and mesas that range from 8-70 percent slopes. The sites consist of shallow soils and the landform position creates greater climatic exposure; however, the presence of surface fragments will mitigate some erosion potential as site stability is increased. Minimal grazing on these sites due to slope, along with high plant diversity, will help to reduce the effects of drought. The herbaceous component of these sites is more vulnerable to short-term drought, whereas the shrubs and succulents are more vulnerable to a long-term drought. The dominant plant community is vulnerable to drought, and sites with salts may influence moisture available to plants. The landform position, steep slopes, vegetation rooting depth, and shallow soils make these ecological sites highly vulnerable to drought.

Table 26. MLRA 41-3 Hills Ecological Site Group Variable Index

CRITERIA	**HILLS ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**				
Primary Variables	**Limestone Hills**	**Shallow Hills**	**Volcanic Hills, Loamy**	**Volcanic Hills, Clayey**	**Description**
Landform Position	Increases	Increases	Increases	Increases	Landform position, steep slopes, higher erosion potential and greater climatic exposure make this site more vulnerable to drought.
Production	Increases	Increases	Increases	Increases	Low plant productivity and species diversity may result in increased bare ground and potentials for erosion and runoff, and reducing site resistance to drought.
Vegetation Rooting Depth	Decreases	Decreases	Decreases	Decreases	The dominant plant community consists of plants with shallow to moderate rooting depths that limit access to water and nutrients and reduces soil stability.
Soil Depth	Increases	Increases	Increases	Increases	Shallow soils are more vulnerable to drought due to landform position, greater erosion potential, less developed soils, and reduced available water.
Salts	Increases	n/a	n/a	n/a	The presence of salts affects the soil and root structure, and the uptake of water by plants
Land Use	Decreases	Decreases	Decreases	Decreases	Minimal to moderate grazing effects due to slope.
Secondary Variables					
Soil Surface Texture	Decreases	Decreases	Decreases	Decreases	The sites have well drained soils with minimal water loss from evaporation or runoff.
Available Water Capacity	Decreases	Decreases	Decreases	Decreases	Sites with higher clay content typically are less vulnerable to drought due to a higher available water capacity.
Fragments	Decreases	Decreases	Decreases	Decreases	Surface and subsurface fragments reduce evaporation and soil temperature, and stabilize the site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	n/a	n/a	The site can occur on all aspects; however, vulnerability to drought is increased on south-facing slopes.
Drought Vulnerability Rating	**high**	**high**	**high**	**high**	

7. The Slopes Ecological Site Group (41-3)

The Slopes Ecological Site Group includes the Loamy, Limy and Clayey Slopes ecological sites that occur on hills, ballenas, and ridges with slopes of up to 45 percent. The steep slopes increase runoff potential, but the moderately deep (51-102 cm), coarse soils and surface fragments should minimize the effects of water loss and drought on these sites. Plant production on the Limy Slopes site is relatively high, and therefore the influence of calcium carbonate on available water appears to be minimal. The high clay content and sod-forming vegetation will limit infiltration and increase evaporation on the Clayey Slopes site. The landform position, steep slopes, and vegetation rooting depth make these sites moderately vulnerable to drought (Table 27).

Table 27. MLRA 41-3 Slopes Ecological Site Group Variable Index

CRITERIA	**SLOPES ECOLOGICAL SITE GROUP - VARIABLE INFLUENCE ON DROUGHT VULNERABILTY**			
Primary Variables	**Loamy Slopes**	**Limy Slopes**	**Clayey Slopes**	**Description**
Landform Position	Increases	Increases	Increases	The landform position, steep slopes, higher potential for erosion, and greater climatic exposure make this site more vulnerable to drought.
Production	Decreases	Decreases	Decreases	High plant production and species diversity mitigate the effects of drought.
Vegetation Rooting Depth	Increases	Increases	Increases	The dominant plant community consists of shallow to moderate rooting depth that limits access to water and nutrients; soil stability is reduced.
Soil Depth	Decreases	Decreases	Decreases	Moderately deep to deep soils have available water deeper in the profile to mitigate the effects of drought.
Salts	n/a	Increases	n/a	High salts affect the soil and root structure, and the uptake of water by plants.
Land Use	Decreases	Decreases	Decreases	This site has minimal to moderate grazing effects due to the slope.
Secondary Variables				
Soil Surface Texture	Decreases	Decreases	Decreases	The well drained soils have minimal water loss due to evaporation.
Available Water Capacity	Decreases	Decreases	Decreases	Sites with higher clay content typically are less vulnerable to drought due to a higher available water capacity.
Fragments	Decreases	Increases	Decreases	Surface and subsurface fragments reduce evaporation and soil temperature and stabilize the site from erosion, thus reducing the effects of drought.
Aspect	n/a	n/a	n/a	The site can occur on all aspects; however, vulnerability to drought is increased on south-facing slopes.
Drought Vulnerability Rating	**moderate**	**moderate**	**moderate**	

Potential Impact

On rangelands, productivity is mainly determined by the distribution of precipitation and its effects on soil water availability (Izaurralde et al., 2011; Knapp et al., 2001). Soil water availability is dependent upon temperature, soil properties, and carbon dioxide (CO_2) concentration via effects on stomatal conductance (Izaurralde et al., 2011). Furthermore, plant species vary in their response to these factors, and alteration of net primary production (NPP) can be expected in the future as species respond to climate change (Morgan et al., 2004). Polley et al. (2013) suggested that NPP will decrease in southern rangelands in response to warmer temperatures and declining precipitation, and will increase on northern rangelands as a result of warmer temperatures and greater precipitation. In southern Arizona, Bodner and Robles (2017) saw a decrease in warm-season perennial grass basal cover and shrubs and an increase in annual grasses and grass mortality, as a dry winter and low spring precipitation resulted in reduced productivity or high grass mortality. The grasses in MLRA 41 depend upon the summer monsoon precipitation to support growth, and below-normal precipitation events can have significant impacts the condition of the Southwestern rangelands.

In MLRA 41, total annual production is highly dependent upon the distribution of precipitation and its effects on soil moisture. Total annual production declines during droughts, which affects grazing management decisions (Table 28).

Table 28. MLRA 41 Ecological Site Total Annual Production (based on Reference Community)

LRU	Ecological Site ID	Ecological Site	Total Annual Production (lbs/ac)		
			Low	Average	High
41-1	R041XA114AZ	Loamy Bottom	ND	ND	ND
41-1	R041XA115AZ	Loamy Swale	1056	2060	3320
41-1	F041XA113AZ	Sandy Bottom, Woodland	3965	4910	6205
41-1	F041XA112AZ	Sandy Wash, Woodland	2005	3900	6450
41-1	R041XA105AZ	Limy Upland	306	720	1125
41-1	R041XA117AZ	Shallow Upland	438	775	1240
41-1	R041XA110AZ	Sandy Loam, Upland	1084	1645	2374
41-1	R041XA108AZ	Loamy Upland	542	1285	1955
41-1	R041XA109AZ	Clay Loam Upland	453	1075	1530
41-1	R041XA126AZ	Clayey Upland	567	1200	1680
41-1	R041XA102AZ	Shallow Hills	524	1240	1985
41-1	R041XA103AZ	Limestone Hills	576	1165	1480
41-1	R041XA111AZ	Volcanic Hills	524	1300	1840
41-1	R041XA107AZ	Loamy Slopes	763	1520	2350
41-1	R041XA104AZ	Limy Slopes	671	1290	1685
41-2	R041XB211AZ	Saline Bottom	422	1060	2070
41-2	R041XB213AZ	Sandy Wash	825	1800	3150
41-2	R041XB209AZ	Loamy Swale	756	2020	3100
41-2	R041XB202AZ	Clayey Swale	231	705	1140

41-2	F041XB218AZ	Sandy Bottom, Woodland	4820	5800	7050
41-2	F041XB221AZ	Loamy Bottom, Woodland	4295	4475	5645
41-2	F041XB222AZ	Saline Bottom, Woodland	4095	4405	5635
41-2	R041XB212AZ	Saline Upland	150	235	570
41-2	R041XB206AZ	Limy Fan	81	200	530
41-2	R041XB219AZ	Gypsum Upland	56	180	380
41-2	R041XB208AZ	Limy Upland	816	200	420
41-2	R041XB214AZ	Sandy Upland	360	420	480
41-2	R041XB215AZ	Sandy Loam Upland	217	450	1065
41-2	R041XB230AZ	Deep Sandy Loam Upland	ND	ND	ND
41-2	R041XB210AZ	Loamy Upland	148	400	825
41-2	R041XB203AZ	Clayey Upland	217	505	900
41-2	R041XB204AZ	Clay Loam Upland	147	300	785
41-2	R041XB205AZ	Shallow Hills	525	595	665
41-2	R041XB223AZ	Basalt Hills	92	271	755
41-2	R041XB207AZ	Limy Slopes	125	340	695
41-2	R041XB216AZ	Clayey Slopes	156	435	855
41-2	R041XB231AZ	Gypsum Breaks/Slopes	90	300	580
41-3	R041XC315AZ	Saline Bottom	422	1060	2070
41-3	R041XC312AZ	Loamy Bottom	3065	4110	6200
41-3	R041XC316AZ	Sandy Wash	825	1800	3150
41-3	R041XC311AZ	Loamy Swale	775	1685	3050
41-3	R041XC302AZ	Clayey Swale	880	1645	2530
41-3	R041XC317AZ	Sandy Bottom, Woodland	4055	5800	7980
41-3	R041XC310AZ	Loamy Bottom, Woodland	4295	4475	5645
41-3	R041XC326AZ	Sandy Upland, Saline	ND	ND	ND
41-3	R041XC328AZ	Saline Upland	150	235	570
41-3	R041XC309AZ	Limy Upland	306	580	960
41-3	R041XC331AZ	Limy Upland, Deep	ND	ND	ND
41-3	R041XC322AZ	Shallow Upland	356	596	915
41-3	R041XC325AZ	Sandy Upland	ND	ND	ND
41-3	R041XC319AZ	Sandy Loam Upland	602	1066	1755
41-3	R041XC318AZ	Sandy Loam Upland, Deep	521	1005	1855
41-3	R041XC313AZ	Loamy Upland	619	1000	1800

41-3	R041XC305AZ	Clay Loam Upland	502	865	1425
41-3	R041XC304AZ	Clayey Upland	520	1000	1520
41-3	R041XC320AZ	Limy Fan	ND	ND	ND
41-3	R041XC307AZ	Limestone Hills	415	810	1275
41-3	R041XC306AZ	Shallow Hills	525	915	1545
41-3	R041XC323AZ	Volcanic Hills, Loamy	430	860	1360
41-3	R041XC330AZ	Volcanic Hills, Clayey	480	1020	1585
41-3	R041XC314AZ	Loamy Slopes	426	905	1505
41-3	R041XC308AZ	Limy Slopes	555	1000	1765
41-3	R041XC303AZ	Clayey Slopes	395	850	1325

*Plant productivity at below-average, average, and above-average precipitation and temperature conditions.
*On-site visit is necessary to determine forage production as site conditions will vary.
*Ecological site reports can be found at https://esis.sc.egov.usda.gov/
*ND - no data available

Changing plant species composition affects forage availability as cattle exhibit grazing preferences, such as selection of herbaceous over woody species (Petersen et al., 2014). Impacts to ecosystem services, such as forage production for wild and domestic animals, are predicted to vary regionally depending upon precipitation, temperature, vegetation type, soils, fire regimes, and carrying capacity of livestock operations (Polley et al., 2013). A primary concern for western U.S. rangelands is the rapid conversion of shrublands and desert into annual grassland through the spread of invasive annual grass species. Another concern is for the negative impacts this conversion will have on wildfire regimes, surface hydrology, and loss of critical habitat for threatened and endangered species (Brooks et al., 2004). Over the past three decades, there has been a significant increase in the abundance and extent of invasive annual grass species in the American Southwest, including cheatgrass and red brome, both of which are expected to increase across U.S. rangelands (Boyte et al., 2016). Impacts on livestock operations vary with lower risk observed on larger ranches with shorter grazing periods, multiple income sources, and livestock diversification. Reduced precipitation across the Southwest will impact livestock production due to both reduced forage production and the increasingly uncertain drinking water supplies. Furthermore, the added heat stress to cattle will likely result in reduced weight gain and production (Howden et al., 2008; Reeves et al., 2017)

In addition to the effects of livestock grazing, drought is an important ecological driver, significantly influencing the composition and distribution of rangeland plant communities. Severe drought can lead to local extirpation in areas where the recolonization potential of the site is low (Samson et al., 2004), such as when extreme droughts occur in the Chihuahuan Desert resulting in grass populations to die and decreased grazing resources for livestock (Frankson et al., 2017b). Both abiotic (ecological site) and biotic (ecological state) factors define how a site will respond to drought. Although heavy grazing can influence plant community dynamics, climate variability has a greater effect on plant community and productivity in arid and semi-arid environments (Biondini et al., 1998).

The duration, magnitude, and spacing of precipitation events, soil moisture, and temperatures has been shown to influence responses to drought. Effects of drought can also be strongly mediated by site conditions like soil characteristics, topographic setting, grazing use, mulch, and vegetation cover and composition. Gremer et al. (2015) showed that soil water accounted for 40-60 percent of the total explained variance in grass cover. Evaluation of how soil properties mediate impacts of climate on plant communities may enhance our ability to predict rangeland community dynamics. Timing of precipitation, not just the total amount, is critical to the condition of perennial grasses in the American Southwest. While plants in arid and semiarid ecosystem usually respond more strongly to larger storm events or a series of events, small pulses of rain, even as small as 5 mm, may alleviate stresses that accumulates during dry periods and maintain physiological processes (Huxman et al., 2004). In arid regions, soil and landscape properties can mediate plant responses to climate, because they influence the timing, scale, and location of available water. For example, surface texture affects infiltration and runoff of precipitation, with more water loss from fine-textured soils relative to coarse-textured soils. Such patterns can lead to greater plant vulnerability to drought at sites with high clay and silt in the surface horizons (Noy-Meir, 1973; Sala et al., 1988).

Livestock operations are expected to be exposed to varying environmental factors such as warming temperatures, highly variable precipitation patterns, more extreme weather, and changing fire regimes, as well as to changing socioeconomic factors such as land use, global market demand, and government subsidy programs (Howden et al., 2008; Izaurralde et al., 2011; Polley et al., 2013). Furthermore, reductions of cool-season rainfall may expand and accelerate drought-induced plant mortality across the southwestern U.S. (Hamerlynck et al., 2013). The projected warmer temperatures, variable precipitation, and high evaporative demands across the southwestern U.S. render most of these rangelands vulnerable to degradation under climate change.

Adaptive Capacity

Management actions to adapt to projected shifts in climate can mitigate the ecological and socioeconomic impacts on rangeland systems. Applying adaptive management strategies before, during, and after a drought are vital to maintain a functioning ecosystem and to ensure an economic return. The highly variable weather patterns and forage production across rangelands requires dynamic, flexible drought and grazing management plans that are capable of adapting to seasonal change. When considering adaptive management strategies, Joyce et al. (2013) recommend taking a systematic approach to evaluate which tools to use before, during, and after drought. Adaptive management should include flexibility to minimize the effects of a natural disaster at multiple levels: enterprise or management, ecological, and the human/social level (Table 29). The ability to adapt to a changing climate involves constantly monitoring weather conditions and patterns as weather varies from region to region and across rangelands. Drought is common in the southwestern U.S., and proactive planning and management will help to ensure stewardship and sustainability of rangeland resources.

Table 29. Adaptation management strategies at the enterprise, ecological, human and social organization categories (Howery, 1999; Joyce et al., 2013; Sprinkle, 2011)

Enterprise	Ecological	Human/Social Organization
• Enhance drought management plan • Reduce stocking rate • Implement rotational grazing plan that allows adequate rest for native plants (60 days depending upon time of year and precipitation received) • Evaluate animal size and keep herd composition flexible • Change species from cattle to sheep or goats, or to heat-tolerant cattle (e.g. Criollo cattle) • Know forage supply and demand before, during, and after drought • Utilization of available forage < 50%; use a high protein ration • Utilization of available forage is ≥ 50%; use a protein/energy or energy supplement • Supplement before calving • Evaluate alternate income sources • Do not graze during the dormant season and maintain minimal stubble heights through winter • Do not graze when pastures are wet • Delay grazing until plants reach 5-6 inches in height or 4-5 leaf stage • Provide shade for cattle and minimize distance between water sources	• Become familiar with ecological sites and their state-and-transition models to assist with management strategy • Know how sensitive your site is to drought • Enhance invasive species monitoring and control • Monitor use of toxic plants (e.g. Western brakenfern *(Pteridium aquilinum),* whorled milkweed *(Asclepias verticillata)*, milkvetch *(Astragalus L.)*, and snakeweed *(Gutierrezia Lag.)* near cattle, and move cattle if necessary • Monitor key forage species and when to graze • Maintain as much carryover forage as possible (minimum 40%). • Monitor how much forage is left after grazing, not how much has been consumed • Graze annuals early and heavily during drought • Properly grazed pasture will have an uneven look • Monitor bare ground areas • Maintain cover to protect the soil • Increase knowledge on rangeland/ soil health	• Willingness to adopt change • Increase knowledge on climate variability • Be flexible and willing to implement different management strategies • Understand the socio-ecological impacts of drought • Work with local, state, and Federal government regarding conservation practices • Become involved with community Collaborative Rain, Hail and Snow Network (CoCoRaHs) • Attend grazing and drought workshops • Engage with USDA Southwest Climate Hub regarding climate-informed decision making and available climate resources • Develop social networks to enhance knowledge on different management strategies

Enterprise – Rangeland and livestock management in the southwestern U.S. is a complex issue due to the highly variable precipitation patterns, extreme heat and evaporative demand, and reoccurring drought. A proactive management plan will help to mitigate the effects from drought and other weather extremes. Livestock grazing is one of the most widespread and important uses of rangelands, and one of the most important adaptive strategies is to have a flexible grazing management plan. The NRCS prescribed grazing standards can be found in Section 4 under the Field Office Technical Guide (EFOTG) at https://www.nrcs.usda.gov/wps/portal/nrcs/az/home/. Shifting climate patterns affect plant production and require flexibility in stocking rates, herd size, herd movement, and use of supplemental feed. Another way to adapt to elevated temperatures and reduced precipitation is changing to cattle that are more heat-tolerant (e.g. Criollo or Brahman) or changing livestock species (from cattle to sheep and/or goats) to minimize forage uptake. Altering stocking schedules to avoid exposure to the greatest temperatures, providing shade, and/or minimizing distance between water sources is also recommended as a way to alleviate heat stress on livestock.

Water availability should be considered when designing adaptation management related to heat. Animal numbers should be reduced during drought because local forage production is insufficient, and competition increases among livestock operations for forage alternatives. Ranchers who attended a drought workshop in southern Arizona in 2013 consider drought as the norm, and all agreed that the primary way to be resilient to drought is to maintain a stocking rate at below carrying capacity (Brugger et al., 2013). In addition, the local ranchers also stated that they don't consider being in a drought until precipitation is 50 percent or more below the average, or when precipitation is below-average for seven months or more (Brugger et al., 2013). A primary concern for the ranchers was the ability to provide enough water for livestock, because maintaining several water sources per ranch was necessary to mitigate drought and heat effects on livestock. Approximately 19 ranchers who attended the drought workshop summarized adaptive management strategies that increase drought resilience on their ranches (Table 30).

Table 30. Drought Management Strategies Implemented by Southern Arizona Ranchers and Issues Implementing Adaptive Management (modified from Brugger et al., 2013)

Herd Management	Pasture Management	Water Management	Issues
Stock below carrying capacity	low utilization	increase number of water points	lack of flexibility of the Federal land management agencies
Flexibility in terms of numbers	flexible pasture rotation	use wells, solar pumps, and pipelines	cost and labor to improve infrastructure
Maintain core herd with genetics and behavior adapted to area	add water sources to use more pasture	deepen dirt tanks to reduce evaporation	reliable water sources
Quality of livestock over quantity	rest pastures	line dirt tanks to reduce leakage	lack of agency-rancher communication
Different classes of livestock (spring and fall calves, yearlings, and stockers)	one-year drought reserve of forage (if possible)	haul water	
Provide several different water sources to disperse the herd	off-ranch grazing		

During a drought, forage quality and availability is reduced, which results in nutritional stress in livestock. Forage production and quality should be monitored to determine if the nutritional requirements of the livestock are being met. During a drought, supplementation may be needed if forage is limited, as providing protein supplement to cattle during a drought can increase weaning weights and conception rates. To maintain next year's forage, utilization of forage should not exceed 60 percent (Sprinkle, 2011). Also, placing water sources in areas that are infrequently grazed will increase forage supply, as cattle will use 80 percent of the allowed harvestable forage up to one mile from a water source, but only 40 percent at one and one-half miles and 20 percent at two miles from the water source (Sprinkle, 2011). Flexibility in cattle numbers, grazing periods, and type of operation could also address changes in production while anticipating increasing variability in precipitation. Producers should include longer-term projections in management plans and implement monitoring to detect initiation of critical impacts (Reeves et al., 2014).

Ecological – Projected changes in climate in the southwestern U.S. are likely to increase the vulnerability of rangeland ecosystems to drought, leading to short-term reductions in forage production and longer-term transitions from one ecological state to another. Knowledge of how ecological sites and states each affect drought sensitivity supports the development of a site-specific drought management plan. Landowners can influence how ecosystems respond to drought through management actions. When developing adaptive management strategies for livestock grazing, it is important to have reliable estimates of the forage supply and demand in order to maintain as much carryover forage as possible (Cook et al., 1997; Hart and Carpenter, 2001). Landowners should monitor key forage species and know when to start and stop grazing, as well as how much forage is left after grazing. After livestock are returned to the pasture, utilization and stubble height of the regrowth should be monitored closely. Utilization of regrowth should be less than or equal to 50 percent, so that stubble height during the second grazing period remains equal to or higher than the initial stubble height (Sprinkle and Bailey, 2004). Continuous monitoring of vegetation productivity, invasive species, and bare ground will help to increase ecosystem resilience. Economic returns and ecological integrity are linked to vegetative resources, therefore, careful consideration of vegetation condition is necessary before, during, and after droughts.

Human/Social Organization – Enhancing adaptive capacity and facilitating social learning across multiple social and ecological levels is a critical component of confronting climate change on rangelands. Individuals, institutions, and government agencies must be willing to adopt change and increase awareness about climate variability and its environmental and economic effects. Combining collaboration and adaptive management is viewed as a way of broadening the scope of information and options considered in decision cycles, instilling accountability into the inherently flexible processes of adaptive management, promoting shared learning, and generating social license for managers to try bold solutions to problems. The combination of stakeholder involvement and adaptive management has yielded many benefits at the Las Cinegas National Conservation Area in southeastern Arizona. This effort has resulted in the adoption of a resource management plan with broad community support, a suite of partners that are invested in implementing the plan, a regular and effective ecological monitoring program, and the ability to work collaboratively to adapt management decisions to suit changing conditions (Bodner et al., 2013). Collaboration between a community-based conservation group (Malpai Borderlands Group), government agencies, and researchers working together toward the mutual goals of sustaining the local community through cooperative management of the land, and to protect the structure and function of the landscape within their community. Malpai Borderlands Group illustrates how local communities, government agencies, and researchers can work together to sustain open landscapes and functioning ecosystems for mutual benefit.

Adaptation to climate variability on a socio-ecological scale includes working with government agencies regarding conservation practices, as well as universities, conservation districts, and the USDA Climate Hubs to learn about available climate adaptation resources and adaptive management options. The USDA Natural Resources Conservation Service (NRCS) provides conservation planning and programs to landowners to assist with grazing management. The NRCS conservation planning process is a nine-step process that develops and implements plans to protect, conserve, and enhance natural resources (https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/cp/). Landowners can apply for NRCS programs once their conservation plans are complete. The two main conservation programs available for rangeland conservation are the Environmental Quality Incentive Program (EQIP) and Conservation Stewardship Program (CSP). Through EQIP, landowners can receive assistance for practices (stock tanks, fencing, pipelines, and wells) that support conservation practices. Increasing the number of stock tanks will minimize heat stress on cattle by reducing the distance between water sources, and installing fencing facilitates more flexible herd management. Conservation planning provides grazing plans that will improve forage and rangeland condition, shrub management, and/or rangeland wildlife habitat. The CSP helps landowners to build on existing conservation efforts while strengthening their operations.

Other resources include the USDA Climate Hubs, which provide data, tools, and assessments to support climate-informed decision making by landowners. Most adaptive management plans include practices that mitigate the impacts of climate change, but few plans consider the socioeconomic incentives or human behavior toward management to promote ecosystem resilience. The availability of information, experience, and training, along with social and economic incentives and resources, is required to implement adaptive management at the socioeconomic level (Joyce et al., 2013).

Summary

Climate in the arid and semiarid regions of the southwestern U.S. is characterized by high temperatures and evaporative demand, combined with low and variable precipitation. The southwestern U.S. has already experienced significant warming and drying, and has been identified as a hot spot for increasing aridity as well as increasing variability in temperature and precipitation. These changes have the potential to push southwestern ecosystems beyond tolerance thresholds, resulting in species loss, declining ecosystem services, and habitat alteration and degradation. Anticipating such consequences requires understanding which aspects of climate drive temporal patterns of vegetation change and how these changes will manifest on the landscape (Gremer et al., 2015). In addition to climate change, cattle production and operations are currently at risk due to land use changes, invasive species, altered fire regimes, and fluctuating global markets. Arid southern and western regions will need a variety of adaption strategies, including adjustments to stocking rates and grazing schedules, or cattle production will need to shift to other regions (Reeve et al. 2014). Increased climate variability, including more frequent and intense drought, is projected for the southwestern United States. Vulnerability assessments and adaptation strategies are needed at the local level to mitigate the effects of climate change on rangelands. Ecological site descriptions and the associated state-and-transition models are tools to help land managers implement and evaluate responses. Awareness of the sensitivity to drought of an ecological site can help to ameliorate the effects of drought at a site-specific level. Incorporating enterprise, ecological, and social/human organization strategies into an adaptive management plan will lessen the effects of drought, which is critical to the social and ecological stability in the region. Improving our ability to sustain grassland services through a variable and shifting climate will require refining our understanding of how grasslands respond to and recover from drought, and how other site conditions and management actions mediate drought effects (Bodner and Robles, 2017).

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Appendix

Table A1. Drought Severity Classification (droughtmonitor.unl.edu)

Category	Description	Possible Impacts	Palmer Drought Severity Index (PDSI)	CPC Soil Moisture Model (Percentiles)	USGS Weekly Streamflow (Percentiles)	Standardized Precipitation Index (SPI)	Objective Drought Indicator Blends Percentiles
D0	Abnormally Dry	Going into drought: short-term dryness slowing planting, growth of crops or pastures Coming out of drought: some lingering water deficits pastures or crops not fully recovered	-1.0 to -1.9	21 to 30	21 to 30	-0.5 to -0.7	21 to 30
D1	Moderate Drought	Some damage to crops, pastures Streams, reservoirs, or wells low, some water shortages developing or imminent Voluntary water-use restrictions requested	-2.0 to -2.9	11 to 20	11 to 20	-0.8 to -1.2	11 to 20
D2	Severe Drought	Crop or pasture losses likely Water shortages common Water restrictions imposed	-3.0 to -3.9	6 to 10	6 to 10	-1.3 to -1.5	6 to 10
D3	Extreme Drought	Major crop/pasture losses Widespread water shortages or restrictions	-4.0 to -4.9	3 to 5	3 to 5	-1.6 to -1.9	3 to 5
D4	Exceptional Drought	Exceptional and widespread crop/pasture losses Shortages of water in reservoirs, streams, and wells creating water emergencies	-5.0 or less	0 to 2	0 to 2	-2.0 or less	0 to 2

Table A2. Common drought indices (modified from Henz et al., 2004; “Integrated Drought Management Programme,” 2014)

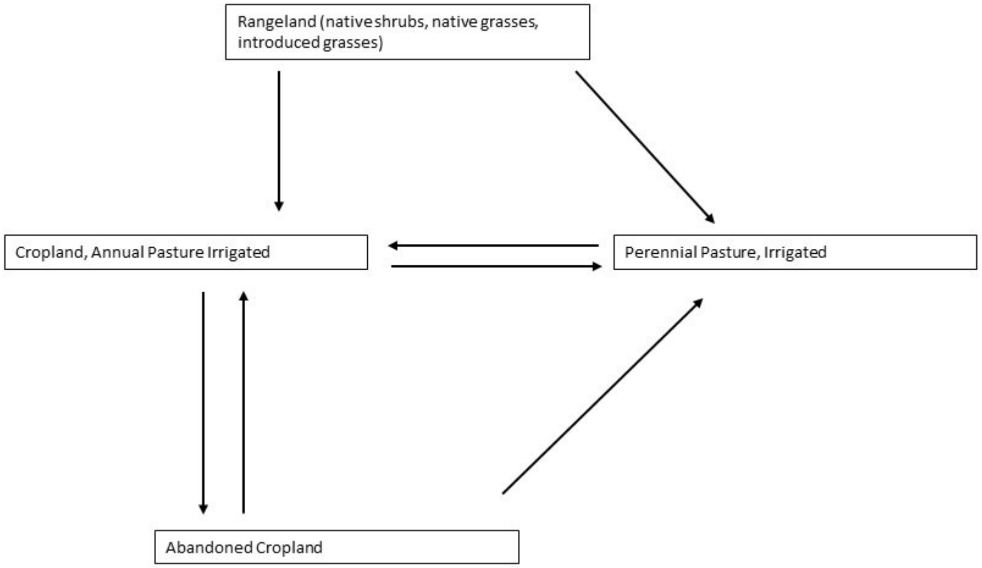
Common Drought Indices	**Description**	**Strengths**	**Weaknesses**
Palmer Drought Severity Index (PSDI)	Relates to meteorological drought and attempts to measure the duration and intensity of long-term drought-inducing circulating patterns. Calculated using monthly temperature and precipitation data along with water-holding capacity of soils.	Used around the world. Uses soil data and total water balance methods strengthening its ability to determine drought	Timescale of ~ 9 months, which leads to a lag in identifying drought conditions based upon simplification of the soil moisture component within the calculations
Standardized Precipitation Index (SPI)	A probability index that considers only precipitation. Uses historical precipitation records for any location to develop a probability of precipitation that can be computed at any number of timescales, from one month to 48 months or longer.	Uses precipitation data and time and is applicable in all climate regimes	does not include temperature component
Palmer Crop Moisture Index (CMI)	Relates to agricultural drought and measures short-term drought on a weekly scale and is used to quantify drought's impacts on agriculture during the growing season.	Can be used to measure the status of dryness or wetness affecting warm-season crops and field activities.	Indicates general conditions and not local variations caused by isolated rain
Palmer Hydrological Drought Index (PHDI)	Quantifies reservoir and groundwater levels. Based on the original PDSI and takes into account longer-term dryness that will affect water storage, streamflow, and groundwater.	Considers the total water system	Frequencies will vary by region and time of year and the impact of management decisions and irrigation are not considered. Responds more slowly to changing conditions than it does to the PDSI.
Surface Water Supply Index (SWSI)	Complements the Palmer indices in Colorado, where mountain snowpack is a key element of water supply. Calculated by river basin, based on snowpack, streamflow, precipitation, and reservoir storage.	Takes into account the work done by Palmer with PDSI but adds additional information including water supply data (snow accumulation, snowmelt and runoff, and reservoir data), and is calculated at the basin level.	As data sources change or additional data are included, the entire index has to undergo a recalculation to account for these changes in the inputs, making it difficult to construct a homogeneous time series. Since calculations may vary between basins, it is difficult to compare basins or homogeneous regions.

s= short-term, typically <6 months (agriculture and grasslands)
l = long-term, typically > 6 months (hydrology and ecology)

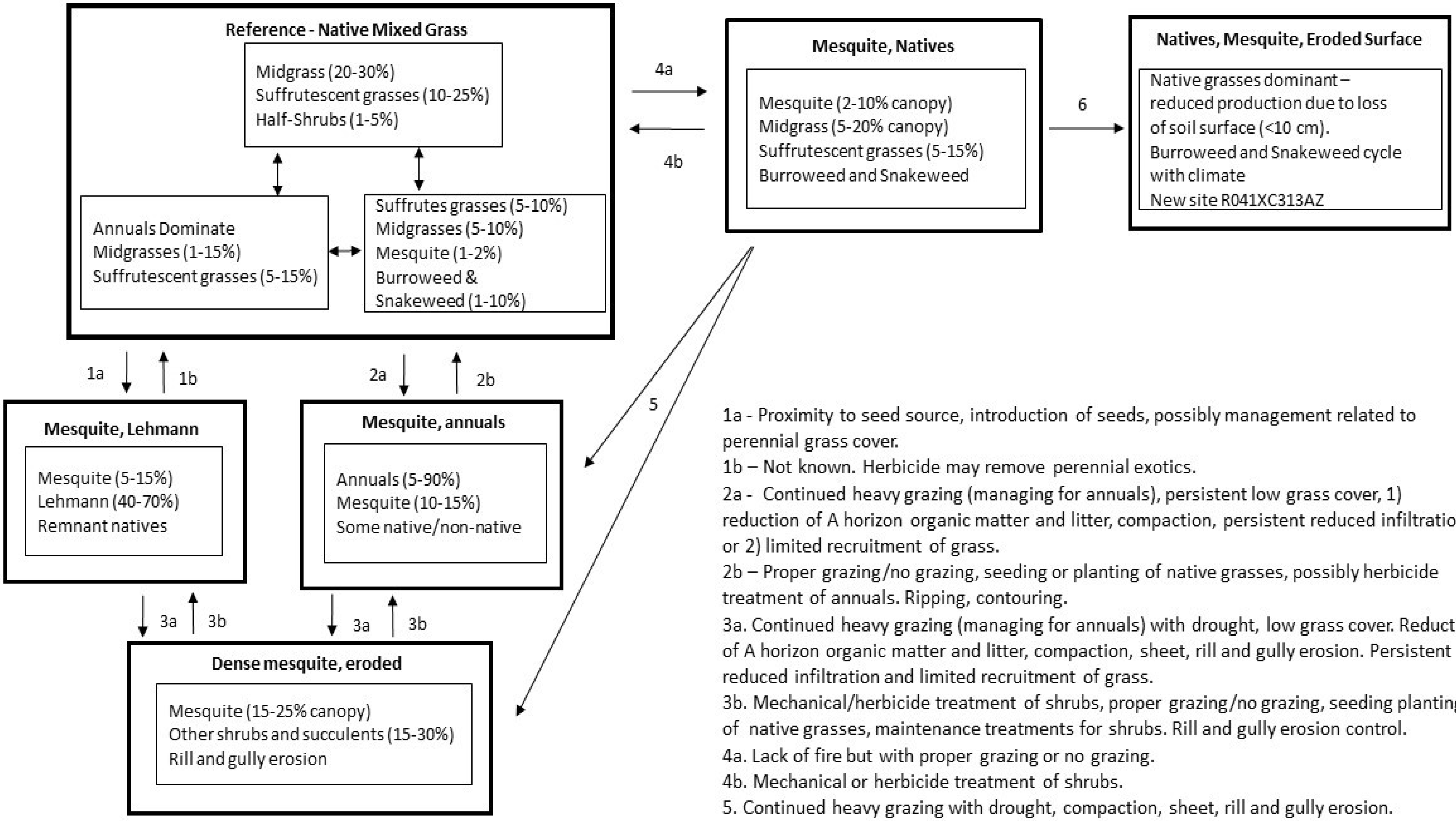
Table A3. Publicly available drought information (modified from Tolleson, 2016)

Website Source	Website Address
Westwide Drought Tracker	http://www.wrcc.dri.edu/wwdt/
U.S Drought Portal	http://www.drought.gov/drought/
National Drought Mitigation Center	http://drought.unl.edu/
University of Arizona DroughtView	http://droughtview.arizona.edu/
High Plains Regional Climate Center Climate Maps	http://hprcc.unl.edu/maps.php?map=ACISClimateMpas/
Multiscale Standardized Precipitation Index Plots	http://cals/arizona/edu/climate/misc/spi/spi_contour.html
Climate Assessment for the Southwest (CLIMAS)	http://www.climas.arizona.edu/
Southwest Climate Hub	https://swclimathub.info/data

Figure A1. MLRA 41 Sandy Loam Upland (R041XC319AZ) Ecological Site State-and-Transition Model.



Land Use STM for Sandy Loam Upland (R041XC319AZ)



1a - Proximity to seed source, introduction of seeds, possibly management related to perennial grass cover.

1b – Not known. Herbicide may remove perennial exotics.

2a - Continued heavy grazing (managing for annuals), persistent low grass cover, 1) reduction of A horizon organic matter and litter, compaction, persistent reduced infiltration or 2) limited recruitment of grass.

2b – Proper grazing/no grazing, seeding or planting of native grasses, possibly herbicide treatment of annuals. Ripping, contouring.

3a. Continued heavy grazing (managing for annuals) with drought, low grass cover. Reduction of A horizon organic matter and litter, compaction, sheet, rill and gully erosion. Persistent reduced infiltration and limited recruitment of grass.

3b. Mechanical/herbicide treatment of shrubs, proper grazing/no grazing, seeding planting of native grasses, maintenance treatments for shrubs. Rill and gully erosion control.

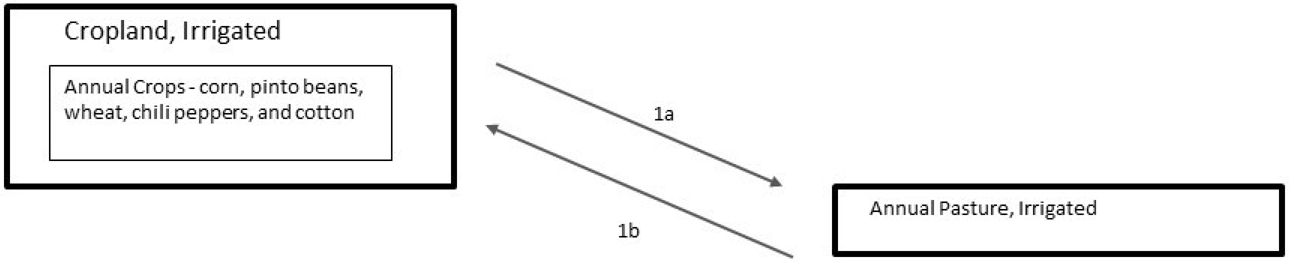
4a. Lack of fire but with proper grazing or no grazing.

4b. Mechanical or herbicide treatment of shrubs.

5. Continued heavy grazing with drought, compaction, sheet, rill and gully erosion.

6. Continued heavy grazing, severe soil surface erosion (sheet) resulting in loss of A horizon to less than 10 cm thick. Site #R041XC313AZ.

Rangeland STM for Sandy Loam Upland (RO41XC319AZ)



Cropland, Irrigated

Annual Crops - corn, pinto beans, wheat, chili peppers, and cotton

1a

1b

Annual Pasture, Irrigated

1a - Ecological processes - no tillage, pasture seeding, erosion potential
Mechanisms - absence of disturbance (tillage)
Practices – Range Planting (550)

1b - Ecological processes - tillage, cropland seeding, erosion
Mechanisms: mortality induced by tillage
Practices: tillage, nutrient addition, herbicide

Cropland STM for Sandy Loam Upland (R041XC319AZ)

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