Chapter

# Climate Change Vulnerability Assessment of Imperiled Plants in the Mojave Desert

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## Abstract

The Mojave Desert in the southwestern United States is one of the hottest and driest areas of North America. Climate change is likely to exacerbate these conditions. The region is home to many endemic plant species, including 24 federally threatened species. The impact of climate change factors on these sensitive Mojave Desert species is relatively unknown. Here we used a climate change vulnerability assessment to determine which imperiled plants may be most affected by changing climatic conditions. We evaluated the vulnerability of each species under future climate scenarios and calculated scores using metrics such as exposure, sensitivity, niche breadth, and dispersal capability. We found that most listed plant species were vulnerable to climate change, with 21% (N = 5) classified as extremely vulnerable, 25% (N = 6) classified as highly vulnerable, and 42% (N = 10) classified as moderately vulnerable. Contributing factors most frequently associated with vulnerability included various barriers to migration, high habitat specificity, and species sensitivity to changes in hydrological patterns. Many of these species are already threatened by ongoing anthropogenic stressors such as urban growth and associated developments, and these results suggest that climate change will pose additional challenges for conservation and management. Natural resource managers can use the vulnerability ranking and contributing factors identified from these analyses to inform ecological decisions related to threatened plants throughout desert regions.

**Keywords:** threatened species, climate change, Mojave Desert, vulnerability assessment, conservation management, endemic species, biodiversity

## 1. Introduction

The Mojave Desert occurs across parts of California, Nevada, Utah, and Arizona in the western region of the United States. It is the smallest and driest desert in North America, with annual precipitation varying widely across the region and an average maximum temperature of 36°C in the summer and average minimum temperature of 13°C in the winter [1]. Although it is not the planet's hottest desert, it does hold the record for the highest land surface temperature ever recorded on Earth (56.7°C), registered at Death Valley National Park in 1913 [2]. The region is ecologically and topographically diverse, with elevations ranging from to −85 to 3,633 meters, and consequently hosts a large number of threatened, endangered, and endemic species. The sunny climate and proximity to national parks and other public lands also attracts human inhabitants. Most of the large cities in the area (e.g., Las Vegas) continue to grow, and anthropogenic developments and recreational activities are increasingly disturbing Mojave Desert ecosystems. Additional stressors on native flora and fauna include invasive species, altered disease dynamics, and increasing wildfire frequency, and populations of many plant and animal species are in decline.

As a patchwork of unique habitats and extreme conditions, the Mojave Desert supports a diverse flora of about three thousand plant species [3]. The number and geological distribution of plants within this landscape is determined by the interaction of many factors such as elevation, precipitation, temperature, soil properties and disturbance. Many Mojave plant species are both regionally endemic, found nowhere else on earth, and locally endemic, restricted to a specific geographic area within the Mojave Desert. Additionally, some species can be defined as rare, having either a narrow geographical range, specialized habitat requirements, or a small population size [4]. Although a species may be considered endemic but not rare, and vice versa, both endemic and/or rare species exhibit attributes which make them more vulnerable to extinction [5]. Consequently, conservation efforts are necessary in some instances to preserve genetic and species diversity as well as ecosystem structure and function [3]. Given the number of endemic and rare species, and their unique habitat requirements, land managers face a daunting task in the Mojave Desert. The United States Endangered Species Act (ESA) of 1973 provided a critical boost to conservation efforts. This legislation was designed to identify and protect plant and animal species facing imminent extinction, and covers species, subspecies, and distinct population segments [6]. The Mojave Desert contains 24 plant species listed as threatened or endangered under the ESA (**Table 1**), many of which are also listed under some level of conservation concern by the International Union for the Conservation of Nature [7].

These 24 listed plants species encompass four states and nine plants families, illustrating the starkly different geographical reaches of the Mojave Desert. They can be further subdivided to exemplify one or more of the three criteria for rarity [4] and/or specific forms of endemism [8]. First, all the listed species have a narrow geographic range, some restricted to soils derived from specific geological formations and some endemic to regional biodiversity hotspots. For example, the seven species from Nevada are all found within the confines of Ash Meadows National Wildlife Refuge and land immediately adjacent (**Figure 1**). This 24,000-acre spring-fed alkaline wetland and alkaline desert upland has the highest concentration of endemic species in the United States [9–10]. Second, all the listed species have highly specialized habitat requirements ranging from eolian dunes of Coachella Valley, California to gypsum outcrops associated with the Harrisburg Member of the Kaibab Formation in northern Mohave County, Arizona. Edaphic endemism (influenced by soils; [8]) is a strong theme running through the Mojave ESA listed species with alkaline-wetland, calcium-carbonate, gypsum, and granite endemism represented. Three listed species from the San Bernardino Mountains in California are restricted to "pebble plains" named for the layer of orange quartzite pebbles that are pushed to the clay soil surface by freezing and thawing [11]. Third, many of the listed species have small or disjointed populations, such as Lane Mountain Milkvetch (*Astragalus jaegerianus*). This species is known from only 4 disjunct populations and is threatened by recreational off-highway vehicle (OHV) use and military activity. Although threats to the 24 ESA listed Mojave Desert plant species are many, climate change remains a ubiquitous concern.

| Scientific Name | Common Name | Family | US ESA Status | Nature Serve Status | State(s) of occurrence |
|---|---|---|---|---|---|
| *Arctomecon humilis* Coville | Dwarf Bear-poppy | Papaveraceae | E | G1 | Utah |
| *Arenaria ursina* B.L. Rob. | Bear Valley Sandwort | Caryophyllaceae | T | G1 | California |
| *Astragalus albens* Greene | Cushenbury Milkvetch | Fabaceae | E | G1 | California |
| *Astragalus ampullarioides* Sheldon | Shivwits Milkvetch | Fabaceae | E | G1 | Utah |
| *Astragalus holmgreniorum* Barneby | Holmgren's Milkvetch | Fabaceae | E | G1 | Arizona, Utah |
| *Astragalus jaegerianus* Munz | Lane Mountain Milkvetch | Fabaceae | E | G2 | California |
| *Astragalus lentiginosus* Douglas var. *coachellae* Barneby | Coachella Valley Milkvetch | Fabaceae | E | T1 | California |
| *Astragalus phoenix* Barneby | Ash Meadows Milkvetch | Fabaceae | T | G2 | Nevada |
| *Astragalus tricarinatus* A. Gray | Triple-rib Milkvetch | Fabaceae | E | G2 | California |
| *Castilleja cinerea* A. Gray | Ash Gray Indian-paintbrush | Scrophulariaceae | T | G1 | California |
| *Centaurium namophilum* Reveal, C.R. Broome & Beatley | Spring-loving Centaury | Gentianaceae | T | G2 | Nevada |
| *Enceliopsis nudicaulis* (A. Gray) A. Nelson var. *corrugata* Cronquist | Ash Meadows Sunray | Asteraceae | T | T1 | Nevada |
| *Erigeron parishii* A. Gray | Parish's Daisy | Asteraceae | T | G2 | California |
| *Eriogonum kennedyi* Porter ex *S. Watson* var. *austromontanum* Munz & I. M. Johnst. | Southern Mountain Buckwheat | Polygonaceae | T | T2 | California |
| *Eriogonum ovalifolium* Nutt. var. *vineum* (Small) A. Nelson | Cushenbury Buckwheat | Polygonaceae | E | T1 | California |
| *Grindelia fraxinipratensis* Reveal & Beatley | Ash Meadows Gumweed | Asteraceae | T | G2 | Nevada |
| *Ivesia kingii* S. Watson var. *eremica* (Coville) Ertter | Ash Meadows Ivesia | Rosaceae | T | T1 | Nevada |
| *Lesquerella kingii* S. Watson ssp. *bernardina* (Munz) Munz | San Bernardino Mountains Bladderpod | Brassicaceae | E | T1 | California |

| Scientific Name | Common Name | Family | US ESA Status | Nature Serve Status | State(s) of occurrence |
|---|---|---|---|---|---|
| *Mentzelia leucophylla* Brandegee | Ash Meadows Blazingstar | Loasaceae | T | G1 | Nevada |
| *Nitrophila mohavensis* Munz & J. C. Roos | Amargosa Niterwort | Chenopodiaceae | E | G1 | California, Nevada |
| *Oxytheca parishii* Parry var. *goodmaniana* Ertter | Cushenbury Oxytheca | Polygonaceae | E | T1 | California |
| *Pediocactus sileri* (Engelm. ex J.M. Coult.) L.D. Benson | Siler Pincushion Cactus | Cactaceae | T | G2 | Arizona, Utah |
| *Sphaeralcea gierischii* N.D. Atwood & S.L. Welsh | Gierisch's Globemallow | Malvaceae | E | G1 | Arizona, Utah |
| *Swallenia alexandrae* (Swallen) Söderst. & Decker | Eureka Dune Grass | Poaceae | E | G2 | California |

*Global conservation status rank according to NatureServe: GX/TX = presumed extinct, GH/TH = possibly extinct, G1/T1 = critically imperiled, G2/T2 = imperiled, G3/T3 = vulnerable, G4/T4 = apparently secure, G5/T5 = secure.*

**Table 1.**
*Name, family, and location of Mojave Desert plants listed as threatened (T) or endangered (E) under the United States Endangered Species Act (ESA).*

There has been multi-decadal warming across the Earth's surface, with each of the previous three decades experiencing progressively warmer temperatures than any preceding decade since 1850 [12]. Ecoregions defined by climatic extremes, such as deserts, are particularly vulnerable to climate change. On a global scale, deserts have experienced faster warming and drying over the last 50 years when compared to other regions [13, 14], and this is projected to continue [15]. Desert dwelling species may be directly impacted by thermal or hydric stress, or indirectly via altered habitats, species interactions, or disease dynamics. Several studies have documented negative effects from increasing temperatures on desert wildlife species, including birds [16, 17], mammals [18], invertebrates [19], and reptiles [20]. Studies focused on desert plants have predicted species range shifts in response to climate change [21], and potential changes in vegetation community composition as a result of altered summer precipitation patterns [22]. Climate change impacts are projected to be particularly severe in the southwestern region of the United States, where the Mojave Desert occurs, and resident plants will have to cope with prolonged drought, fewer frost days, warmer temperatures, and an increase in extreme weather events [23–25]. Many species may not be able to survive in such highly transformed environments. Climate change has emerged as one of the greatest threats to biodiversity, with potential to hasten species extinctions, elevating the need to understand how threatened and endangered species may be affected [26]. Management actions have traditionally focused on the establishment of protected areas to conserve habitat and halt species decline, but the efficacy of these strategies is questionable under predicted future climatic regimes [27]. One way to better integrate climate change considerations into management planning for imperiled plant species is to conduct climate change vulnerability assessments (CCVAs).

Vulnerability assessments offer a standardized approach for measuring climate change sensitivity that is efficient, repeatable, and directly comparable among


**Figure 1.**
*Illustration panel by Tiffany J. Pereira portraying the federally threatened and endangered plants of Ash Meadows National Wildlife Refuge, a vulnerable biodiversity hotspot in Nevada, USA. From left to right:* Centaurium namophilum, Astragalus phoenix, Enceliopsis nudicaulis var. corrugata, Grindelia fraxinipratensis, Ivesia kingii var. eremica*, and* Mentzelia leucophylla*. Not pictured:* Nitrophila mohavensis*.*

different species. Vulnerability can be defined as the degree to which a species is susceptible to climate change, taking into consideration the magnitude of predicted change where the species occurs and the adaptive capacity of the species [28]. Species within an area or ecoregion can be ranked according to their expected sensitivity to changing climatic conditions [29]. A CCVA can be conducted using several different methods, such as a correlative, mechanistic, or trait-based approach, or a combination of several of these types of models. Correlative approaches have frequently been used for plants, but a trait-based approach is best for rapid assessment of a larger number of species [30]. A trait-based method identifies and scores attributes of a species that are relevant to avoiding or tolerating climate change, such as dispersal ability or sensitivity to temperature or precipitation changes. A species' overall vulnerability to climate change is represented by the sum of these scores. Here we utilize a trait-based approach to assess climate change vulnerability of threatened and endangered plants in the Mojave Desert, and provide suggestions for incorporating these considerations into management actions and conservation planning efforts.

## 2. Methods

We accessed the United States Fish and Wildlife Service's (USFWS) website to obtain the most up to date list of plant species identified as threatened or endangered under the ESA [31]. This list was reduced to only those species occurring in the Mojave Desert, as defined by the EPA Level III Ecoregions [32]. We overlaid spatial data of plant species distribution with a boundary of the selected ecoregion? (Mojave Basin and Range) to verify species occurrence, which resulted in 24 plant species in the Mojave Desert listed as threatened or endangered (**Figure 2**).

We used NatureServe's Climate Change Vulnerability Index (https://www.natureserve.org/conservation-tools/climate-change-vulnerability-index, last accessed 19 Nov 2020) to investigate the susceptibility of Mojave Desert listed plants to climate change (CCVI) [33]. This index incorporated future climate projections, along with data for each species related to natural history, current distribution, and ecological associations, to predict range contraction and/or population extirpations. The CCVI used a total of 24 factors in several categories

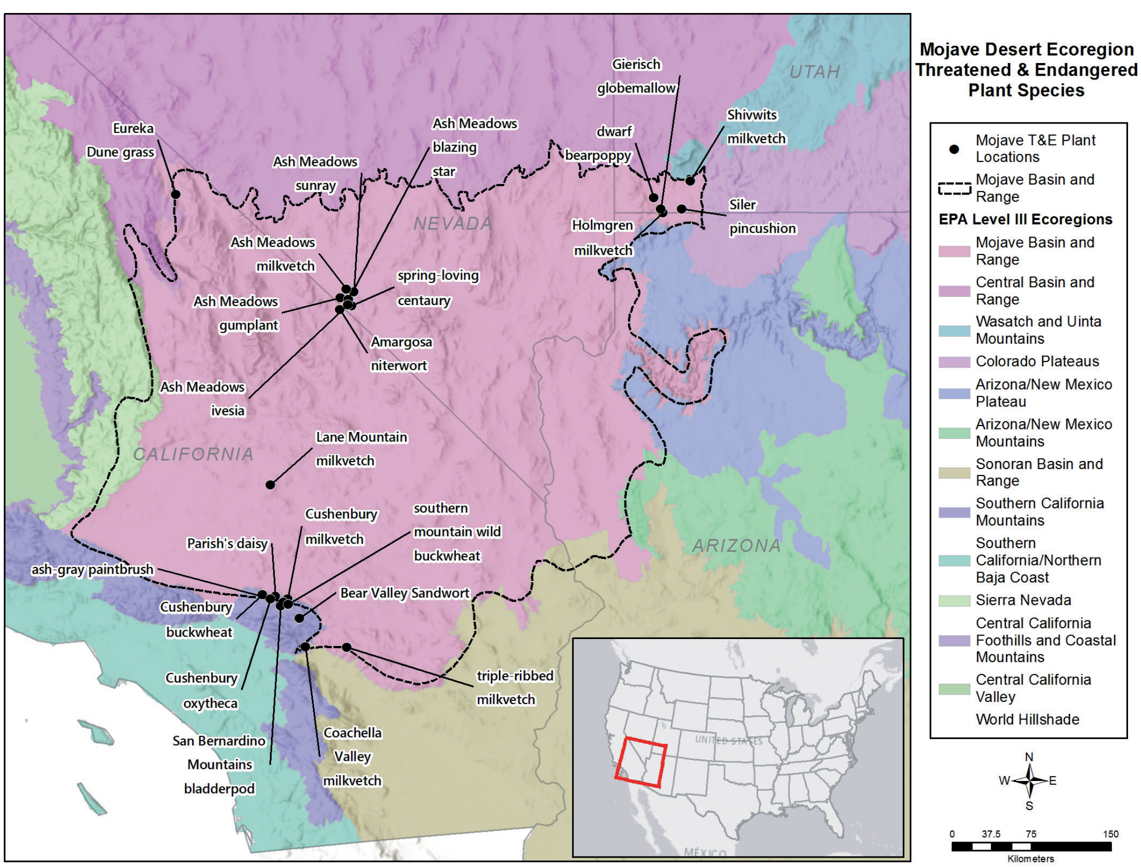


**Figure 2.**
*Plant species listed as threatened or endangered under the United States Endangered Species Act in the Mojave Desert.*

| |
|---|
| Extremely Vulnerable (EV): Abundance and/or range extent within geographical area assessed extremely likely to substantially decrease or disappear by 2050. |
| Highly Vulnerable (HV): Abundance and/or range extent within geographical area assessed likely to decrease significantly by 2050. |
| Moderately Vulnerable (MV): Abundance and/or range extent within geographical area assessed likely to decrease by 2050. |
| Less Vulnerable (LV): Available evidence does not suggest that abundance and/or range extent within the geographical area assessed will change (increase/decrease) substantially by 2050. Actual range boundaries may change. |
| Insufficient Evidence (IE): Information about a species' vulnerability is inadequate to calculate an index score. |

**Table 2.**
*Climate Change Vulnerability Index Score Descriptions [33].*

to assess the three major elements of vulnerability; exposure to climate change (direct and indirect), sensitivity, and species-specific adaptive capacity. We reviewed information about the species and entered a score for each factor according to guidance and criteria set by the CCVI [33]. Direct climate exposure was calculated by estimating projected temperature and moisture change within the assessment area, while indirect exposure was assessed by evaluating future distribution relative to barriers that may restrict a species ability to shift its' range. Mid-century (2040–2069) climate projections were used based on an ensemble-average of general circulation models and a medium emissions scenario [33]. For sensitivity and adaptive capacity, we evaluated a variety of factors including dispersal capability, reliance on specific thermal or hydrological conditions, dependence on disturbance regime or snow/ice cover, restriction to uncommon habitat types or landscape features, reliance on interspecific interactions, and genetic variation. For each sensitivity factor, we assigned a score of decrease, somewhat decrease, neutral, somewhat increase, increase, or greatly increase vulnerability to climate change. A score of unknown was given when information was lacking for a particular factor. Although some sensitivity factors were optional, the CCVI required a minimum number of factors (10) in order to avoid a determination of insufficient evidence [33].

Each species was assigned one of the following five categories based on CCVI scores: extremely vulnerable, highly vulnerable, moderately vulnerable, less vulnerable, and insufficient evidence (**Table 2**). The CCVI also calculated a categorical confidence estimate (very low, low, high, very high) for each species ranking, which was based on certainty in the factor values as represented by the frequency of multiple categories of vulnerability being selected for a given factor.

## 3. Results

The majority of the species assessed (N = 21, 88%) were found to be moderately, highly, or extremely vulnerable to climate change (**Figure 3**). Five species (21%) were extremely vulnerable to climate change, six species (25%) were highly vulnerable, and ten species (42%) were moderately vulnerable to climate change (**Figure 3**). Only three species were determined to be less vulnerable to climate change and no species received a score of insufficient evidence. The confidence

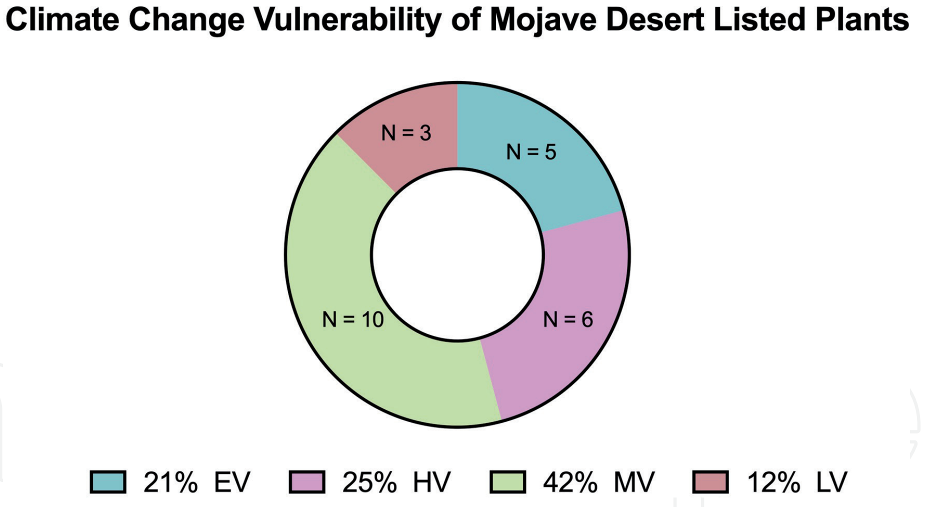


**Figure 3.**
*Proportion of Mojave Desert listed plants categorized by the following climate change vulnerability indices: EV = extremely vulnerable, HV = highly vulnerable, MV = moderately vulnerable, LS = less vulnerable. N is the number of species within each category, out of 24 species total.*

estimate for each species score was very high, indicating a large degree of certainty in the vulnerability ranking.

Among key factors, limited dispersal capability increased climate change vulnerability for almost every species assessed (N = 23), with the one exception being the only grass species, Eureka Dune Grass (*Swallenia alexandrae*), which is wind pollinated (**Table 3**). Likewise, natural or anthropogenic barriers that may impede range shifts, increased or somewhat increased climate change vulnerability for the majority of plant species assessed (N = 22, **Table 3**). Physical habitat, or restriction to uncommon geological formations or substrates, also emerged as one of the most important factors in our assessment, as it somewhat increased or increased vulnerability for most species (N = 22). The potential for climate change mitigation projects (e.g., alternative energy facilities) also somewhat increased vulnerability for many species (N = 15, **Table 3**), which is not surprising given that these desert plants inhabit areas often identified as prime locations for solar energy projects. Additionally, physiological hydrological niche was a key factor affecting vulnerability ranking in many species (N = 9), with species reliant on a particular hydrologic regime (e.g., desert springs) being assessed as more vulnerable than species not dependent on these habitats. Competition from other native or non-native species favored by climate change somewhat increased vulnerability for roughly half of the species assessed (N = 11). Genetic variation appeared to be a less important factor (N = 1), similar to reproductive system which somewhat increased vulnerability in only a few species (N = 6, **Table 3**).

The five species classified as extremely vulnerable occurred in the same geographic area (southwest Utah and northwest Arizona, **Figure 2**). Among species classified as highly vulnerable (N = 6), five of these were located primarily in a protected area at Ash Meadows National Wildlife Refuge in Nevada (**Table 3**). Species classified as less vulnerable (N = 3) also included one that inhabited a protected area (**Table 3**). Roughly 38% of the species assessed (N = 9) were located exclusively or primarily on lands under protection status, with seven species endemic to Ash Meadows National Wildlife Refuge in Nevada, one species occurring in Death Valley National Park in California, and one species in Zion National Park in Utah. In addition to climate change, many plant species were also found to be threatened by other anthropogenic factors such as agriculture, grazing, groundwater pumping, invasive species, mining, recreational off-highway vehicle (OHV) use and activities, and urban development (**Table 3**).

| Common name | CCVI | Key factors | Occurs in Protected Area | Additional Anthropogenic Stressors |
|---|---|---|---|---|
| Dwarf Bear-poppy | EV | Natural barriers, climate change mitigation, dispersal, physical habitat, pollinators, reproductive system | No | mining, power line construction, recreational OHV use, road construction, urban development |
| Shivwits Milkvetch | EV | Anthropogenic barriers, climate change mitigation, dispersal, physical habitat, competition, reproductive system | Yes | agriculture, grazing, urban development |
| Holmgren's Milkvetch | EV | Natural barriers, climate change mitigation, dispersal, physical habitat, competition, reproductive system | No | grazing, mineral development, power line construction, recreational OHV use and activities, road construction, urban development |
| Siler Pincushion Cactus | EV | Natural barriers, anthropogenic barriers, climate change mitigation, dispersal, physical habitat | No | grazing, mining, oil pipeline construction, recreational OHV use, urban development |
| Gierisch's Globemallow | EV | Natural barriers, climate change mitigation, dispersal, physical habitat, competition | No | grazing, invasive species, mining, recreational OHV use |
| Bear Valley Sandwort | HV | Natural barriers, anthropogenic barriers, dispersal, physiological hydrological niche, physical habitat, competition, reproductive system | No | mining, grazing, recreational OHV use and activities, urban development |
| Ash Meadows Milkvetch | HV | Natural barriers, climate change mitigation, dispersal, physiological hydrological niche, physical habitat, pollinators | Yes | agriculture, grazing, urban development |
| Ash Meadows Gumweed | HV | Natural barriers, climate change mitigation, dispersal, physiological hydrological niche, physical habitat, competition | Yes | agriculture, grazing, groundwater pumping, invasive species, mining, recreational OHV use, road construction |

| Common name | CCVI | Key factors | Occurs in Protected Area | Additional Anthropogenic Stressors |
|---|---|---|---|---|
| Ash Meadows Ivesia | HV | Natural barriers, climate change mitigation, dispersal, physiological hydrological niche, physical habitat, competition | Yes | agriculture, grazing, groundwater pumping, mining |
| Ash Meadows Blazingstar | HV | Natural barriers, climate change mitigation, dispersal, physiological hydrological niche, physical habitat | Yes | agriculture, groundwater pumping, mining |
| Amargosa Niterwort | HV | Natural barriers, climate change mitigation, dispersal, physiological hydrological niche, physical habitat | Yes | agriculture, grazing, groundwater pumping, mining, recreational OHV use, road construction |
| Cushenbury Milkvetch | MV | Climate change mitigation, dispersal, physical habitat | No | mining, recreational OHV use and activities, road construction, urban development |
| Lane Mountain Milkvetch | MV | Climate change mitigation, dispersal, competition, genetic variation | No | military activities, mineral collecting, mining, recreational OHV use |
| Coachella Valley Milkvetch | MV | Anthropogenic barriers, climate change mitigation, dispersal, physical habitat, competition | No | flood control projects, recreational OHV use, road construction, urban development |
| Ash Gray Indian-paintbrush | MV | Natural barriers, dispersal, physiological hydrological niche, physical habitat, competition, reproductive system | No | grazing, invasive species, mining, recreational development (e.g., ski resorts), recreational OHV use, urban development |
| Spring-loving Centaury | MV | Natural barriers, climate change mitigation, dispersal, physiological hydrological niche, physical habitat | Yes | agriculture, groundwater pumping, mining, recreational OHV use, urban development |

| Common name | CCVI | Key factors | Occurs in Protected Area | Additional Anthropogenic Stressors |
|---|---|---|---|---|
| Ash Meadows Sunray | MV | Natural barriers, climate change mitigation, dispersal, physiological hydrological niche, physical habitat | Yes | agriculture, groundwater pumping, mining, recreational OHV use, road construction |
| Parish's Daisy | MV | Natural barriers, dispersal, physical habitat | No | grazing, mining, recreational OHV use, urban development |
| Southern Mountain Buckwheat | MV | Natural barriers, dispersal, physical habitat, reproductive system | No | invasive species, mining, recreational development (e.g., ski resorts), recreational OHV use, urban development |
| San Bernardino Mountains Bladderpod | MV | Natural barriers, dispersal, physical habitat, competition | No | grazing, invasive species, mining, recreational development (e.g., ski resorts), recreational OHV use, urban development |
| Cushenbury Oxytheca | MV | Natural barriers, dispersal, physical habitat | No | hydroelectric development, mining, power line construction, recreational development (e.g., ski resorts), recreational OHV use, urban development |
| Triple-rib Milkvetch | LV | Natural barriers, dispersal, competition | No | grazing, oil pipeline construction, recreational OHV use |
| Cushenbury Buckwheat | LV | Natural barriers, anthropogenic barriers, dispersal, physical habitat | No | hydroelectric development, mining, power line construction, recreational development (e.g., ski resorts), recreational OHV use, urban development |

| Common name | CCVI | Key factors | Occurs in Protected Area | Additional Anthropogenic Stressors |
|---|---|---|---|---|
| Eureka Dune Grass | LV | Natural barriers, physical habitat | Yes | recreational OHV use and activities |

*Key factors contributing to vulnerability for each species. Factors related to indirect climate exposure include natural and anthropogenic barriers that restrict species movement in response to changing climatic conditions, and the degree to which the species may be affected by climate change mitigation actions (ie, placement of solar arrays in desert plant habitat). All other listed key factors relate to species sensitivity and adaptive capacity. Dispersal refers to the ability to move through unsuitable habitat, while physiological hydrological niche pertains to plant species dependent upon a narrowly defined water source (e.g., desert springs). Physical habitat refers to a species dependence upon a particular uncommon landscape or geological feature (e.g., gypsiferous soils). Pollinators relates to pollination strategy (e.g., dependence on only one pollinator may increase vulnerability), while competition identifies species that may be outcompeted by another species (native or non-native) favored by climate change. Reproductive system serves as a measure of genetic diversity in plants where genetic information is lacking, and genetic variation serves as a proxy for a species capacity to adapt to novel conditions. Protection area status is indicated by whether or not a species occurs exclusively or primarily in a protected area (e.g., wildlife refuge, park, area of environmental concern). Non-climate related anthropogenic stressors that are negatively affecting plant populations are also displayed.*

**Table 3.**
*Climate change vulnerability index score for threatened and endangered plants in the Mojave Desert (EV = extremely vulnerable, HV=highly vulnerable, MV = moderately vulnerable, LV = less vulnerable).*

## 4. Discussion

Our results suggest that climate change may pose additional threats, or exacerbate current stressors, for threatened and endangered plants in the Mojave Desert. Many listed plants are rare species characterized by relatively narrow ecological niches, small population sizes and restricted geographic ranges [34]. Although these traits may contribute to a species decline in a world increasingly influenced by human activity, these factors alone do not determine likelihood of extinction. Numerous species that were once locally common or abundant (e.g., elephants, lemurs, orangutans) have become endangered due to hunting, habitat loss, agriculture, or other human endeavors. Rarity may have been a contributing factor, but Mojave Desert listed plants became threatened or endangered primarily because of anthropogenic stressors. Climate change has not been considered in measures of extinction risk in the past, and this phenomenon has the potential to accelerate extinction processes for species already struggling to persist. For example, the five plant species classified as extremely vulnerable by our CCVI (Dwarf Bear-poppy, Shivwits Milkvetch, Holmgren's Milkvetch, Siler Pincushion Cactus, Gierisch's Globemallow) occur only in a small geographic area located in southern Utah and northern Arizona. Climate change is projected to be particularly severe for this part of the Mojave Desert, with a 2.2°C–4.4°C increase in annual temperature predicted by the end of the century (2070–2099) and a 30% reduction in snowpack, which functions as the regions' main source of water [35].

Although Shivwits Milkvetch occurs predominantly in a protected area (Zion National Park), the remaining four plants categorized as extremely vulnerable do not. These species are habitat specialists restricted to gypsiferous soils located largely on federally managed public lands where populations are also threatened by recreation, grazing, and gypsum mining. One frequent suggestion for managing imperiled species under climate change is to reduce existing threats in order to increase resilience to climate change [36]. Threats could be minimized by placing core habitat areas under protection status, which has been successful in recovery efforts for another listed plant in the Mojave Desert, the Eureka Dune Grass. The species was recently down listed from endangered to threatened, mainly as a result of habitat areas becoming part of Death Valley National Park which prohibits OHV use in Eureka Dunes [37]. This strategy may not be effective throughout the Mojave Desert, however, as listed plant species in Ash Meadows National Wildlife Refuge continue to decline despite similar protection status [38]. Endemic species in this refuge rely upon rare, wet microhabitats sustained by desert springs or shallow groundwater, which are vulnerable to groundwater pumping and drought. Groundwater pumping is very likely to increase throughout the Mojave Desert as droughts become more frequent and dry conditions are intensified by climate change, and the future of many Ash Meadows species remains uncertain.

Similar to other studies related to CCVAs of imperiled plants, our vulnerability scores were strongly associated with two analogous factors, natural or anthropogenic barriers and dispersal ability. In highly urbanized and densely populated regions of California, anthropogenic barriers limited the dispersal capability of 63% of plant species assessed [39]. A lack of topographical variation presented a bigger challenge in other regions, as plant species inhabiting areas of topographical homogeneity may experience climate change effects sooner since they are unable to move up or down in elevation [40]. For plants in relatively flat regions of the United States, such as Illinois, latitudinal migration may be the only effective survival mechanism, which will require assisted migration as individuals will not be able to disperse through highly urbanized areas [40]. In contrast, the Mojave Desert is relatively undeveloped and topographically diverse, thus offers opportunities for plants to shift to higher elevations and more mesic microhabitats. Hot, dry desert valleys and other areas of unsuitable habitat may present similar barriers to dispersal, however. *Some* of the plant species assessed here *could* be good candidates for assisted migration, assuming appropriate substrates and ecological conditions (e.g., pollinators, hydrological regimes) are available on the landscape and successful restoration techniques are established.

## 5. Conclusion

Information produced by the CCVA can be used to identify threatened and endangered plants most vulnerable to climate change in the Mojave Desert. Species vulnerability assessments break down the complexity of climate change impacts on overall biodiversity, and facilitate the integration of societal, economic, and other environmental concerns into conservation planning efforts. Our assessments also identified knowledge gaps for each species, which promotes the development and testing of new hypotheses about climatic tolerances. Furthermore, the identification of particular traits that make a species vulnerable allow for targeted management actions. Recovery and management plans for threatened or endangered species can be updated to include climate change vulnerability and its implications, which may necessitate the inclusion of different stakeholders or increased frequency of monitoring to detect distribution shifts. The Mojave Desert is a unique ecoregion beloved by many and there is still much uncertainty related to the magnitude and extent of global atmospheric and climatic change. Our hope is that results presented here contribute to the larger body of knowledge for the region, and aid in better stewardship of these irreplaceable ecological systems and inhabitants.

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