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*Comment Received From: Pat Flanagan*
*Submitted On: 2/26/2026*
*Docket Number: 24-OPT-03*

## MBCA Soda Mtn Solar comments

*Additional submitted attachment is included below.*

morongo basin conservation association

Post Office Box 24, Joshua Tree CA 92252 http://mbconservation.org

*MBCA is a 501 (c)3 non-profit, community based, all volunteer organization*

California Energy Commission
715 P Street
Sacramento, California 95814

Subject: Docket Unit, MS-4
Docket No. 24-OPT-03 Email: docket@energy.ca.gov

As requested, this letter explains the importance of the individual Pdfs I submitted to CEC staff during the Soda Mountain Solar Project public meeting on February 5, 2026. The Pdfs speak to

- dust generation in the Mojave Desert when soils are disturbed during the construction, operation, and following shutdown of utility solar projects;
- the ability of the desert to sequester carbon underground for millennia when left undisturbed.

I felt an obligation to provide this science based information because I live directly downwind 7.5 miles from the original solar project constructed outside the town of Joshua Tree in 2014. My property is surrounded by intact desert and until the solar project construction my air was clean no matter the wind. Then one day with a strong wind coming from the west a cloud of dust enveloped my house and closed me in until the cloud passed. Such dust clouds continue to this day. Because of the changing climate our communities were originally excited by local solar development until we learned the perils to air quality (PM10 and PM2.5), our health, and the desert environment when the intact desert is destroyed. Below are photos showing what we have experienced and what you can expect will cloud the I-15 and surrounding desert and mountains when the wind blows should Soda Mountain Solar be constructed.

Figure 1: Dust rising off the 150-acre Cascade Solar in Joshua Tree on 03/28/**2016**. The facility went on line 04/**2014**. Photo courtesy of Tom O'Keye.

Figure 2: Dust rising off Cascade Solar 01/**2025**. Photo courtesy of Laraine Turk.

For an introduction to the interconnection between carbon sequestration and dust generation in the desert read

(1) *The Desert Under Our Feet* by Robin Kobaly published in the March 2019 Desert Report, and the

(2) *Science Brief: Climate Mitigation in California: The importance of conserving carbon in deserts* by Defenders of Wildlife.

(3) The *AB 1757 Desert Sector Letter* is a brief introduction to the report *Nature Based Solutions: Desert Sector.* This report was later upgraded to richly referenced chapters in

(4) *The California Desert's Role in 30X30: Carbon Sequestration and Biodiversity.* Below is the Report Overview with the list of chapters.

**REPORT OVERVIEW**



And the chapter authors


**Dr. Michael Allen**, Ph.D. Distinguished Professor Emeritus. Department of Microbiology and Plant Pathology, University of California, Riverside

**Dr. Cameron Barrows,** Ph.D. Conservation Ecologist, Emeritus. Center for Conservation Biology, University of California, Riverside

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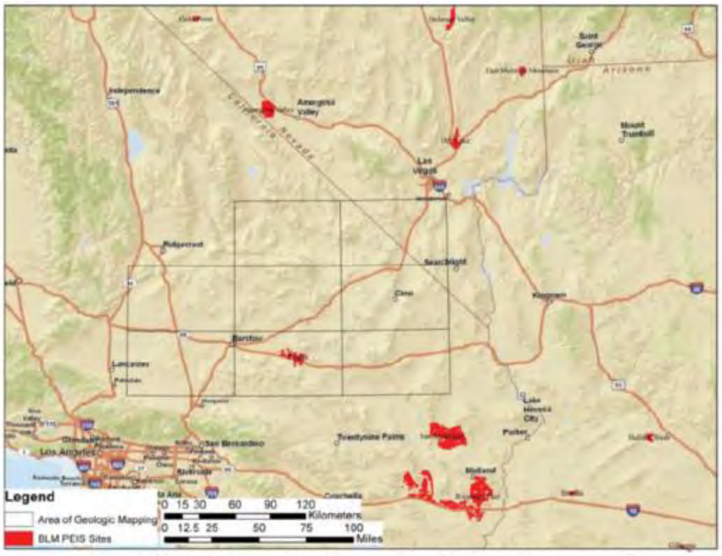
**Arch McCulloch,** M.S. Computer Science. Azusa Pacific University. B.S Geology / Computer Science. California State University, Dominguez Hills

**Joan Taylor,** Governing board of the Coachella Valley Mountains Conservancy, and boards of Friends of the Desert Mountains and The Wildlands Conservancy. Chairperson, California Conservation Committee and California/Nevada Desert Committee of Sierra Club

This report was developed to support the State's Pathway's to 30X30 project with more accurate data for the Sparsely Vegetated Land (includes the desert) category – Chapter VIII Biodiversity in our deserts.

(5) USGS Poster (2012?) *Assessing the geology and geography of large footprint energy installations in the Mojave Desert, California and Nevada*. David R. Bedford and David M. Miller. U.S. Geological Survey.




Area of analysis in the three-state Mojave Desert region. BLM-designated PEIS sites are also shown

Figure 3: Overview Map from the poster showing the area analyzed which includes Soda Mountain Solar on the I-15 east of Barstow.
From the Abstract: "About 48%of the entire area is less than 5% slope, and 8.3% is less than 1% slope, the favored slope category. For this lowest-slope category, deposits underlying about 98% of the area are either mixed eolian-alluvial origin or are fine-grained alluvial deposits, and thus susceptible to eolian dust and sand transport, especially after disturbance. In addition, in this low-slope category, 89% of the area is susceptible to flooding, based on the age and geomorphology of alluvial deposits." (emphasis added)

(6) USGS *Soil Surface Susceptibility to Wind Erosion*. Jayne Belnap, Sue Phillips, David M. Miller etc. This study analyzes the Threshold Friction Velocity (TFV), the wind speed at which particles move and the amount of soil blown off the soil surface at high spring wind speed. The Mojave National Preserve was selected to physically assess the vulnerability to wind erosion including the soil surface characteristics and climate and the percent time per month that a TFV is exceeded.

The town of Baker and the Soda Mountain Solar Project are within the boundary of the area analyzed.

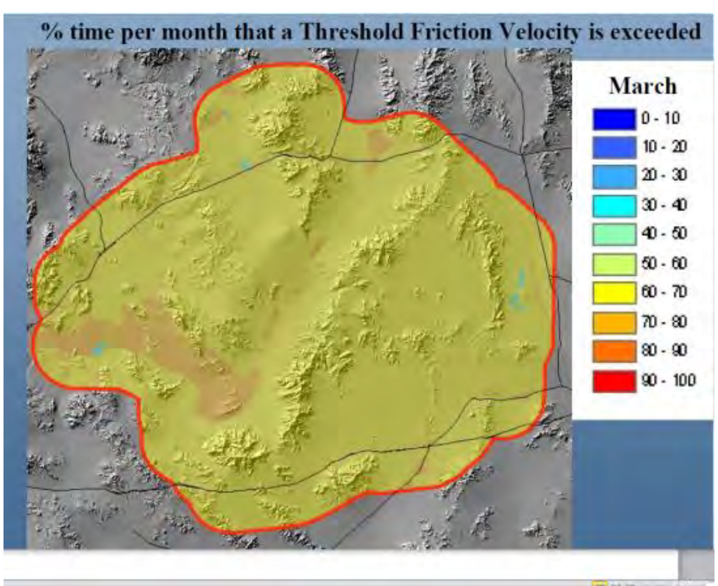



Figure 4: Soil Surface Susceptibility to Wind Erosion showing the percent time per month that a TFV is exceeded in the Mojave National Preserve. From March through October the TFV can exceed more than 60% of the time. (emphasis added)

(7) *Vulnerability of desert biological crusts to wind erosion: the influences of crust development, soil texture, and disturbances. Jayne* Belnap and Dale A. Gillette. Journal of Arid environments (1998) **39**: 133-142 Article No. ac980388. This article was not in the original Pdfs provided but is important to completely understand wind erosion in the desert.

From the Abstract: "Biological soil crusts, consisting of cyanobacteria, green algae, lichens, and mosses, are important in stabilizing soils in semi-arid and arid lands. Integrity of these crusts is compromised by compressioned disturbance such as foot, vehicle, or livestock traffic. Using a portable wind tunnel, we found threshold friction velocities (TFVs) of undisturbed crusts well above wind forces experienced at these sites; consequently, these soils are not vulnerable to wind erosion. <u>However, recently disturbed soils or soils with less well-developed crusts frequently experience wind speeds that exceed the stability thresholds of the crusts</u>." (emphasis added)

(8) *Sand Transport Paths in the Mojave Desert, Southwestern United States*. James B. Zimbelman, Steven H. Williams, and Vatche P. Tchakerian, Desert Aeolian Processes Edited by Vatche P. Tchakerian. Published in 1995 by Chapman & Hall. London.

Remote sensing and field evidence are used to describe sand deposits found in associated pathways of emplacement in the eastern Mojave Desert.

Figure 1. (b) Simplified sketch map of the area shown in Figure 1a. Selected playas (gridded pattern, names in parentheses), mountains (names listed at appropriate location), and rivers (arrows show direction of flow) are labeled for reference. Sand deposits are shown in dotted patterns; the open pattern represents active (relatively unvegetated) dunes (KD = Kelso Dunes, CD = Cadiz Dunes, AD = Algodones Dunes) and the dense pattern represents inactive (stabilized by vegetation) deposits. Note that foreshortening due to the oblique viewing geometry causes horizontal scale variations across the area.


Figure 5**:** Sketch map of the analyzed Sand Transport Paths. Note locations along the Mojave River.

Figure 6:
Screen shot of
Daggett Solar in
Newberry Springs
12/21/2021.
Courtesy of
Ted Stimpfel.

Figure 6 shows what happens when development occurs in the sand transport path. The picture, taken December 21, 2021, shows dust blowing over the “protective” fence surrounding Daggett Solar Power Project in Daggett-Newberry Springs, in the Mojave River Valley.

These materials should be incorporated into the library of reports and scientific papers used by the CEC staff for analysis of utility solar power projects in the desert. As noted in the *California Desert’s Role in 30x30,* the two key takeaway messages are that in order to maintain desert biodiversity, carbon sequestration, and air quality the following are necessary:

1. The desert’s carbon storage process differs significantly from more widely understood sectors such as forests, grasslands, chaparral, and wetlands.
2. Because of the distinct carbon storage process found in the desert ecosystem, there is one recommended strategy to maximize the desert sector’s contribution to carbon emission reduction: intact desert lands need to be left undisturbed.

The proposed Soda Mountain Solar Project does not support the goals of the 30x30. The DEIR does not accurately reflect the soil conditions or the impact of the development on dust and air quality. Further the DEIR does not recognize the important role intact desert systems play in the sequestration of carbon thus the analysis in the DEIR is not complete and must be reanalyzed.

Further, if the proposed project goes forward, it will have detrimental impacts on the state’s 30x30 goals. The purpose of AB205 surely did not include development of projects that are counter to the state’s interest. The County of San Bernardino did not approve this project for good reasons which still apply especially related to water used to manage dust. The amount of water that is estimated to be necessary to control dust is a vast underestimate of actual water use by other projects. This is predicated on the erroneous assumption that dust can be controlled using water, see figures 1, 2, and 6. This dust will also obscure visibility on Interstate 15 and pose a significant risk for drivers.

The no-action alternative is the only sustainable alternative and should be the one adopted by the CEC for the project.

Sincerely,

Pat Flanagan,
Board member MBCA

Pdfs attached to email:

1. The Desert Under Our Feet, Robin Kobaly
2. Science Brief: Climate Mitigation in California: the Importance of conserving carbon in deserts. Defenders of Wildlife, Defenders of Wildlife
3. AB1757 Desert Sector Letter
4. The California Desert's Role in 30X30: Carbon Sequestration and Biodiversity
5. USGS Poster: Assessing the geology and geography of large footprint energy installations in the Mojave Desert, California and Nevada, David R. Bedford and David M. Miller
6. USGS Soil Surface susceptibility to Wind Erosion, Jayne Belnap, Sue Phillips, David M. Miller
7. Vulnerability of desert biological crusts to wind erosion: the influence of crust development, soil texture, and disturbances. Jayne Belnap
8. Sand Transport Paths in the Mojave Desert, Southwestern United States. James Zimbelman et.al.

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The SummerTree Institute

FACTS
Families Advocating for Chemical & Toxics Safety
A project of Center for Environmental Health

MOJAVE DESERT LAND TRUST

September 14, 2023

Email to: naturebasedsolutions@resources.ca.gov

RE: Desert Sector Targets for AB 1757

Dear CNRA, CARB, and CDFA:

Thank you for the opportunity to provide input to the California Natural Resources Agency [CNRA], California Air Resources Board [CARB], and California Department of Food and Agriculture [CDFA] on the importance of desert carbon sequestration as part of AB 1757's commitment to reaching our state's broad climate change goals. We are writing to you as a science-focused subgroup of the 30 X 30 Inland Deserts Working Group, affiliated with the statewide 30 by 30 Power in Nature coalition, to urge CNRA's, CARB's, and CDFA's affiliated staff to read the attached comprehensive report, *Nature Based Solutions: Desert Sector*. Our detailed biographies are in the report.

The California desert region has been largely overlooked as a significant carbon sink for several reasons. First, the scarce aboveground vegetation is visually misleading if one assumes a singular correlation between aboveground biomass and carbon sequestration capacity. This misperception is tied to a second reason for overlooking the desert sector: the desert ecosystem primarily sequesters carbon underground. Finally, as an underfunded research ecosystem, the desert sector remains woefully behind its companion ecosystems such as forests, grasslands, chaparral, and wetlands in terms of quantifying, measuring, and modeling carbon sequestration capacity. But

there is more than sufficient research to make this salient point: the desert lands of California are a significant carbon sink and must be included in regional and global carbon accounting.
Our analysis offers three key takeaway messages:

- The desert's carbon storage process differs significantly from more widely understood sectors such as forests, grasslands, chaparral, and wetlands.
- Due to the distinct carbon storage process found in the desert ecosystem, there is one recommended strategy to maximize the desert sector's contribution to carbon emission reduction: it needs to be left undisturbed.
- Large-scale disturbance of deserts, particularly within critical ecosystems such as creosote bajadas and microphyll woodlands, will not only result in the reduction of California's biodiversity, but also in the removal of a long-term carbon sequestration source, releasing calcite carbon that has been stored for millennia.

**Specifically, our recommended target for the desert sector is conservation of 100% of <u>undisturbed</u> non-military public lands annually based on current levels, starting in 2024, and that regions displaying higher densities of microphyll woodlands and creosote bajadas be especially prioritized due to their higher capacity for carbon sequestration.**

The discrepancy between our group's recommendation and CARB 's (which is to cut land conversion of deserts and sparsely vegetated landscapes by at least 50 percent annually from current levels, starting in 2025) is based on fundamental characteristics of the unique and fragile desert ecosystem. Whereas a forest ecosystem can be disturbed (harvested) with a relatively brief recovery time, and even managed to restore carbon sequestration over the long term, the desert region has no options for recovery of lost carbon within the time-scale of this planning effort. And once the carbon is stored underground in caliche soil layers, it remains there for upwards of thousands of years if left undisturbed. So it is critical to understand that CARB's recommendation would result in *permanent loss of carbon storage for all desert land that has been disturbed*. Here is further reasoning behind our recommendation:

**(1) How the desert captures and stores carbon is unique in process and timescale.**
While desert plants do capture and store carbon aboveground in foliage and woody tissue, they store much of their captured carbon deep underground in a massive network of connected roots and fungal root-partners, unlike forests which store most of their carbon aboveground or near the soil surface. Some of this carbon is stored in the tiny but numerous filaments of root-partnering fungi, and because there can be so many miles of fungal hyphae in each cubic foot of desert soil, it is attributed with storing one-third of the world's soil organic carbon. Also, much of the carbon that desert plants capture aboveground from the air eventually turns into inorganic carbon underground in mineralized deposits called calcite or caliche. These calcite/caliche deposits can store captured carbon in this inorganic form for millennia.

**(2) Quantification of net ecosystem exchange (NEE).**

Our recommendation is based on scientific analysis of photosynthesis data from the desert ecosystem [Appendix A]. In plants and soils, atmospheric $CO_2$ is absorbed during photosynthesis and released during respiration which can be quantified as "net ecosystem exchange", or NEE. In individual years, it can be highly positive or negative depending on the environmental conditions and the variability is extremely high in deserts.

NEE values are critical in assessing carbon sequestration capacity. In many cases, these are short term datasets. We are desperately in need of long-term background data for good decisions.

*Based on surface area in vegetation maps, the extrapolated NEE value amounts to 1.5 to 1.88 million tons of carbon annually pulled out of the atmosphere by desert vegetation.*

Based on scientific analysis of photosynthesis data from the desert ecosystem, highest priority should be given to conservation of microphyll woodlands and creosote bajadas. The transfer of atmospheric carbon to desert biomass in microphyll woodlands and creosote shrubland is relatively insensitive to local precipitation. These vegetation types have access to alternate sources of water, including moisture from large rain events even miles away that saturate the soil, and access to groundwater by deep roots. These factors allow plants in microphyll woodlands and creosote bajadas to photosynthesize and sequester carbon through the seasons even without local precipitation. For this reason, it is inaccurate to assume that the arid desert climate equates with poor NEE values that form the basis for carbon sequestration.

**(3) The undisturbed desert is a long-term carbon sink.**

*Carbon storage capacity is a function of both quantity and timescale.* The desert ecosystem, long regarded as an insignificant carbon sink, outperforms other ecosystems in carbon storage by holding on to that carbon for longer periods of time if left undisturbed. For instance, while a temperate forest may have an average organic turnover time of 25 years, the desert's turnover time is 38 years. That difference is of a higher magnitude for soil/sediment of each ecosystem: the temperate forest average turnover time is 55 years, but the desert's is much more extended at 200 years. **See Appendix B** for a comparison of average organic carbon turnover in years across a spectrum of ecosystems. Unlike the large storage of organic C in most ecosystems, much of the desert total carbon is stored as calcites, generated from soil respiration. If buried and undisturbed, this carbon can remain sequestered for millennia (Schlesinger 1985). *There could be more than 262 million tons of C stored in California deserts as calcites.*

**(4) Modeling.**

Our group acknowledges the critical role that modeling will play in projecting, measuring and quantifying carbon sequestration within the desert sector. We recommend an additional carbon sequestration modeling framework to reconcile the desert carbon budgets using an ecohydrology approach. Deep water use (rather than precipitation) of microphyll woodlands and creosote bajadas is a more accurate representation of moisture dynamics for these vegetation types. By incorporating deeper water use and using the normalized difference vegetative index {NDVI} as a driver of $CO_2$ fixation (Rohde et al. 2021), we produce more accurate modeling projections by linking the NEE to deep carbon sequestration [please see attached *Nature Based Solutions: Desert Sector* report for additional supporting data and studies].

**(5) Tools, frameworks, collaborations and investments to deliver recommended targets.** There are planning tools currently available that allow decision makers the opportunity to simultaneously develop solar installations on desert lands, while protecting conservation values including carbon sequestration all at once. This is the kind of pioneering work that establishes California as an environmental leader. It is laudable that through your work the California Natural Resources Agency (CNRA) and the CARB will have a better understanding about how Natural and Working Lands can contribute to CARB's total carbon stock percent change of -4% by 2045, but we strongly recommend that *the state energy agencies, California Public Utilities Commission and California Energy Commission, also be closely engaged to ensure on-the-ground consistency* with this unprecedented effort.

*One planning tool is the Carnegie Energy and Environmental Compatibility [CEEC] model*, a multiple criteria model that quantifies each solar installation based on environmental and technical compatibility. *Techno-ecological synergies [TES] is a second tool* for decision-makers seeking to integrate the advancement of utility-scale solar with conservation of our desert lands. This is a framework proposed by a group of researchers led by Dr. Rebecca R. Hernandez of UC Davis which engineers the mutually beneficial relationships between technological and ecological systems to bolster the sustainability of solar energy across a suite of environments including land, water, and built-up systems. Details for both of these planning tools are available in our report.

*There are alternative options to disturbance of intact desert lands***.** We recognize that there is an urgent need to transition to clean energy. Although perhaps well-intended, development of large-scale utility projects across previously undisturbed desert lands is counterproductive. Disruption of desert soils and vegetation releases significant carbon back into the atmosphere, defeating the purpose of natural and working lands utilized as a natural carbon sink. Further, such development on intact lands is not necessary because there are numerous feasible options for developing utility scale solar in California that can deliver the state-estimated need for 70,000 MW of new utility scale solar (CEC 2021) which, if entirely ground-mounted with current technology, would require approximately 350,000 acres of land. Some of these options include:

- Water-deprived ag lands in the Central Valley estimated to be a minimum of 500,000 acres (Hanak et al, 2019) or as much as 900,000 acres (Escriva-Bou et al, 2023)
- 250,000+ acres of selenium- contaminated land in the Westlands Water District
- 200,000+ acres of parking lots in California (USGS 2019)
- 11,500 megawatts on commercial/industrial rooftops near substations (RETI 2009), with far greater rooftop potential today
- 4,000 miles of canals and 16,000 miles of highway right of ways
- Agrivoltaics (ie, slightly elevated or spaced photovoltaic panels) on a portion of the 25+ million acres of farm and ranch lands throughout the state

*Investments needed to deliver on targets*. Our group has assessed a long-standing need to invest in scientific, peer-reviewed research relevant to identifying, mapping, quantifying, and modeling carbon sequestration in arid desert lands. The desert ecosystem is far behind other ecosystems in obtaining measurable data critical for 30X30 work. There is adequate data to confirm the existence of carbon sequestered underground in the desert, but substantial gaps exist for more granular analysis.

Additionally, we strongly recommend investment in expansion of already existing tools, and consultation with experts in integrating conservation strategies in the desert with technology. For example, the work of Dr. Rebecca Hernandez from UC Davis and her team would provide a mechanism for achieving the dual goals of desert conservation while utilizing technology schemes to maximize carbon sequestration in the desert and protecting biodiversity.

*Additional benefits of desert land conservation.* Conserving intact desert lands offers additional benefits that are essential to 30 X 30 goals. Conservation of undisturbed desert lands provides protection for one of the most biodiverse ecosystems on the planet. So-called desert “wastelands” are not only richer from a biodiversity standpoint, but they also appear to be incubators of speciation, with many species occurring nowhere else on earth. A recently published study, Pillay et al. (2022, *Frontiers in Ecology and the Environment*, vol. 20, issue 1) looked at patterns of vertebrate animal species richness across our planet. As expected, they found that the tropics ranked number one. However, deserts were the next most species-rich biome when it came to mammals, birds, and reptiles, higher than temperate forests, shrublands, and grasslands. Critical health benefits are conferred by conservation of undisturbed desert lands which include preventing mobilization of dangerous desert dust particulates that contribute to a suite of respiratory illnesses (particularly among disadvantaged communities), and sustaining economic stability provided by tourism and recreation to the desert region’s intact landscapes.

**Conclusion.**

Our recommendation that the best strategy for employing natural and working lands in the desert region is ***conservation of 100% of undisturbed non-military public lands annually based on***

***current levels, starting in 2024 is based on a foundation of scientific literature.*** The carbon sequestration process in California's deserts occurs primarily underground, and avoidance of disturbance to desert soils is the means to maximize carbon sequestration within the desert sector.

Thank you for the opportunity to contribute comments. We stand by for further discussion and to provide additional guidance.

Sincerely,

**Dr. Michael Allen**, Ph.D.
Distinguished Professor Emeritus, Department of Microbiology and Plant Pathology
University of California, Riverside

**Dr. Cameron Barrows,** Ph.D**.**
Conservation Ecologist Emeritus, Center for Conservation Biology
University of California Riverside

**Colin Barrows**
Co-founder, CactusToCloud Institute

**Susy Boyd,** MNR
Master of Natural Resources, Oregon State University
Public Policy Coordinator, Mojave Desert Land Trust

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Families Advocating for Chemical and Toxics Safety

## Appendix A

**Comparison of desert regions with other ecosystems of published net ecosystem exchange [NEE].**

| | |
|---|---|
| Mesquite stands [Desert] | 200 kg.ha$^{-1}$y$^{-1}$ [[Huxman et al. 2004] |
| Creosote bajada [Desert] | 1,000 kg ha$^{-1}$y$^{-1}$ [Jasoni et al. 2005] |
| Baja California [wet year] | 520 kg ha$^{-1}$y$^{-1}$ [Hastings et al. 2005] |
| Sky Island coniferous forest above SoCal de | 300 kg ha$^{-1}$y$^{-1}$ [Allen et al. 2014) |
| Chaparral [100 y/o, wet year] | 520 kg ha$^{-1}$y$^{-1}$ |
| Sky Island coniferous forest above SoCal deserts | 300 kg ha$^{-1}$y$^{-1}$ [Allen et al. 2014] |
| Chaparral [100 y/o, drought year | 180 kg ha$^{-1}$y$^{-1}$ |
| La Selva tropical rainforest | 3,000 kg ha$^{-1}$y$^{-1}$ |
| Boreal forest | 780 kg ha$^{-1}$y$^{-1}$ |

## Appendix B

Deserts undertake the conversion of CO2 (from soil respiration) into calcites. Deserts effectively store both calcites and organic carbon. The table below illustrates average turnover time (years) of organic carbon in both ecosystem types and soil/sediments.
Desert organic carbon once fixed stays in the system longer than in other ecosystems, releasing back to the atmosphere slowly. This storage benefit is most notably pronounced in desert soil and sediment. Calcites, layered into caliche, form from autotrophic respiration from deep roots and symbiotic microbes, and from heterotrophic respiration from the transferred organic matter. Disturbance to desert lands undermines the carbon storage process. Importantly, buried calcites are dissolved upon exposure to air and water. Upon exposure, the $CO_2$ in calcium carbonates can be released from disturbed soils up to 2.4g $C \cdot m^{-2} \cdot day^{-1}$, or 24 $kgC \cdot ha^{-1} \cdot day^{-1}$ following a precipitation event (Swanson 2017).

| **Ecosystem Type** | **Ecosystem Organic C Turnover Time** | **Soil/Sediment Organic C Turnover Time** |
|---|---|---|
| Desert | 38 years | 200 years |
| Temperate forest | 25 years | 55 |
| Cropland | 22 years | 40 |
| Perennial grassland | 36 years | 100 |

**Reichie 2020**

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NEWS OF THE DESERT FROM SIERRA CLUB CALIFORNIA & NEVADA DESERT COMMITTEE MARCH 2019

# DESERT REPORT

BY ROBIN KOBALY

## THE DESERT UNDER OUR FEET

### An extraordinary biological web that serves us in countless ways

**WE ARE WITNESS TO ASSAULTS ON OUR DESERT LANDSCAPE EVERY** day, but we usually recognize only what we see above ground. In fact, these surface alterations result in critical changes below ground that have far-reaching implications that are mostly unnoticed or unappreciated. If we could see the intricate systems that hum along invisibly underground, we would likely fight even harder to protect our desert landscapes from unnecessary disturbance.

Research around the world is showing that the biggest contributors to soil stability in deserts are the smallest of microorganisms. Tiny microbes hold our desert landscape together. The valuable role of hidden microorganisms in keeping our air cleaner, preventing dust storms, controlling erosion, and helping us reduce carbon dioxide levels in our atmosphere is enormous, but that role is mostly overlooked when we make land-use decisions in our desert.

**Biological Soil Crusts: Stabilizing Soil and Influencing Water Runoff**

Across arid soils, a thin crust often forms within the top few centimeters of the soil surface. Surprisingly, these crusts are not exclusively formed from excess minerals, as is often thought, but are created by microscopic and somewhat larger macroscopic organisms that live together in a tiny but profound world.

Whenever it rains, a cast of soil creatures (including cyanobacteria, formerly called blue-green algae, plus bacteria, fungi, and other microbes) that have been patiently sleeping wakes up like a scene in Sleeping Beauty's castle. Released from the spell of drought, these microscopic creatures start making food and creating miniature subway tunnels as they move through the soil, reproducing as long as the soil is moist. Tunnels of sticky mucilage around algae filaments allow the algae to move into new frontiers while moisture paves their way.

As the soil dries out after rain, a slumber again falls over the entire

→ PAGE 14

Deep roots, evening primrose.
2018 © Robin Kobaly

# THE DESERT UNDER OUR FEET

→ PAGE 1

community, and the soft, gluey tunnels start to dry out – but not before tightly binding all the soil grains they have touched. The value of this thin, living "skin" across our desert soil is not only expressed during its wet "waking hours," but also during its dry dormant time when it performs the critical role of gluing soil particles together against wind and water erosion.

During the following months or years of drought, these sticky tunnels continue to bind soil grains together. The result of this microscopic community is a protective seal across the soil surface called a biological soil crust that keeps dust, particulate matter (PM10s and PM2.5s), and harmful fungal spores like valley fever from being blown up into the air wherever soil has not been disturbed. These living soil crusts take hundreds of years to develop into effective soil sealants, but when they are allowed to remain intact, they not only hold back wind and water erosion, but also supply nutrients to neighboring higher plants, improve water infiltration, prevent choking dust storms, and help keep our air clean and healthy. Plus, they do all this for us while they are sleeping.

**Mycorrhizae: A Strategic Partnership Between Plants and Fungi**

Working both above and below this marvelous crust, plants are breathing in massive amounts of carbon dioxide from the air, reassembling the carbon into sugar, then transporting it underground to grow roots. Byproducts from this growth (photosynthesis) become locked in hidden carbon storage vaults underground, both living and non-living, for many hundreds of years. Small shrubs like Blackbrush can live at least 400 years, while Mormon Tea can live over 250 years. Our Mojave Yuccas are youngsters at 500 years old, and may live to several thousand years old. And even more impressive are Nolinas, Desert Ironwood trees, and California junipers that may live to over 1000 years.

Roots from these carbon-eating plants reach far underground, some as much as 150 feet deep (roots of succulents like cacti and yuccas are not as deep; they have other survival tricks). Roots this deep are essential to reach soils still moist from rains that may have fallen many years ago, and these deep, living "straws" create an upside-down forest of craggy wood, resulting in a greater mass of living tissue below ground than what we see above ground.

All these deep roots are not separate and alone in their quest to gather water and nutrients to survive. Eons ago, they struck upon a partnership with fungus that helps them absorb moisture and nutrients from an arid soil that is almost devoid of either. Over 90% of plants on earth belong to this "root partners' club," a lifelong membership that grants participating plants special privileges.

Moisture and valuable resources like phosphorus and nitrogen are all gathered and delivered to the plant partner through thin threads of widely dispersed fungal hyphae called mycelium. In exchange, the plant host supplies sugars to their "mycorrhizal" fungal root partners, which, for all their near-magical powers, cannot make their own food. A good trade indeed. This partnership has been called a "subterranean swap meet."

But the fungal partner offers more to this relationship; it offers immune-boosting compounds and antibiotics and bitter-tasting chemicals that deter animals and insects from eating its host's leaves. Even more mind-boggling, fungal threads from neighboring plants can merge with adjacent fungal threads to connect plant to plant in a massive community network that "exchanges information" between plants for the good of the whole community.

Without seeing anything above ground, the mycelia below ground transmit information about dangers like insect attacks and initiate the production of pest-repelling compounds in the leaves of the plants connected to this "root partner's club." No single plant has to fight an intruder on its own. This information-sharing network of fungi has been dubbed "nature's internet" or the "Wood Wide Web."

Mycorrhizal Mushrooms. 2018 © Robin Kobaly

The benefits of this hidden relationship extend beyond the exchange of resources between plants and fungi. Both the root and the fungus are breathing out carbon dioxide in the dark (plants breathe *in* carbon in the light, and breathe *out* carbon in the dark). Right at the point where a tiny fungal thread connects to the plant root, some of the carbon dioxide exhaled by roots and fungi reacts with calcium in the soil to form crystals of calcium carbonate, or what is called caliche. Carbon in these crystals becomes locked into the soil.

Over time, large chunks or even vast layers of caliche are built up underground, capturing carbon from our atmosphere in an underground lock-box and reducing its potential escape into the atmosphere. This transfer of carbon from air to leaf to root to fungal partner and into caliche deposits is one of nature's ways to sequester carbon and hold it in natural storage underground.

All that we need to do to keep the carbon safely stored in the underground caliche is to allow the desert plants to keep living and sequestering carbon. It is thought that some of the vast caliche beds in our southwest desert soils may have been formed over thousands of years. Some of our longest-lived desert plants may have germinated right after the last ice age receded 10,000 years ago and are still growing today, capturing carbon underground over millennia (King Clone, a cloning creosote in Johnson Valley, estimated to be almost 11,000 years old, is one example).

**Glomalin: Hiding Place for a Third of the World's Carbon**

There is still more to this incredible story. Every hyphae (the thread-like "root" of a fungus) of the most common kind of root-partnering fungus in our desert (arbuscular mycorrhizal fungi) is coated with a waterproof sealant called "glomalin." This coating of sticky protein around each fungal thread prevents leakage when water and nutrients move through the hyphae. Glomalin is made directly from carbon gathered by its plant partner, so again atmospheric carbon is being moved from air into soil for long-term storage.

Remarkably, each hyphae's *coating of glomalin* persists in the soil after the fungal thread dies (when the growing root section matures and barks over). For another 30 to 100 years, the sloughed off glomalin glues soil grains together in packets containing carbon, nitrogen, phosphorus, and other valuable nutrients. This waxy coating of glomalin helps to form tiny soil clumps called "aggregates," and prevents nutrients vital to plant growth from being leached out of the soil. Glomalin will continue to hold carbon underground long after death of the hyphae that produced it – helping us in our quest to reduce greenhouse gases in our atmosphere.

This entire kingdom of incredible creatures works twenty-four hours a day, year after year, without any input from humans, unseen by us and mostly unappreciated by us. These life-forms in mutual partnership will continue to glue our soils together and capture our excess carbon in perpetuity . . . *unless we remove the plants and disturb the soil that makes all this magic work.*

We are now faced with decisions about whether to allow thousands of acres of functioning desert systems to be sacrificed for solar energy developments – on the premise of reducing carbon dioxide levels in the atmosphere. Scientists estimate that after the removal of desert vegetation and disturbance of the top soil, the pre-existing plant community requires about fifty to three hundred years before it returns to pre-disturbance cover and biomass, but requires about three thousand years before the disturbed area returns to the function it had before disturbance. The ancient nature of both the plants and the living soil crust organisms make this a credible prediction.

We once thought that carbon was held in meaningful amounts only in ocean creatures and forest trees and humus. Now we know that soils, including desert soils, are a significant storage facility for carbon. Without these biological partnerships, significant amounts of carbon would be released from the soil back into the atmosphere, and no additional carbon would be sequestered. Not only are desert soils holding carbon in caliche deposits, they also store vast amounts of organic carbon in soil organisms, including root-partnering fungi with their coating of glomalin. The importance of glomalin's carbon storage capacity is stated by a USDA scientist this way:

*"As carbon gets assigned a dollar value in a carbon commodity market, it may give literal meaning to the expression that good soil is black gold. And glomalin could be viewed as its 'golden seal.' "*
– Don Comis, USDA Agricultural Research Service, (2002) in *"Hiding Place for a Third of the World's Stored Soil Carbon"*

Wherever possible, we need to steer developments, especially large-scale projects like utility-scale solar facilities, to pre-disturbed, severely impacted soils or pre-developed sites such as parking lots and roofs. Then, we get the best of all options: progress with preservation.

Leave these microscopic soil magicians alone to do their work. The desert's underground life-support systems can only function if the aboveground systems (desert plants and living soil crusts) are kept alive and intact. We must be their voice and their champion in protecting them – so they can silently continue to protect our potential for carbon sequestration, our air quality, our health, our economy, our landscape, our ecotourism, our property values, and our quality of life. To ensure our own sustainable future, we need to keep our desert soils intact and alive . . . it benefits everyone. The choice is ours.

*With a Master's Degree in biology, Robin Kobaly had a twenty-year career as a botanist with the BLM, and continues to work in botany, wildlife biology, and natural history interpretation. She is currently executive director of the SummerTree Institute, a 501(c)3 nonprofit corporation dedicated to providing responsible viewpoints toward our environment, our place in it, and our responsibility to it.*

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# 5 SAND TRANSPORT PATHS IN THE MOJAVE DESERT, SOUTHWESTERN UNITED STATES

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## ABSTRACT

Remote sensing and field evidence are used to describe sand deposits found in associated pathways of emplacement in the eastern Mojave Desert. Two separate pathways are identified here: one extending eastward from the Bristol Playa through the Cadiz and Danby Playas and Rice Valley to the Colorado River, and a second parallel path extending eastward from Dale Playa through the Palen and Ford Playas to the Mule Mountains near the Colorado River. The preferential location of sand ramps on the west slopes of mountains along each path suggests that the eastward moving, wind-driven sand was not confined by topographic divides between separate drainage basins around the individual playas and valleys. Sediment analysis of selected samples shows that there are discreet associations of sand characteristics along the sand pathways, with an inferred similarity between the stabilized (vegetated) sands in Rice Valley, west of the Colorado River, and stabilized sand dunes on Cactus Plain and La Posa Plain in Arizona, east of the Colorado River. Sand transport along the paths appears to have been episodic, based on multiple paleosols present in several dissected sand ramps. Future testing of the sand transport path hypothesis will require additional sediment analyses, spectral studies of remote sensing data, and obtaining dates for selected soil horizons along the sand paths.

## INTRODUCTION

Wind has long been recognized as a powerful agent for sediment transport in arid environments. Sand transport in the hyper-arid Sahara Desert in northern Africa can be traced for thousands of kilometers, providing physical evidence of the wind patterns prevalent throughout the region (Wilson 1971, El-Baz et al. 1979, El-Baz and Maxwell 1982). However, significant aeolian transport is not restricted to hyper-arid deserts. Semi-arid regions also can preserve evidence of substantial deposits of aeolian sand, but many of these deposits may be stabilized at present by a variety of desert flora adapted to the intermittent rainfall.

The advent of airborne and satellite-based remote sensing data allow both the surface materials and their associated flora to be examined in a regional context. In particular, spacecraft images have been used to identify aeolian deposits throughout the Earth (Breed and Grow 1979), as well as on Mars (Sagan et al. 1972, Greeley and Iversen 1985) and Venus (Greeley et al. 1992).

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Conclusions derived from remote sensing data must be corroborated by "ground truth" investigations at key localities. The present study combines preliminary field observations with satellite remote sensing data to document aeolian deposits along hypothesized sand transport pathways in the eastern Mojave Desert of California. While a considerable amount of field work remains to be carried out, our intent here is to describe the primary features which suggest that an association exists between various sand deposits. Integrated pathways of sand transport would imply that aeolian processes have regional significance well beyond the confines of individual drainage basins. The time scale of this aeolian activity is not well constrained at present, but exposures described here suggest that the dissected sand ramps in the eastern Mojave Desert contain climatic information which predates the Holocene activity evidenced by the present isolated accumulations of active dunes.

## BACKGROUND

The Mojave Desert is located in southern California at the southern end of the Basin and Range physiographic province. It is an important field geology study area because it contains numerous, accessible, well-exposed examples of a variety of geologic features (Dohrenwend 1987). The Garlock and San Andreas faults define sharp boundaries to the western margin of the Mojave Desert, while the eastern boundary with the arid region surrounding the Colorado River is more gradational. The sand transport paths described in this study lie in the eastern part of the Mojave Desert, possibly including sand deposits east of the Colorado River (Figure 1). A synopsis of the geology of the study region can be found in Jahns (1954) and in Bassett and Kupfer (1964).

Aeolian activity has formed sand sheets at several locations in the Mojave Desert. Sand ramps over 100 m thick occur in places where topography has impeded local sand migration (H.T.U. Smith 1967, R.S.U. Smith 1982). These sand ramp deposits include soil layers and other features that contain paleoclimatic information (Tchakerian 1991). The deposition of each layer presumably followed the desiccation of pluvial lakes lying upwind, with soil formation occurring between pulses of aeolian activity (Smith 1982, McFadden et al. 1987, Wells et al. 1987, Chadwick and Davis 1990, Tchakerian 1991). Some sand ramps are so large that they surmount the windward side of the topographic obstacle responsible for their formation. This study presents a hypothesis of regional aeolian transport that provides a unifying framework in which to interpret the results obtained from widely distributed sand ramps in the Mojave region.

A synoptic view of the Mojave Desert is best obtained from remote sensing data. Several recent remote sensing and field studies have focused on aeolian processes in the Mojave region (e.g., Blount et al. 1990, Paisley et al. 1991, Lancaster et al. 1992, Laity 1987, 1992, Zimbelman and Williams, in preparation). These efforts revealed that active sand can be distinguished from sand

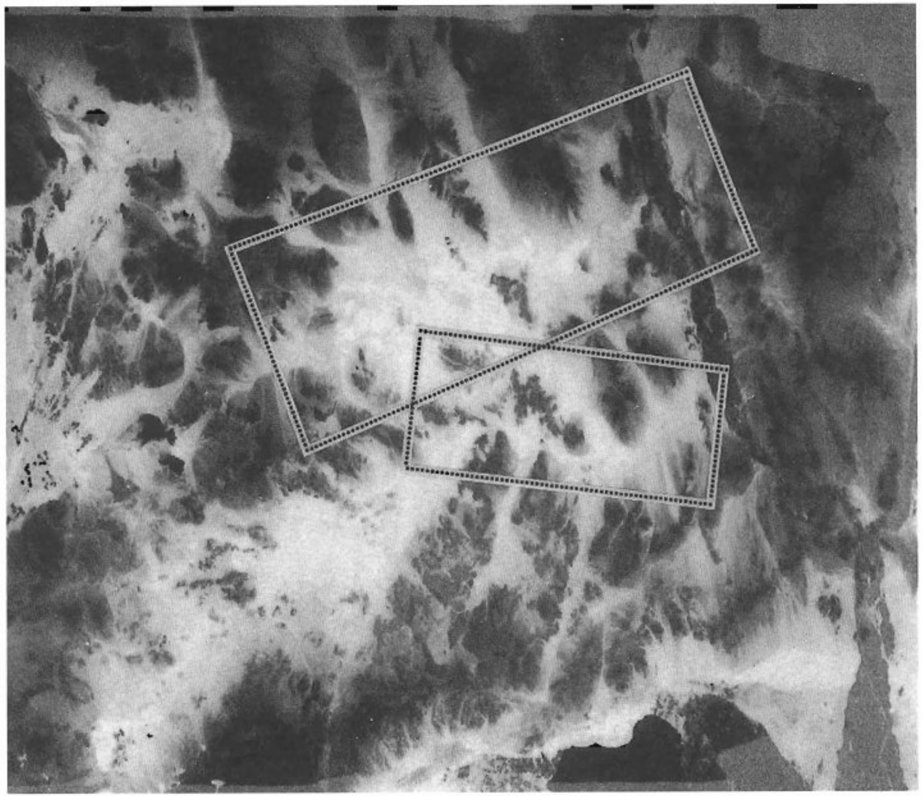

Figure 1. (a) Oblique view of the eastern Mojave Desert, taken with the Linhof camera on board the Space Shuttle. This view shows the Mojave Desert area from the outwash plains of the Mojave River (near Barstow, California) at left, to the agricultural fields along the Colorado River at right. The line of sight is nearly coincident with the paths of sand transport described in the text. Dotted lines show the locations of Figures 2 (top) and 7 (bottom). See Figure 1b for selected feature names near the pathways. Portion of frame 51B-146-111, obtained during Shuttle flight STS 51B, between April 26 and May 6, 1985.

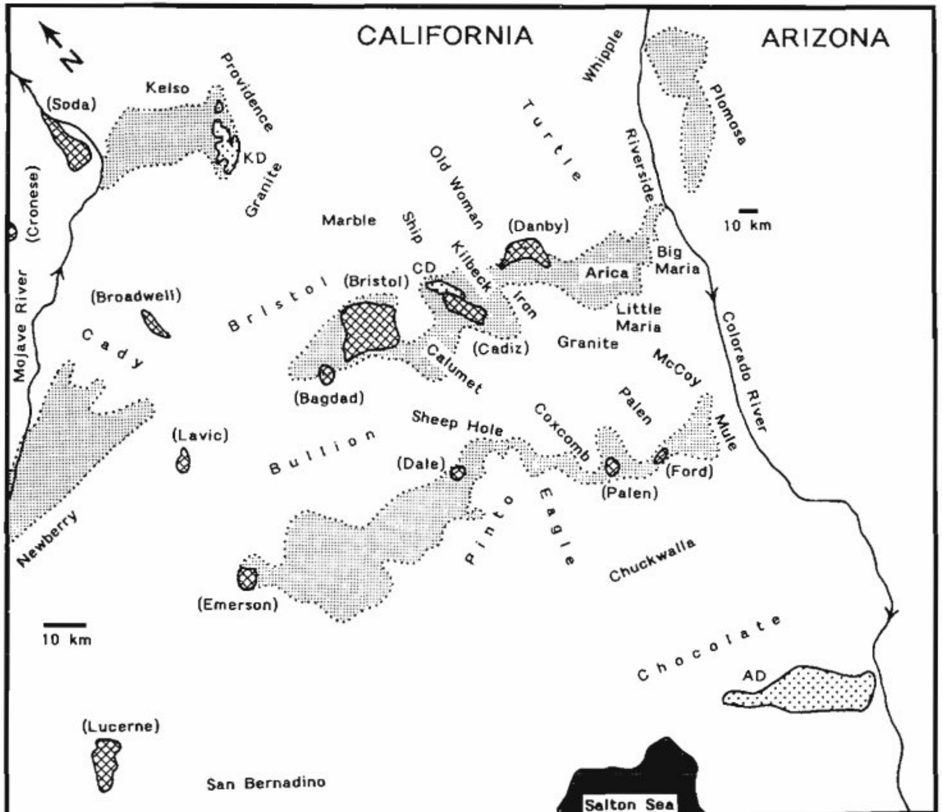


Figure 1. (b) Simplified sketch map of the area shown in Figure 1a. Selected playas (gridded pattern, names in parentheses), mountains (names listed at appropriate location), and rivers (arrows show direction of flow) are labeled for reference. Sand deposits are shown in dotted patterns; the open pattern represents active (relatively unvegetated) dunes (KD = Kelso Dunes, CD = Cadiz Dunes, AD = Algodones Dunes) and the dense pattern represents inactive (stabilized by vegetation) deposits. Note that foreshortening due to the oblique viewing geometry causes horizontal scale variations across the area.

stabilized by vegetation through subtle but consistent differences in reflectance properties between the Landsat Thematic Mapper spectral bands. Similar spectral differences exist in the Landsat data used in the present study, although the differing plant populations appear to play a significant role in the reflectance properties of aeolian deposits in the Mojave region (Zimbelman and Williams, in preparation). Consequently, seasonal variations may prove to be critical to the spectral response of certain Mojave sand deposits. These relationships are still under active investigation, so the results presented here will be based primarily on morphology as observed in a single spectral band.

## SAND TRANSPORT PATHS

Three principal locations of aeolian deposits in the eastern Mojave Desert are described here: the Bristol Trough (which includes the Bristol, Cadiz, and Danby playas), Clark's Pass (which includes the Dale, Palen, and Ford playas), and the Cactus and La Posa Plains in Arizona (Figure 1). Both the active and stabilized (vegetated to the point of nonmobility) sand deposits observed at these locations are hypothesized here to be part of regional sand transportation paths which cross the Mojave Desert southeast to the Colorado River, and possibly beyond the river. These locations are all south and east of the Kelso Dunes (Figure 1), the most prominent and intensively studied dune field in the Mojave Desert (Sharp 1966, 1978, Paisley et al. 1991, Lancaster et al. 1992, Lancaster 1993). The sand in the Kelso Dunes originated in broad outwash plains associated with the Mojave River, was transported to the southeast by the prevailing winds, and collected at the base of the >1800-m Providence and Granite Mountains, which formed an insurmountable barrier to the windblown sediments (Sharp 1978). The sands associated with the Bristol Trough and Clark's Pass also are oriented along the prevailing northwest-to-southeast wind direction (Greeley and Iversen 1985), but these sand deposits have traversed several distinct drainage basins on their way to the Colorado River. Sand from the Bristol Trough may have even contributed to a third major sand deposit, a field of stabilized dunes on the Cactus Plain and La Posa Plain east of the Colorado River. Each of the three sand localities is described in greater detail in the following sections.

### *Bristol Trough*

The most prominent association of sand deposits begins at the Bristol Playa near the head of a broad topographic low called the Bristol Trough (Thompson 1929). Sand occurs continuously over a distance of almost 150 km, eventually terminating at the Colorado River (Figure 2). The sand deposits concentrate around three large playas (Bristol, Cadiz, and Danby), and consist of both active dunes and vegetation-stabilized sand sheets and linear dunes (Figure 2). The relation of the sand deposits to the mountains they traverse indicates that the sand movement was toward the east-southeast, with prominent sand ramps present on the west side of several mountain ranges along the pathway.

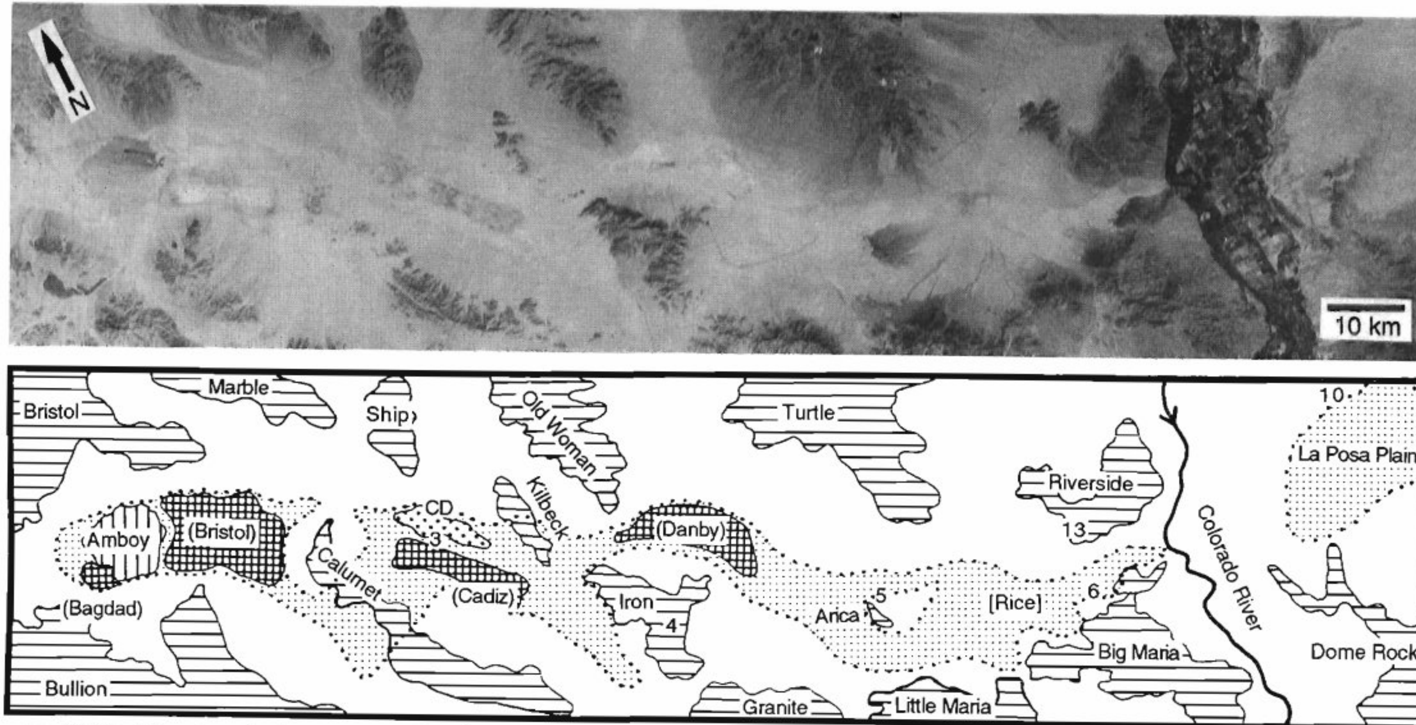


Figure 2. Bristol Trough sand path, seen on a portion of a Large Format Camera photograph, frame 2063, taken during the STS 41-G Space Shuttle flight between October 5 and 13, 1984. The sketch map below the photograph labels mountains (horizontal lined pattern), playas (gridded pattern), and sand deposits (dotted pattern). The active Cadiz Dunes (CD) are shown in a large dotted pattern. Rice Valley is identified by the name within square brackets. The Amboy lava flow (vertical lined pattern) is a Holocene basaltic eruption that covered the western portion of Bristol Playa. Numbers indicate the approximate centers of the orbital views shown in the corresponding figures.

Sand accumulations first become discernible west of the Bristol Playa, in the broad valley between the Bristol and Bullion Mountains (Figure 2). The Holocene basalt flow associated with the Amboy cinder cone covered the western portion of the Bristol Playa, leaving the small Bagdad Playa west of the Amboy flow as a remnant of the ancestral Bristol Playa (Bassett and Kupfer 1964). Sand derived from Bristol Mountains alluvium traverses the Amboy lava flow from WNW to ESE (Greeley and Iversen 1985), consistent with the annual wind flow in the region during the Holocene (Laity 1992). A prominent low-albedo wind streak is present downwind from the Amboy cinder cone (Figure 2). Sand transport across the flow is obstructed by the cinder cone, and enhanced turbulent wind scour in the lee of the cone aids in inhibiting sand migration into the wind streak (Greeley and Iversen 1978, 1985). There is no evidence, either in remote sensing data or on the ground, that sand from the Mojave River has traversed the Cady Mountains to enter the Bristol Playa basin from the west (Figure 1); the Bristol area is interpreted here to represent the beginning of the aeolian sand deposits that extend east to the Colorado River (Figure 2).

Sand is abundant southeast of the Bristol Playa, where it has built large ramps against the western slopes of the Calumet Mountains (Figure 2). The sand ramps provide shallow slopes for saltating sand to climb the western flanks of the mountains, as well as shallow slopes along which the sand moves

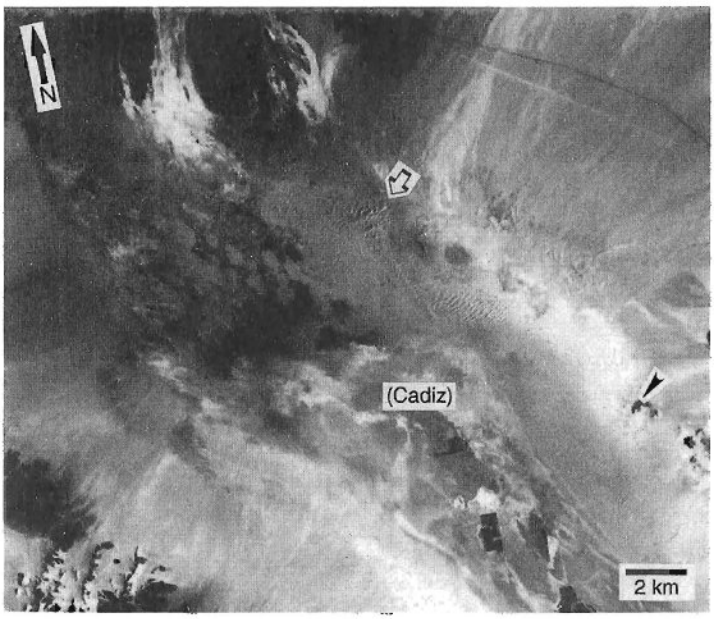


Figure 3. (a) Portion of a Landsat Thematic Mapper image showing the northern end of Cadiz Playa and the Cadiz Dunes north of the playa. The largest dunes (open arrow) have 30 m of relief. Transverse dunes are present along the northern margin of the playa; the dark arrow shows the location and orientation of Figure 3b. Landsat TM band 5, obtained on September 26, 1986.

**Table 1**
**Mean values of grain size, sorting, and percent silt and clay for selected samples from the Mojave Desert, California**

| Aeolian unit | Mean (ϕ) | Standard deviation | Skewness | Kurtosis | % silt and clay |
|---|---|---|---|---|---|
| Dale Lake | | | | | |
| Unit 1 | 2.24 | 0.83 | 0.10 | 1.17 | 2.90 |
| Unit 2 | 1.91 | 0.91 | 0.14 | 1.15 | 3.10 |
| Unit 3 | 2.15 | 0.85 | 0.08 | 1.10 | 3.25 |
| Unit 4 | 1.70 | 1.21 | 0.05 | 1.05 | 1.25 |
| Unit 5 | 2.23 | 0.78 | -.07 | 0.93 | 2.40 |
| Calumet Mtns | 2.91 | 0.97 | 0.22 | 1.29 | 4.83 |
| Cadiz Dunes | 2.35 | 0.29 | -.03 | 0.89 | |
| Iron Mtns | 2.45 | 0.88 | 0.15 | 1.10 | 7.20 |
| Rice Valley | 2.95 | 0.75 | 0.20 | 1.25 | 6.25 |
| Cactus Plain | 2.87 | 0.87 | 0.25 | 1.35 | 5.98 |

down the eastern flanks of the mountains. Neither climbing nor falling dunes are observed on the Calumets, but Landsat spectral data indicates that stabilized sand dominates a 10-km-long reach of the central portion of the mountains, where sand ramps were evident on the ground. Alluvial fan deposits around the northern end of the Calumets lack any prominent sand accumulations, leading to the interpretation that most sand from the Bristol area crossed the central Calumets instead of going around the northern alluvial fans.

East of the Calumet Mountains, sand deposits are concentrated around the Cadiz Playa, which is in the broad valley between the Calumet Mountains and the Kilbeck Hills (Figure 2). The sand deposits attain a considerable thickness on the northern margin of the Cadiz Playa; individual dunes display 30 m of relief and are clearly resolved in Landsat Thematic Mapper data (Figure 3a). Ground investigation showed that the dunes north of Cadiz Playa are the only substantive area of active dunes observed along the Bristol Trough path. The active sand gradually thins to the east, where transverse dunes with 1-2 m of relief become the dominant aeolian landform (Figure 3b).

Stabilized sand sheets extend eastward from the Cadiz Valley across the southern end of the Kilbeck Hills into the Danby Valley (Figure 2). Extensive sand ramps are present around the southern Kilbeck Hills, and are particularly well developed on the western slopes of the Iron Mountains (Figure 4a). Where ephemeral streams dissect the Iron Mountain sand ramps, tens of meters of sand are exposed within the channels, both in the western sand ramps (some of which have active dunes on the channel crest, Figure 4b), and in stabilized sand ramps on the northern flanks (Figure 4c).

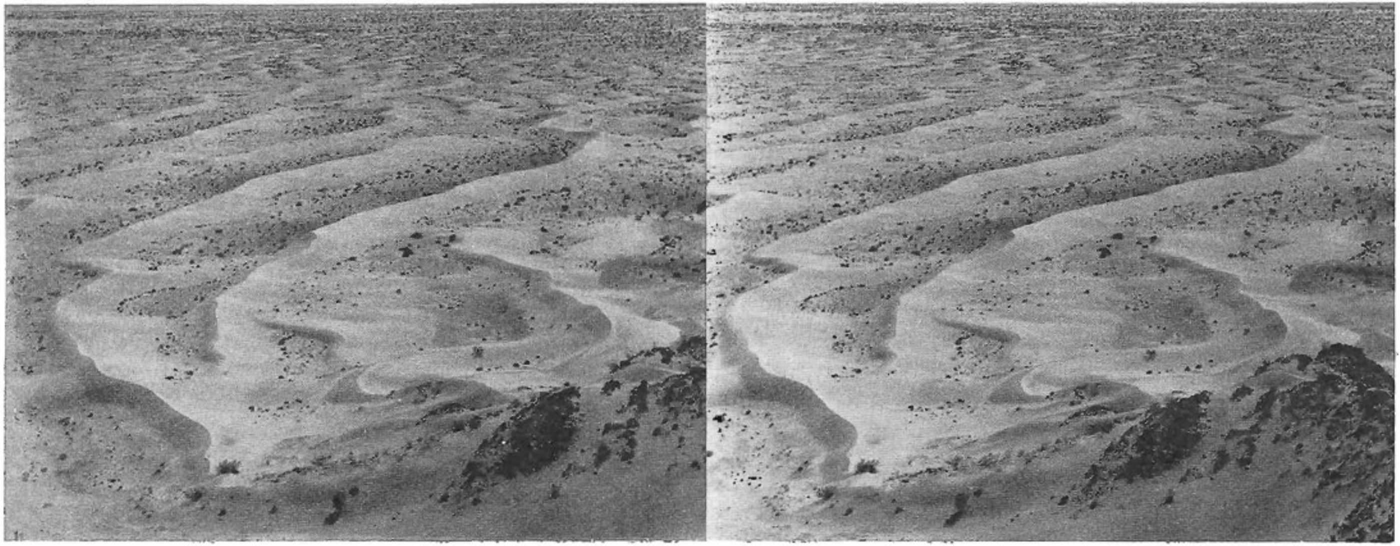

Figure 3. (b) Oblique stereo pair of transverse dunes north of the Cadiz Playa, looking southwest. Stereo view shows exaggerated topography; the dunes have 1 to 2 m of vertical relief and an average spacing of 40 m. Photographs taken on September 26, 1986, from the top of a small hill north of the playa.

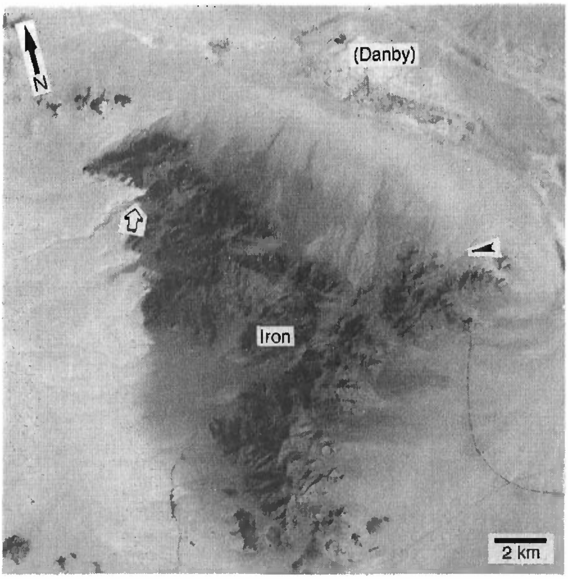


Figure 4. (a) Portion of a Landsat Thematic Mapper image showing the Iron Mountains south of Danby Playa. Prominent sand ramps are present on the western slope of the mountains; open arrow shows the location and orientation of the photograph in Figure 4b. Less active (more vegetated) sand ramp on the northern slope was sampled in 1991; the dark arrow shows location and orientation of the photograph in Figure 4c. Landsat TM band 5, obtained on September 26, 1986.

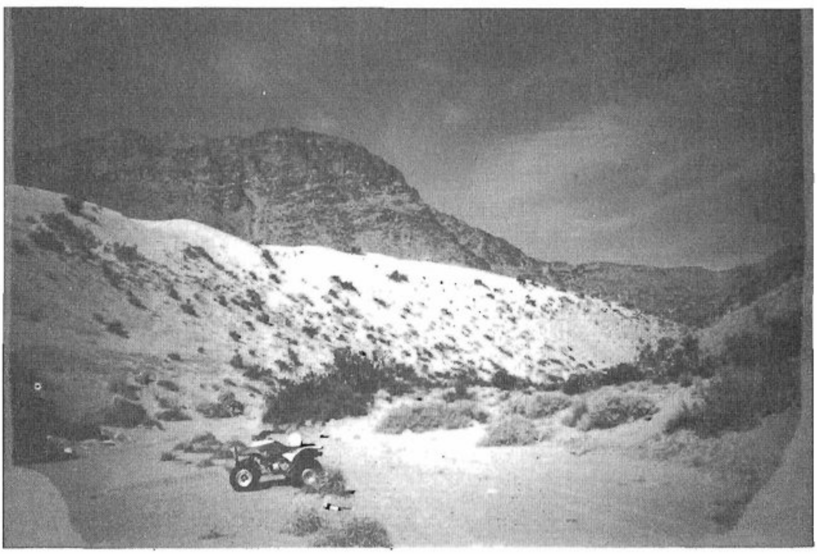

Figure 4. (b) View of entrenched sand ramp on the western slope of the Iron Mountains, taken from the channel floor. The 25-m-high channel wall has considerable vegetation cover at this locality, but the channel crests consist of active dune patches. Photograph was taken on October 9, 1993.

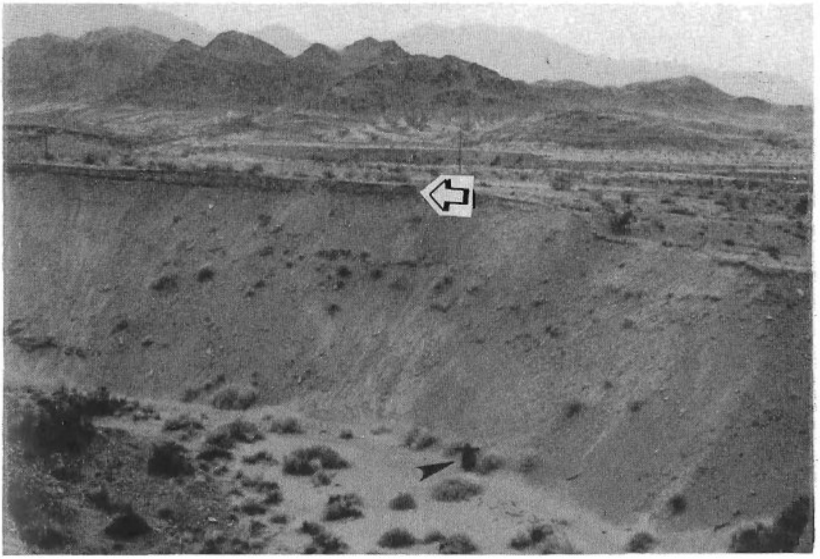

Figure 4. (c) Entrenched sand ramp on the northern slope of the Iron Mountains, with a paleosol complex (open arrow) capping the deposit. Note the outstretched arms of a 1.6 m field assistant (dark arrow) in the ephemeral wash, which exposes the sediments of the sand ramp. The top of the sand ramp is mantled with taluvium (talus and alluvium). Photograph was taken in 1992.

South of Danby Playa, the sand deposits spread to cover much of the Rice Valley with linear dunes and sand sheets, both of which are stabilized by desert vegetation (Figure 2). Sand surrounds the 500-m-high Arica Mountains (Figure 5a); a prominent sand ramp on the western slope almost reaches the top of the highest peaks, while the eastern slope is essentially sand-free (Figure 5b). Fields of stabilized linear dunes cover the southern side of the Rice Valley (Figure 6a). Sand ramps terminate at stream margins within the Big Maria Mountains, exposing up to 10 m of accumulated sand (Figure 6b). A narrow strip of sand exits the eastern end of Rice Valley, extending east to the Colorado River. Basic sedimentological characteristics of four sand deposits sampled along the pathway are listed in Table 1.

*Clark's Pass*

A second association of sand deposits roughly parallels the Bristol Trough path, but along a more southerly route (Figures 1 and 7). Sand ramps east of the Dale Playa at the eastern end of the Twentynine Palms Valley allowed sand to exit the valley through Clark's Pass, a narrow gap between the Sheep Hole and Pinto Mountains (Figure 8a).

The orientation of the Sheep Hole and Pinto Mountains acted like a funnel to concentrate migrating sand rather than trapping it completely, as at the Kelso Dunes. The sand ramps developed between the mountains allow wind-blown sand to climb more than 250 m from the level of Dale Playa to Clark's Pass.

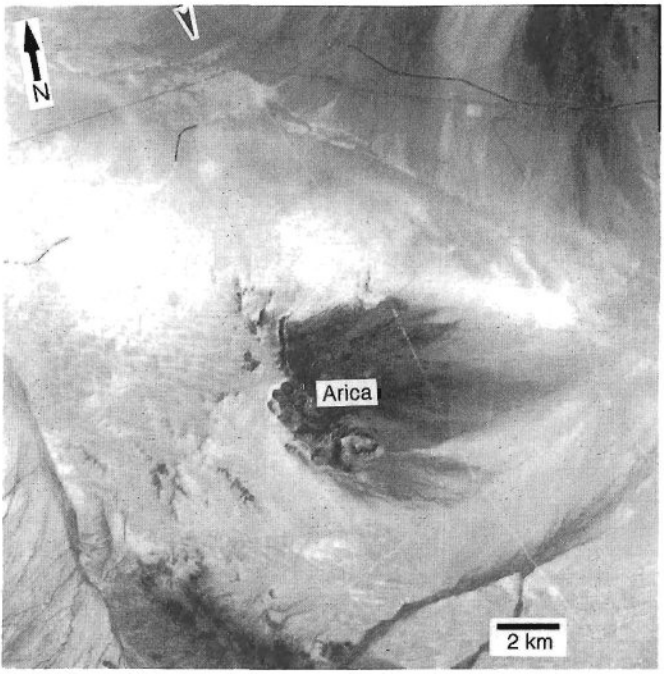


Figure 5. (a) Portion of a Landsat Thematic Mapper image showing the Arica Mountains at the west end of Rice Valley. The dark arrow at the top shows the orientation of the photograph in Figure 5b, taken from a position just off the northern edge of the image. Landsat TM band 5, obtained on September 26, 1986.

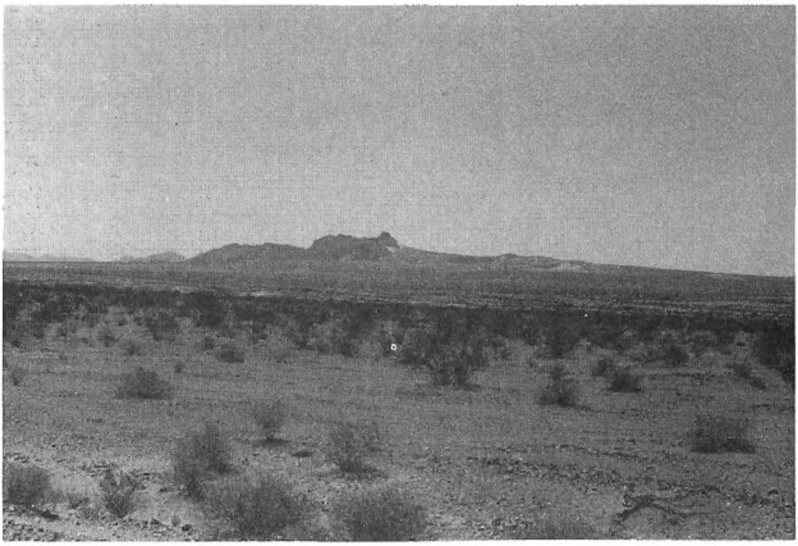

Figure 5. (b) Profile view of the Arica Mountains, looking south from a road that follows the railroad tracks north of Danby Playa. A prominent sand ramp is present on the west slope (right) while the east slope (left) is relatively sand-free, in the lee of the 500-m-high mountains. Photograph was taken in May 1991.

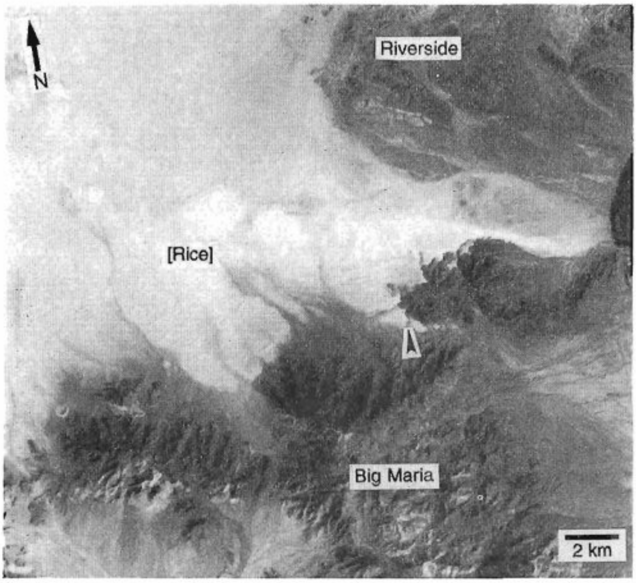


Figure 6. (a) Portion of a Landsat Thematic Mapper image showing stabilized dunes in Rice Valley. The sand deposits occur against the northern slopes of the Big Maria Mountains, and are cut by emphemeral channels from those mountains. The dark arrow shows the location and orientation of Figure 6b. Landsat TM band 5, obtained on September 26, 1986.

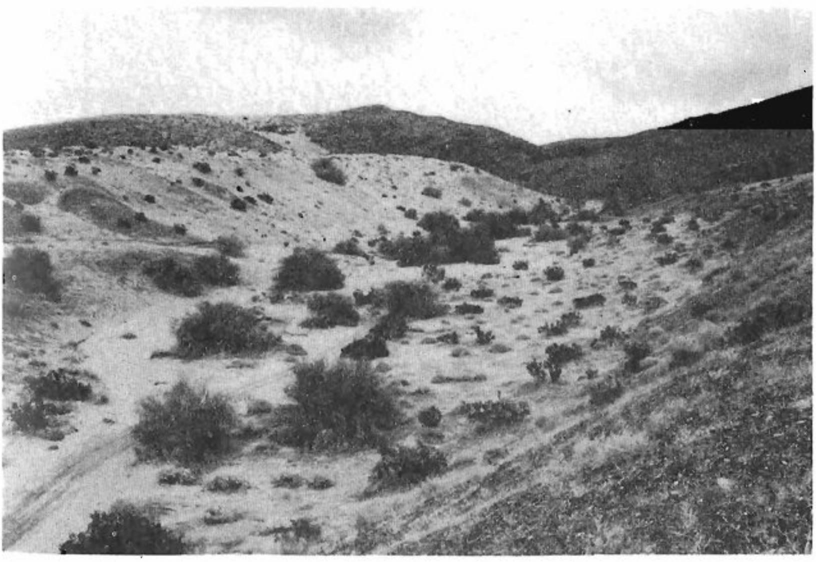

Figure 6. (b) Upper portion of the sand ramp on the northern slope of the Big Maria Mountians. The top of the section exposed by an ephemeral stream is stabilized by vegetation and taluvium, and capped by a prominent paleosol. Photograph was taken in 1991.

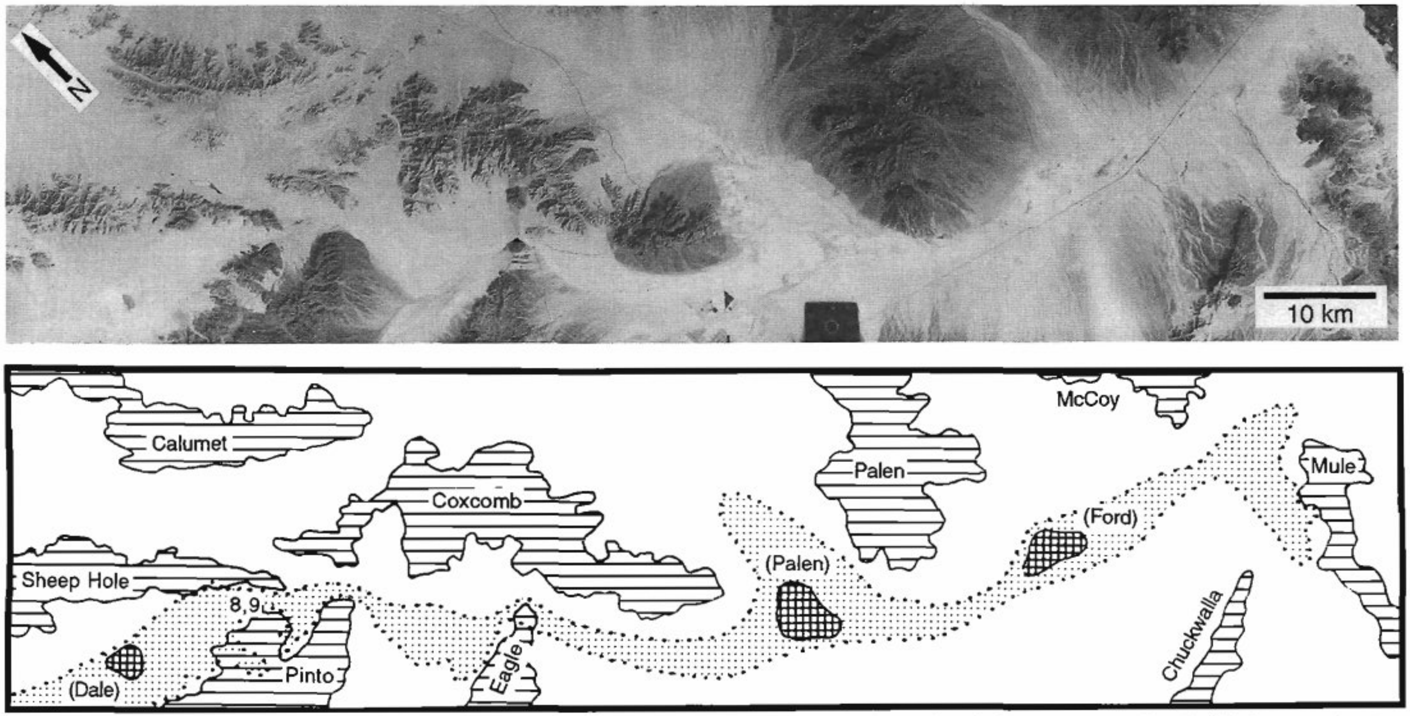


Figure 7. Clark's Pass sand path, seen on a portion of a Large Format Camera photograph, frame 2063, taken during the STS 41-G Space Shuttle flight between October 5 and 13, 1984. The sketch map below the photograph labels mountains (lined pattern), playas (gridded pattern), and sand deposits (dotted pattern).

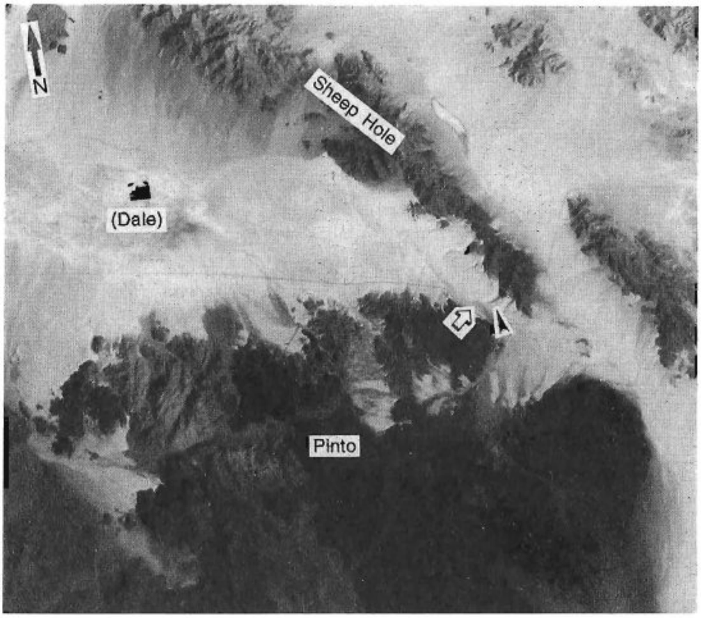


Figure 8. (a) Portion of a Landsat Thematic Mapper image showing the Clark's Pass area. Sand is ramped against the Sheep Hole (top) and Pinto (bottom) Mountains, providing an exit from the Twentynine Palms Valley, past Dale Playa, through Clark's Pass. The dark arrow shows the location and orientation of Figure 8b, and the open arrow shows the location and orientation of Figure 9a. Landsat TM band 5, obtained on September 26, 1986.

Some sand has been trapped in small valleys along the northern margin of the Pinto Mountains (Figure 8a), but the volume of sand deposits within the mountains appears to be much smaller than that of the sand ramps leading up to Clark's Pass. Ephemeral streams from the Sheep Hole Mountains cut into the sand ramps at several locations (Figure 8b), providing a cross-section through tens of meters of sand and exposing several soil horizons.

Several major stratigraphic units are identified within the Dale sand ramp (Tchakerian 1991) by the combination of geomorphic and soil-stratigraphic relations (Figure 9, Table 1). The units are predominantly aeolian in origin, with some intermixed fluvial deposits. Unit 1 contains fine to medium ($Mz = 2.24\ \phi$) moderately sorted ($\sigma = 0.83$) aeolian sands with grus and a silt/clay content of 2.9%. It is capped by a reddish yellow (5YR/6/6) paleosol with discontinuous carbonate nodules. Unit 2 comprises fine to medium ($Mz = 1.91\phi$) poorly sorted ($\sigma = 0.91$) aeolian sands and has a silt and clay content of 3.1%. It contains numerous fluvial cut and fill lenses. The unit is capped by a prominent reddish yellow (7.5YR/6/6) paleosol with calcrete disseminated throughout the matrix, and carbonate enriched root pseudomorphs. Unit 3 consists of mostly yellowish red (5YR/5/8) medium to coarse ($Mz = 2.15\phi$) moderately sorted ($\sigma = 0.85$) aeolian sands with large percentages of grus. It is capped by a poorly developed discontinuous paleosol with some calcareous

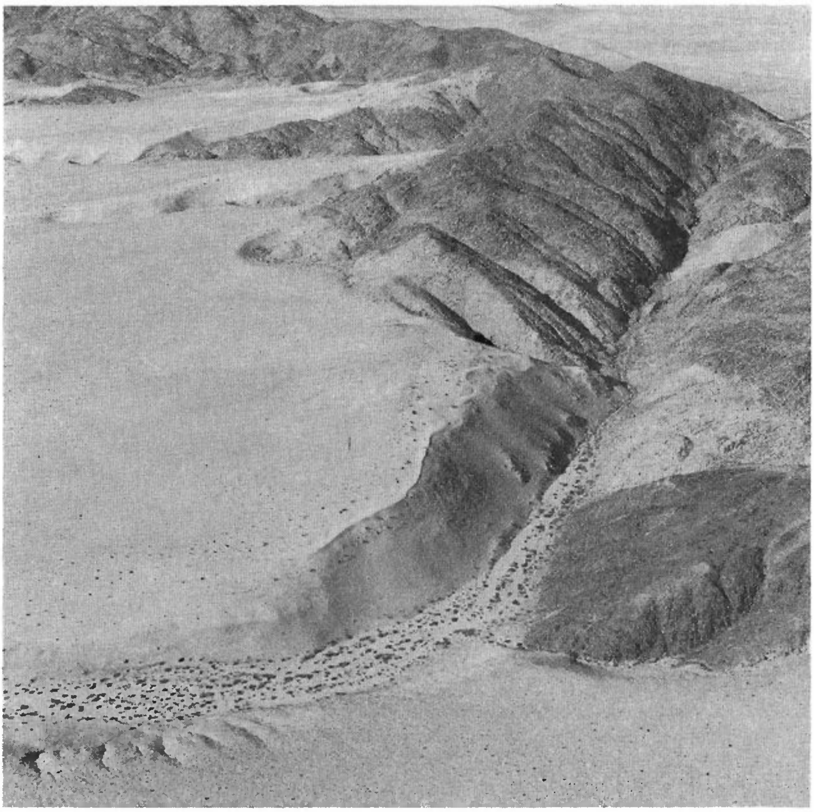

Figure 8. (b) Sand ramp on the western side of the Sheep Hole Mountains near Clark's Pass, at the east end of the Twentynine Palms Valley (Shelton et al. 1978, figure 9-21). Note the active dune along the crest of the channel. Oblique aireal photograph taken by R. Greeley.

rhizoliths. Unit 4 contains primarily fluvially redistributed dune sands, cut-and-fill structures, and coarse gravel alluvial channels. The sediments are mostly coarse sands (Mz = 1.70$\phi$), and are poorly sorted ($\sigma$ = 1.21).

The section is topped by weakly consolidated sand that forms the surface of the sand ramp. Unit 5 contains brownish yellow (10YR6/6) fine to medium (Mz = 2.23$\phi$), moderately well sorted ($\sigma$ = 0.78) aeolian sands, with a silt/clay content of 2.4%. The uppermost section of Unit 5 is obscured by loose aeolian sands. However, about 500 m to the west of this section, further aeolian depositional units have been identified which are stratigraphically equivalent to or younger than Unit 5. They consist of brownish yellow, fine to medium, moderately well sorted aeolian sands similar in composition to Unit 5. Additional units in the area are similar, with respect to grain size, sorting, percent silt/clay, and quartz grain surface micromorphologies (SEM analysis), to Unit 5, suggesting emplacement by a single aeolian episode with multiple depositional pulses (Tchakerian 1991).

After exiting through Clark's Pass, the sand traversed the northern end of the Eagle Mountains and passed the Palen and Ford Playas (Figure 7). The sand deposits around the Palen and Ford Playas are primarily in the form of broad sand sheets, with very limited development of isolated, stabilized dunes. There is no evidence at present that sand reached the Colorado River after passing the Mule Mountains (which have prominent sand ramps on their western slopes), but the lack of visible sand likely results from the extensive agricultural activity along the Colorado River in the vicinity of Blythe, California.

*Cactus Plain–La Posa Plain*

A third accumulation of sand deposits possibly may be related to the proposed sand transport pathways through the Mojave Desert. Large fields of stabilized linear dunes are present on the eastern bank of the Colorado River near the town of Parker, Arizona (Figure 10). These dunes are directly opposite the termination point of the Bristol Trough path at the Colorado River (Figure 1). There is no obvious source for the stabilized dunes on the Cactus Plain and the La Posa Plain (Figure 10); the adjacent mountains display typical alluvial fan development with no apparent accumulation of sand-sized materials to supply the sand to the extensive dune fields. The Colorado River could be a source for the sand, except that the Cactus Plain–La Posa Plain area is the only sand accumulation next to the river but not next to a large lake or playa (such as the Algodones Dunes near the Salton Sea; Figure 1).

The Arizona linear dunes generally have from 2 to 4 m of relief and are oriented approximately transverse to the prevailing wind direction evident within the Bristol Trough (Greeley and Iversen 1985, Laity 1992). No prominent sand ramps are evident around the dunes; the sand accumulation progressively thins leading up to the adjacent mountains. However, the silt/clay content of the Cactus Plain dunes is nearly twice as large as that of the Dale units exposed within the Clark's Pass path, but is similar to the silt/clay content of the Iron Mountain and Rice Valley sands from the eastern portion of the Bristol Trough path (Table 1). The increased silt/clay content does not appear to be pedogenic in origin; the loose sand covers the dunes but they are no longer mobile because of the desert vegetative cover. The adjacent locations and the overall similarities between the Rice Valley and Cactus Plain sands raise the possibility that the Arizona sands may be genetically related to the "apparent" termination of the Bristol Trough path at the Colorado River; this intriguing possibility is discussed in the following section.

## DISCUSSION

The alignment of the Mojave sand paths is because of a combination of topography and prevailing winds. Our observations led to the hypothesis that the paths represent the aeolian part of a combined aeolian/alluvial/fluvial drainage system, as discussed below. Also described are the possibility of net sand migration across the Colorado River, and some paleoclimatic implications of the sand transport path hypothesis.

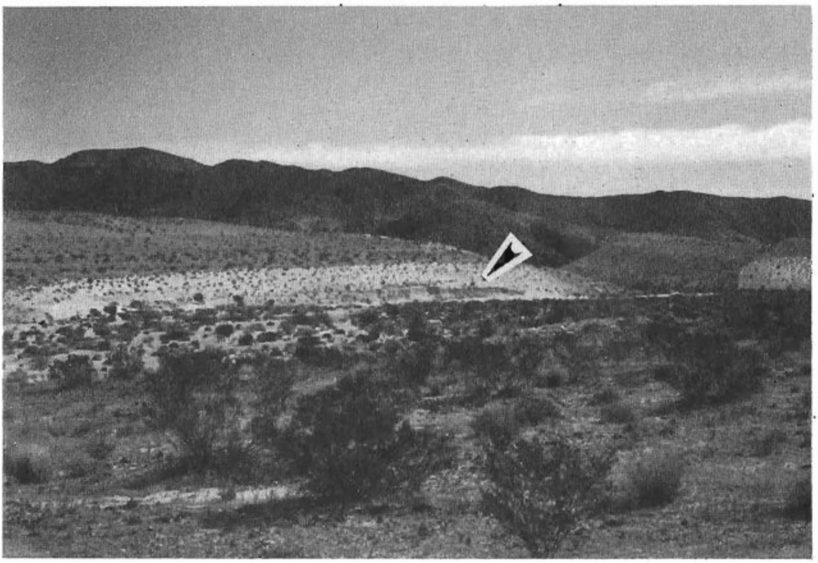

Figure 9. (a) The upper part of the Dale Lake sand ramp, with an ephemeral fluvial wash in the foreground (see also Figure 8). The Sheep Hole Mountains are in the background. The dark arrow points to the paleosols shown in Figures 9b and 9c, exposed by the streamcut in the sand ramp. Photograph taken in 1987.

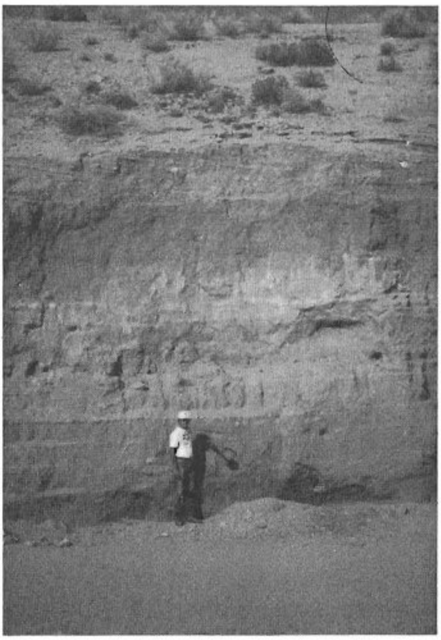

Figure 9. (b) A close up view of the middle section of the sand column exposed in the wash of the ephemeral stream described in Figure 9a. The section exposed here is about 10 m thick. Photograph taken in 1987.

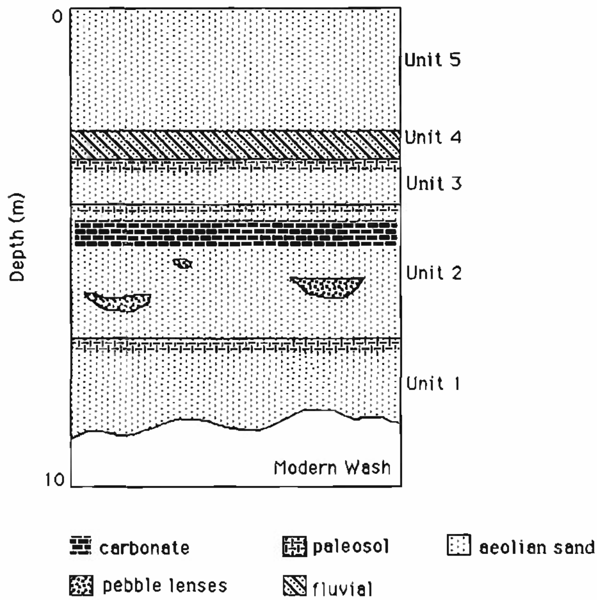


Figure 9. (c) A detailed geomorphic and soil-stratigraphic cross-section of the sand ramp exposure shown in Figure 9b.

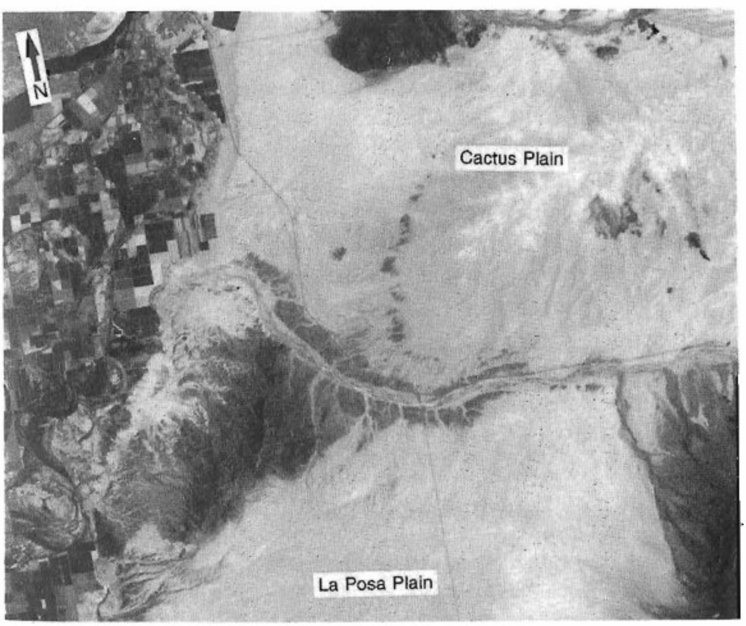


Figure 10. Portion of a Landsat Thematic Mapper image showing the stabilized dunes near Parker, Arizona. Agricultural use of the Colorado River floodplain is evident at left. The dunes are concentrated on the Cactus Plain (top) and the La Posa Plain (bottom), with no apparent source area evident in the sourrounding mountains. Landsat TM band 5, obtained on June 9, 1984.

*Sand Transport Pathways As "Rivers Of Sand"*

The pathways followed by the sand in transport toward the Colorado River can be compared to the path followed by a tributary stream on its way toward a higher order primary river. Both systems show sensitivity to local topography, but windblown sand is not forced always to flow down the local topographic gradient. The longitudinal profile of a river generally is concave upward, in accord with a steady downstream decrease in slope (e.g., Leopold et al. 1964, p. 248-255). In contrast to fluvial systems, aeolian sand can surmount or bypass significant topographic obstacles under favorable conditions of wind orientation and sand supply. Sand deposition on the windward side of the mountain ranges built sand ramps that facilitate continued access by saltating sand up the gentle windward slope of the ramp. Sand along the Bristol Trough path surmounts relief of up to 100 m on portions of the Calumet and Iron Mountains (Figure 11a), while the Clark's Pass path traverses 250 m of relief to provide an outlet for the sand from the Dale Playa (Figure 11b). Sufficient sand was available from the Dale Basin to build the large sand ramps that characterize the Clark's Pass path. In contrast, smaller ramps were sufficient to surmount the topography along the Bristol Trough path.

The Mojave and Colorado River systems may have been connected in earlier epochs (Blackwelder 1933, 1954, Miller 1946). Blackwelder (1954) postulated a Mojave/Colorado connection via the Bristol Trough that coincides exactly with the observed sand path (Figure 12). The hypothesized drainage connection was then disrupted by a combination of climate change, tectonic processes, and the eruption of the Pisgah volcanics. The association of the Mojave Desert sand deposits with (sometimes large) playas contributed to an assumption that the sand was locally derived, solely from the nearest paleolake. Our preliminary remote sensing analysis and field observations suggest that the present-day playas may be intermediate concentration points (at local topographic lows) for a more through-going movement of windblown sand. The tectonic trough enclosing the Bristol, Cadiz, and Danby Playas provides a preexisting trend along which the wind-blown sediments now encounter only minimum topographic obstacles, which were surmounted or bypassed through prolonged aeolian activity. In this sense, the sand transport paths might be considered "rivers of sand" that have reclaimed and actually shortened a possible drainage path from an earlier epoch. Considerable field work remains to be done to test the validity of this hypothesis, as well as much more extensive sediment analyses.

*Possible Trans-Colorado River Sand Transport*

Two intriguing questions are raised by the possibility of sand transport paths in the Mojave region: what is the ultimate fate of sand in transit along each path, and what is the source of the sands on the Cactus and La Posa Plains? Much of the sand entering the Colorado River is transported downstream, with much of it perhaps contributing to the Gran Desierto dune field in Mexico (Merriam 1969, Lancaster et al. 1987, Blount and Lancaster 1990). However, we

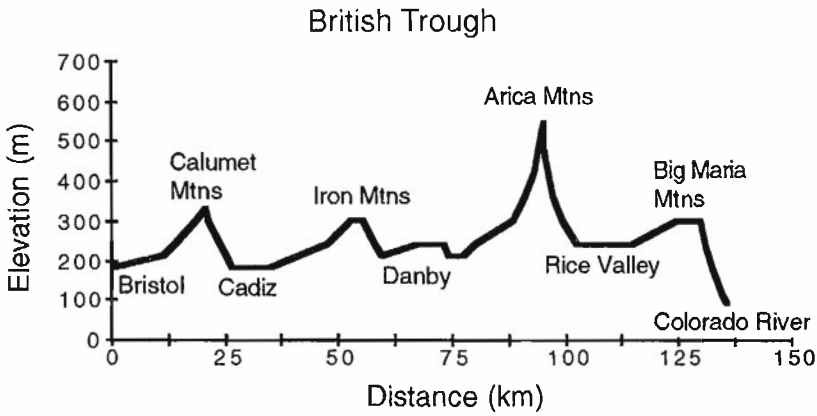


Figure 11. (a) Topographic profile along the Bristol Trough path. Vertical exaggeration is approximately 87X. The profile follows the approximate centerline of the sand path, including both active and inactive sand deposits. Mountain ranges encountered along the path are labeled above the profile; these topographic obstacles are crossed by the sand through emplacement of thick sand ramps. Playa names and Rice Valley are labeled below the profile, which ends at the Colorado River near Quien Sabe Point. Topographic data are from 1:250,000 Needles (USGS 1969a) and Salton Sea (USGS 1969b) map sheets.

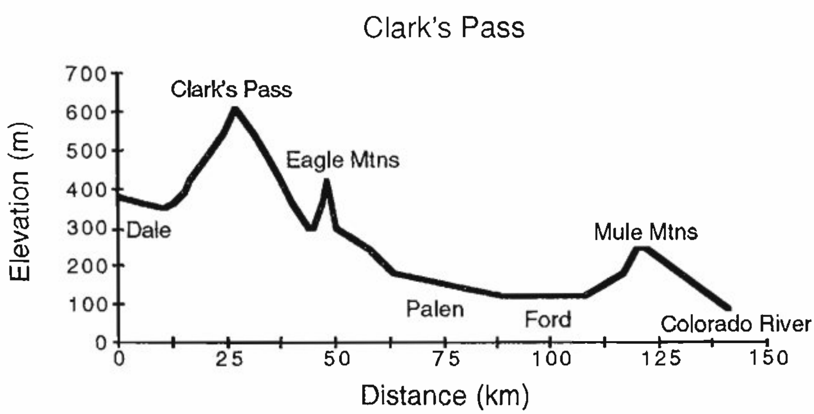


Figure 11. (b) Topographic profile along the Clark's Pass path. Vertical exaggeration is approximately 87X. The profile follows the approximate centerline of the sand path, including both active and inactive sand deposits. Mountain ranges encountered along the path are labeled above the profile; these topographic obstacles are crossed by the sand through emplacement of thick sand ramps. Playa names are labeled below the profile, which ends at the Colorado River near Blythe, California. Topographic data are from 1:250,000 Needles (USGS 1969a) and Salton Sea (USGS 1969b) map sheets.

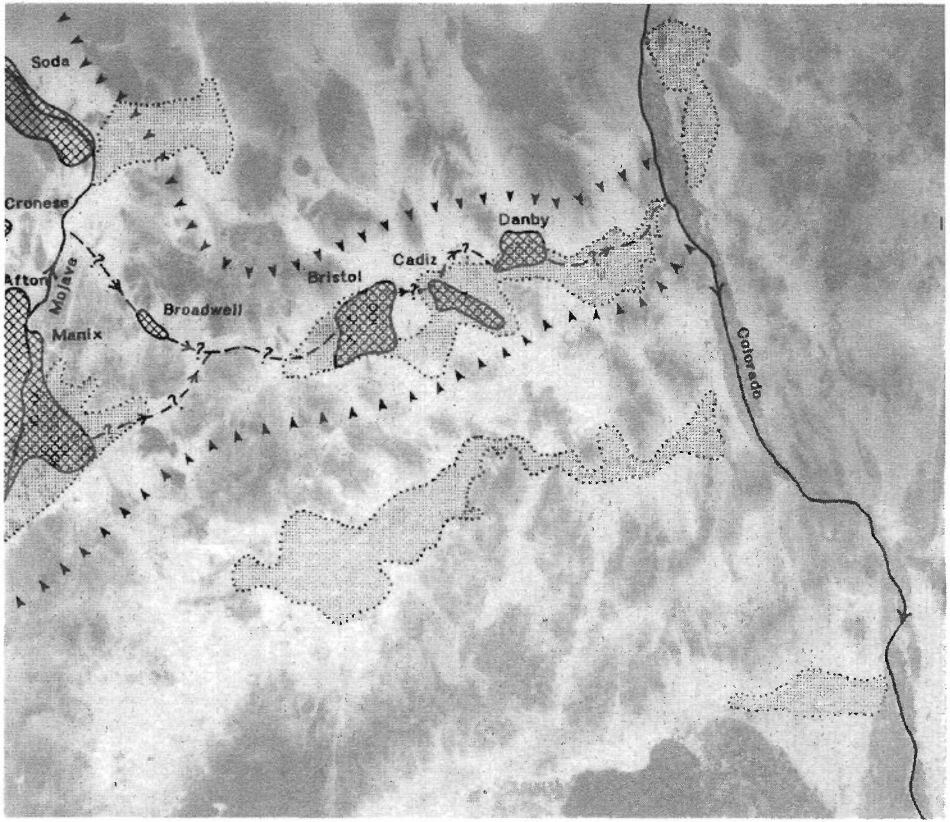


Figure 12. The paleodrainage reconstruction of Blackwelder (1954) is superposed on the oblique photograph in Figure 1a. Arrows outline the drainage into the paleolakes (gridded pattern). Dotted patterns show sand deposit locations from Figure 1b. Note the close match of the Bristol Trough sand path and the inferred drainage from the Mojave River to the Colorado River.

speculate that some of the sand transported down the pathways may have crossed the Colorado River and ended up on the Cactus and La Posa Plains (Williams et al. 1991, Tchakerian et al. 1992). The lack of other sand accumulations east of the Colorado River argues against the river itself as the primary sand source and argues for a mechanism which could bring mobile sand to this particular location. Batches of aeolian sand appear to enter the river floodplain at the western end of the sand transport paths (Figure 13). Eventually, the river may have opened a new meander channel west of aeolian sand deposits on the floodplain, which were then remobilized by the wind and exported onto the Cactus and La Posa dunefields. It is difficult to assess how effective such a process may have been prior to regulation of flow along the Colorado River. However, this mechanism could account for the presence of a large quantity of sand on the plains east of the Colorado River and is coincident with the termination of sand transport paths through the Mojave Desert.

*Paleoclimatic Implications*

The presence of well-developed paleosols and multiple aeolian depositional units within the sand ramps along the sand transport paths indicates that aeolian activity in the Mojave Desert has been widespread and episodic. A description of the units exposed in the Dale sand ramp was given earlier, and additional exposures of multiple soil-horizons were observed during a recent reconnaissance survey of the more remote portions of the Bristol Trough sand pathway. Such exposures within the sand pathways may be related to more extensively studied paleosols in the western Mojave Desert.

In the Silver Lake basin (part of Pleistocene Lake Mojave), an aeolian depositional period (Qe2) that took place between 12 and 8.7 ka, has been recognized by Wells et al. (1987) and Brown (1989). An older aeolian depositional episode prior to 22 ka has also been identified by Brown (1989) in sediment cores from the Silver Lake basin. The sedimentary record from Lake Mojave indicates that lake levels were low to intermediate between 13.5 and 9 ka, with final dessication around 8.7 ka (Brown 1989). It seems likely that the sand ramps observed along the sand transport pathways also witnessed increased levels of aeolian sediment input during low stands of the desert paleolakes, as sediments became available for transport from dried lake basins and their surrounding piedmont areas.

Sediment supply from desert lake basins was drastically curtailed after 9 ka, as a result of the changing environmental conditions which caused most lakes either to dry up or to reach very low water levels (Benson et al. 1990). The sand ramps probably underwent a period of stabilization through vegetation development and soil formation because of the reduction in sediment supply. They were subsequently mantled by rock debris from the adjoining mountains and later entrenched by ephemeral streams. In the middle Holocene, from about 7 to 5 ka, the Mojave Desert experienced a drier than present climatic regime, a period referred to as the climatic optimum or the Altithermal, first recognized

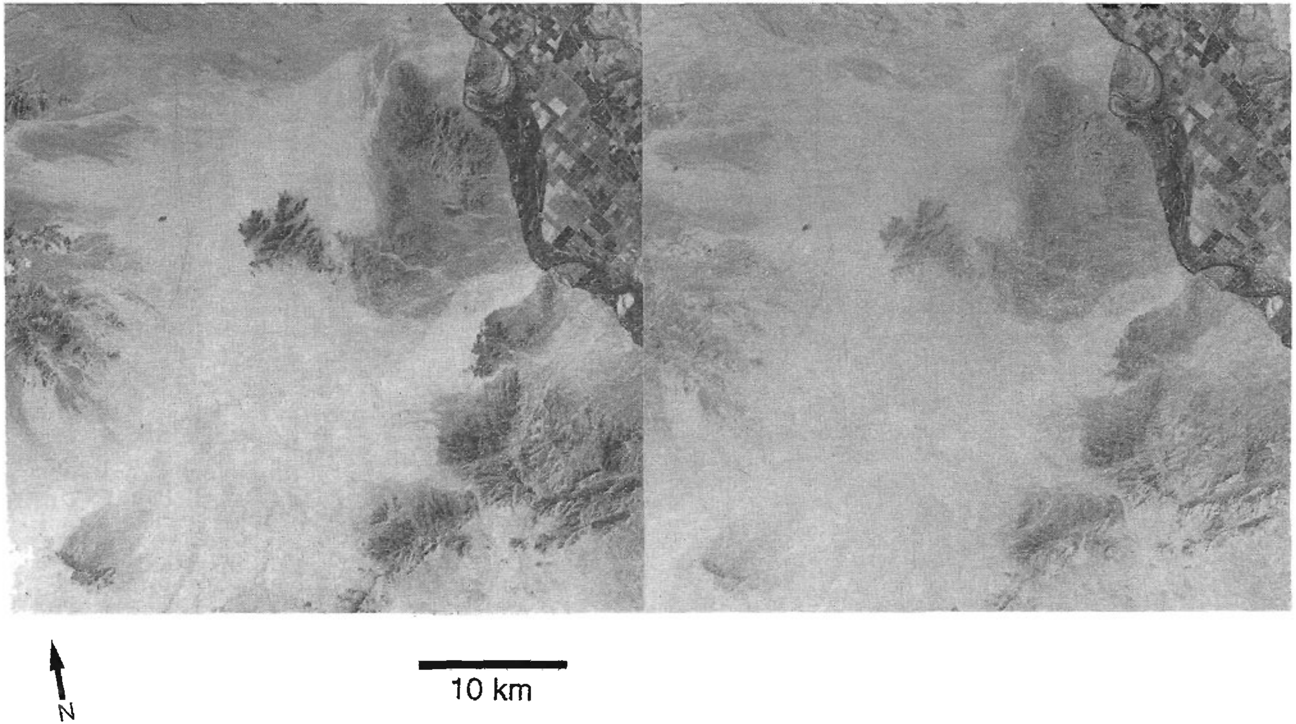


Figure 13. Stereo view of Rice Valley and the Quien Sabe Point area, from portions of Large Format Camera photographs, frames 2062 (left) and 2064 (right), taken during the STS 41-G Space Shuttle flight between October 5 and 13, 1984. The vertical relief is highly exaggerated in this stereo pair, but this view emphasizes the relation between the sand deposits, the mountains, and the Colorado River.

by Antevs (1962). According to Spaulding (1991), Middle Holocene macrofossil (packrat middens) records from the southern Mojave Desert indicate a more arid period than the present between 6800 and 5060 yr B.P. It is thus highly probable that the Middle Holocene period witnessed little aeolian activity as desert lakes were already dessicated by the time of the Altithermal, and most sand ramps fully stabilized.

Accelerator Mass Spectroscopy (AMS) $^{14}C$ and cation-ratio dating of varnished ventifacts on stabilized debris mantling sand ramps in the Cronese Basin in the Mojave Desert (see left margin of Figure 1b) indicate that aeolian activity ceased or was at a minimum, and that debris deposits were already stabilized, between 5.5 and 5 ka (Dorn et al. 1989). Hence (given the absence of numerical ages directly from dune deposits), most of the sand ramps were probably stable with rock talus and vegetation before the onset of more xeric conditions during the Altithermal, and aeolian activity was at a minimum or mostly restricted to those few desert basin areas that had active sediment input, such as the Mojave River Wash supplying sediments for the Kelso Dunes. Using luminescence dating measures, Lancaster et al. (1991) report a lack of ages older than 5000 yr B.P. from the main Kelso Dune fields, and suggest that the majority of the sediments have been extensively reworked prior to the mid-Holocene.

The entrenched sand ramps within the Bristol Trough and Clark's Pass sand pathways represent a valuable resource for studying paleoclimatic information preserved within the paleosols. The Dale sand ramp is presently the only locality within the sand pathways that has been thoroughly studied for sedimentological characteristics, but our field studies have identified other localities within the Bristol Trough path where entrenched sand ramps expose paleosol sequences. Comparison of the paleosol sequences, both along a given pathway and between adjacent pathways, should provide a test for the emplacement scenarios proposed here. Luminescence dating of key paleosol horizons is perhaps the most critical information required to quantify the climatic information recorded within the sand ramps.

## FUTURE WORK

We have presented here the preliminary descriptions and interpretations of the sand deposits present in the eastern Mojave Desert. A considerable amount of field work remains to be carried out, particularly in terms of describing and documenting the sediment characteristics and internal stratigraphy within the thick sand ramps evident at several locations. The sand transport pathway hypothesis can be tested through additional analyses of samples already collected, particularly looking for mineralogical information which could indicate whether or not the sand at the proposed "upstream" end of the pathways could have supplied the sands observed at the termination of the pathways. Additional sedimentological studies may also help to test whether or not the sands along the pathways are consistent with transport away from the inferred source of each pathway. Obtaining samples specifically collected for luminescence dating measurements (Lancaster et al. 1991) from geographically separated soil horizons is essential to the development of a regional stratigraphic history of the eastern Mojave Desert.

The remote sensing data have been used in the present work for basic geomorphic and geographic descriptions, but spectral variations between different bands of Thematic Mapper data should be useful in refining the distribution of active and stabilized sand deposits (Blount et al. 1990). We also hope that the spectral information will be useful for estimating sand thickness throughout the region based on vegetation that is sensitive to particular sand thicknesses (Zimbelman and Williams, in preparation).

## CONCLUDING REMARKS

We have presented both remote sensing and field evidence for the emplacement of aeolian sand pathways in the eastern Mojave Desert. Two pathways are described in detail: one extending eastward from the Bristol Playa past the Cadiz and Danby Playas through Rice Valley to the Colorado River, and a second path extending eastward from Clark's Pass past Palen and Ford Playas to the Mule Mountains by the Colorado River. The preferential development of sand ramps on the west slopes of mountains along each path indicates that the eastward-moving, wind-driven sand was not restricted by topographic divides between separate drainage basins around the individual playas and valleys. Preliminary sediment analysis of selected samples shows that there are discrete associations of sand characteristics along the sand pathways, with an inferred possible relationship between the stabilized sands in Rice Valley (within the Bristol Trough path) west of the Colorado River and stabilized linear dunes on the Cactus Plain and La Posa Plain east of the Colorado River. Sand transport along the paths appears to have been episodic, based on multiple soil horizons present in several dissected sand ramps.

## ACKNOWLDGEMENTS

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Science Brief

# Climate Mitigation in California:

## The importance of conserving carbon in deserts

As climate change continues to accelerate, it is essential to protect natural habitats that act as carbon sinks. When these areas are developed and disturbed, additional carbon is released into the air and the plants and soils in those ecosystems are impacted, reducing their ability to absorb and store carbon. Studies around the world have shown that desert ecosystems can act as important carbon sinks. With desert ecoregions comprising 27% of California, protecting this biome can contribute to securing carbon stores in the state. By limiting development, excessive OHV use, livestock grazing and other activities that disturb desert soils, the state can help ensure these carbon reserves stay in the ground and out of the atmosphere.

### Quick take

- Desert ecosystems provide important carbon storage functions now and in the future given climate change.
- Conserving California deserts can help ensure that the stored $CO^2$ stays in the ground.
- Key results include:
  - Inland deserts account for 10% of the state's total stored carbon.
  - 7% of carbon-rich areas in California deserts may already be impacted by human activities.
  - Ensuring sufficient desert representation in conserved areas will protect unique species assemblages and ecosystem services.

## Carbon Capture in Deserts

There are several ways in which deserts store carbon. To start, desert plants store carbon in their biomass just as other plants do; through photosynthesis, plants take in $CO_2$ from the air and convert that into tissue. Many desert plants also have important relationships with underground fungi: roots bond with these fungi in a mutually beneficial relationship. As part of this relationship, the plants transfer carbon to the mycorrhizae, which also store carbon. The majority of stored and sequestered carbon, however, is in soils. Plant or animal excretion and decomposition releases some carbon, which reacts with calcium in the desert soil to create calcium carbonate crystals. Since some desert plants' roots grow to over a hundred feet, these crystals, called caliches, can be deep underground. Caliches build into larger chunks over time and create carbon sinks. Additionally, when the root fungi die, they leave behind their waxy coating, which aggregates and helps keep carbon in the soil. For their storage and sequestration potential, arid-semiarid soils are considered the third largest global pool of carbon (Emmerich 2003).

Read more about the desert carbon storage process here: http://www.desertreport.org/?p=2270

## California Carbon Sinks

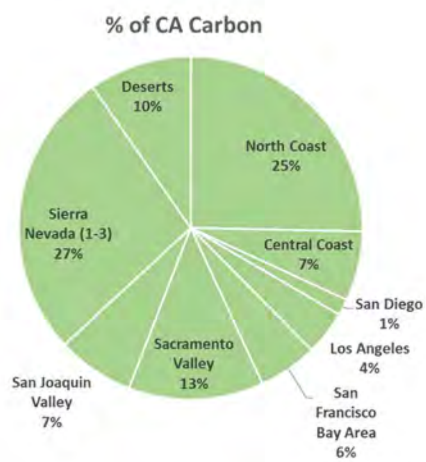
The most conclusive evidence of California desert carbon storage potential comes from a 10-year study in the Mojave Desert at the Nevada Desert Free-Air $CO_2$ Enrichment Facility (NDFF). This study compared plots of desert with current $CO_2$ levels to plots with projected 2050 $CO_2$ levels. To do this, they piped extra $CO_2$ over the plots. At the completion of the study, the researchers compared the carbon between the plots with current $CO_2$ levels and those with projected $CO_2$ levels. They found that the plots that received extra carbon were able to store significantly more carbon than those that received current carbon levels. This indicates that as atmospheric $CO_2$ levels rise, deserts will have increased capacity to sequester in response to projected elevated atmospheric $CO_2$. Deserts store 9.7% of California carbon and based on the NDFF experiment, and this amount may increase with climate change. A report by the National Parks Service shows that Death Valley and Joshua Tree National Parks and the Mojave National Preserve were within the top 10 park units with the highest annual net ecosystem carbon balance.

Read the full scientific article for this experiment here: https://doi.org/10.1038/nclimate2184

## Results

The data indicate that 27% of lands within the state of California fall within desert ecoregions (Inland Desert and Sierra Nevada-East). These lands alone account for nearly 10% of the total carbon stored in the state. Importantly, the top carbon-rich locations in deserts are less impacted by human activity compared to other ecoregions: 7% overlap with areas of higher human footprint compared to nearly one quarter of carbon-rich areas in the San Joaquin Valley. Currently, 42% of carbon-rich areas in desert regions fall into areas managed for conservation. An additional 35% fall on public lands managed for multiple uses (including extractive activities). Based on these results, California deserts sequester and store a significant amount of the state's carbon. Though desert environments have relatively low sequestration on a per area basis, they represent a large proportion of the state's area and are relatively undisturbed by human activity.

Carbon can be stored in a number of different reservoirs. Here we analyzed total ecoregion carbon in above- and belowground biomass and in soil (Soto-Navarro et al. 2020). We compared the top carbon-rich areas for each ecoregion with human footprint metrics and the protected areas database of the U.S.


*Map highlighting carbon-rich areas (top 20%) within each ecoregion and current coincidence with higher human disturbance. Sierra Nevada – East was combined with the Inland Desert ecoregion to represent California's deserts as a singular unit.*

## Recommended Actions

Given their carbon storage capabilities, conservation of large, intact desert areas could have a high return on investment for climate mitigation. Decision-makers will need to account for desert ecosystems in short- and long-term conservation planning efforts to ensure the persistence of these ecosystem services under future climate change scenarios. Great opportunity exists for desert protections on public lands, but some carbon-rich areas could benefit from private lands conservation, especially around the Salton Sea. Particular care should be taken in recognizing Death Valley (Sierra Nevada – East sub ecoregion) as a desert ecosystem that is unique and separate from others in the Sierra Nevada ecoregion. Failing to do so results in underestimation of Death Valley's carbon storage potential, which has been noted in other works. Finally, local stakeholders, Tribes and desert communities should be part of the decision-making process to ensure that those groups disproportionately impacted by conservation (or other) efforts in this ecoregion are well represented.

**Questions?**
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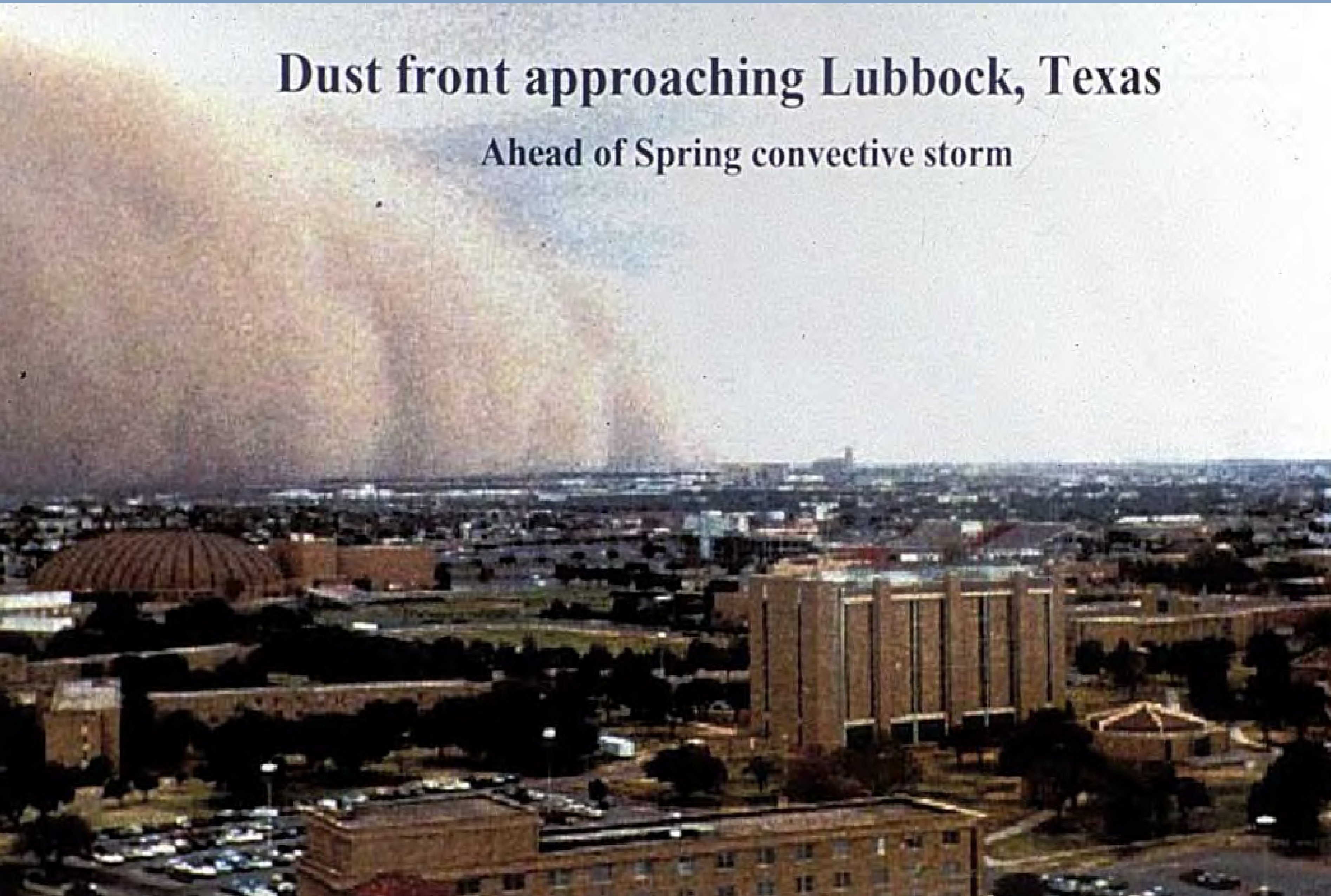
# Soil Surface Susceptibility to Wind Erosion

Jayne Belnap, Sue Phillips, David M. Miller, David Bedford, Geoffrey Phelps Alan Flint, Lorraine Flint, Joseph Hevesi, Susan Benjamin

USGS
science for a changing world

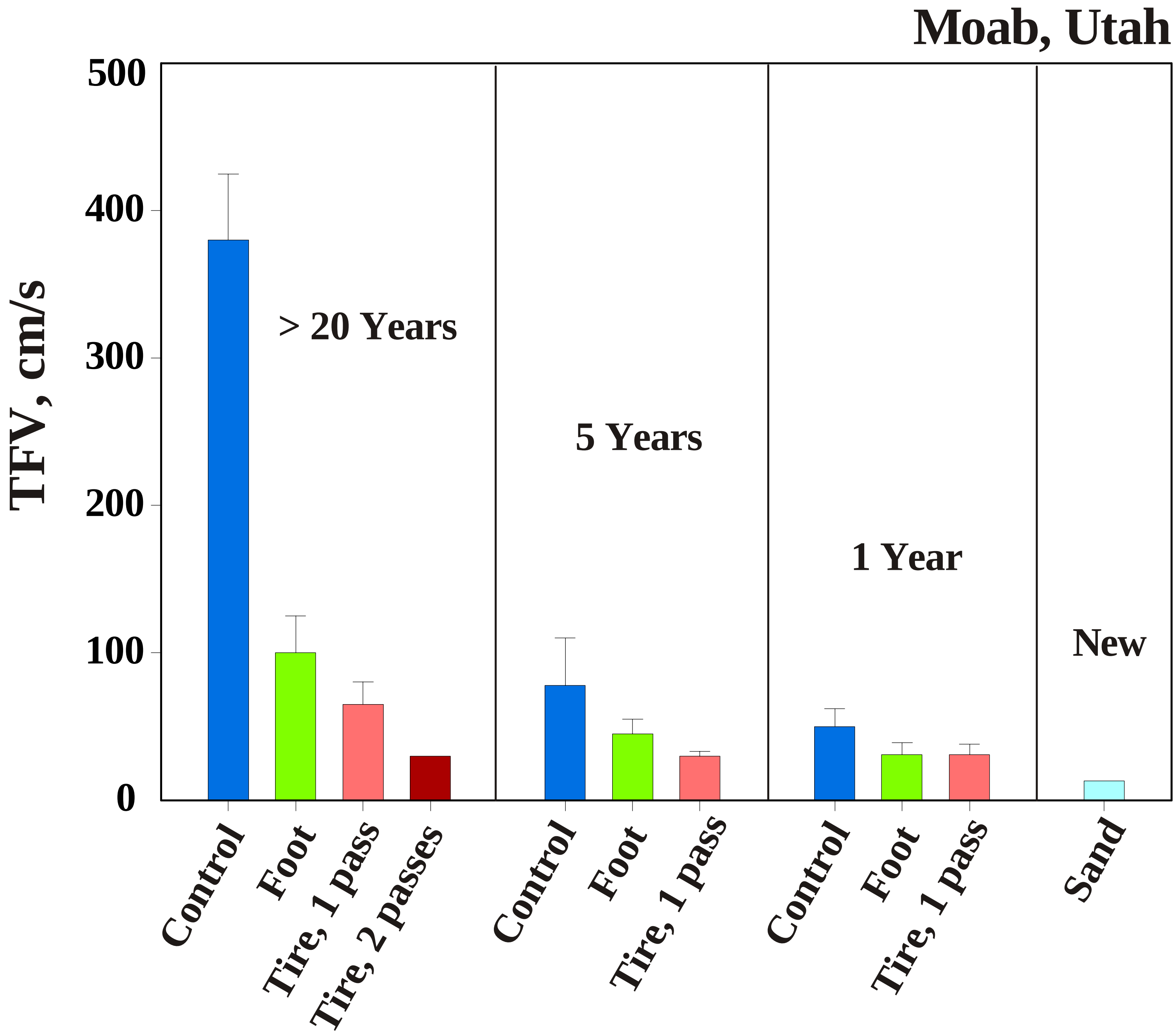


Dust front approaching Lubbock, Texas
Ahead of Spring convective storm

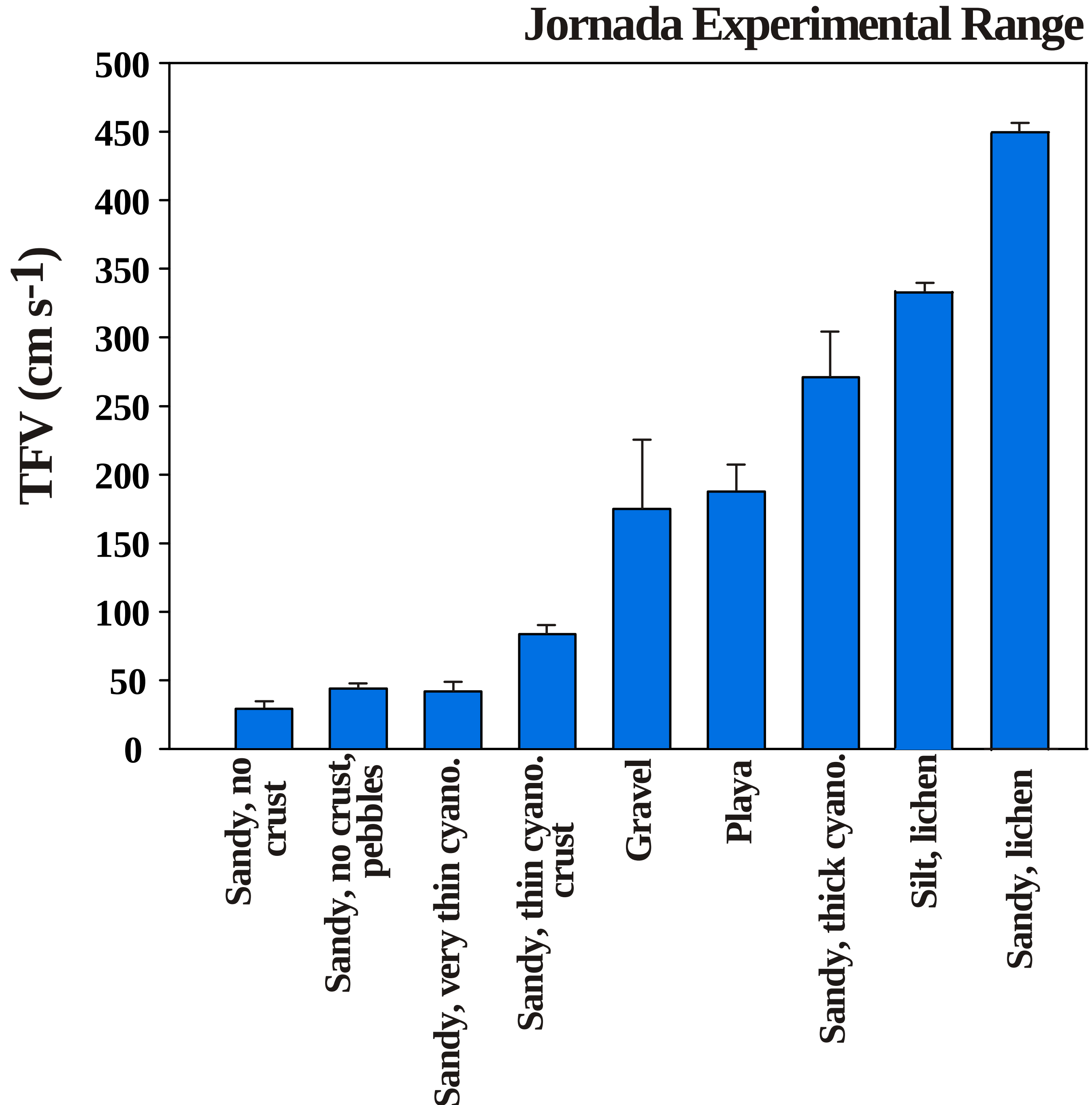
**TFV= Threshold Friction Velocity**

**The wind speed at which particles move**

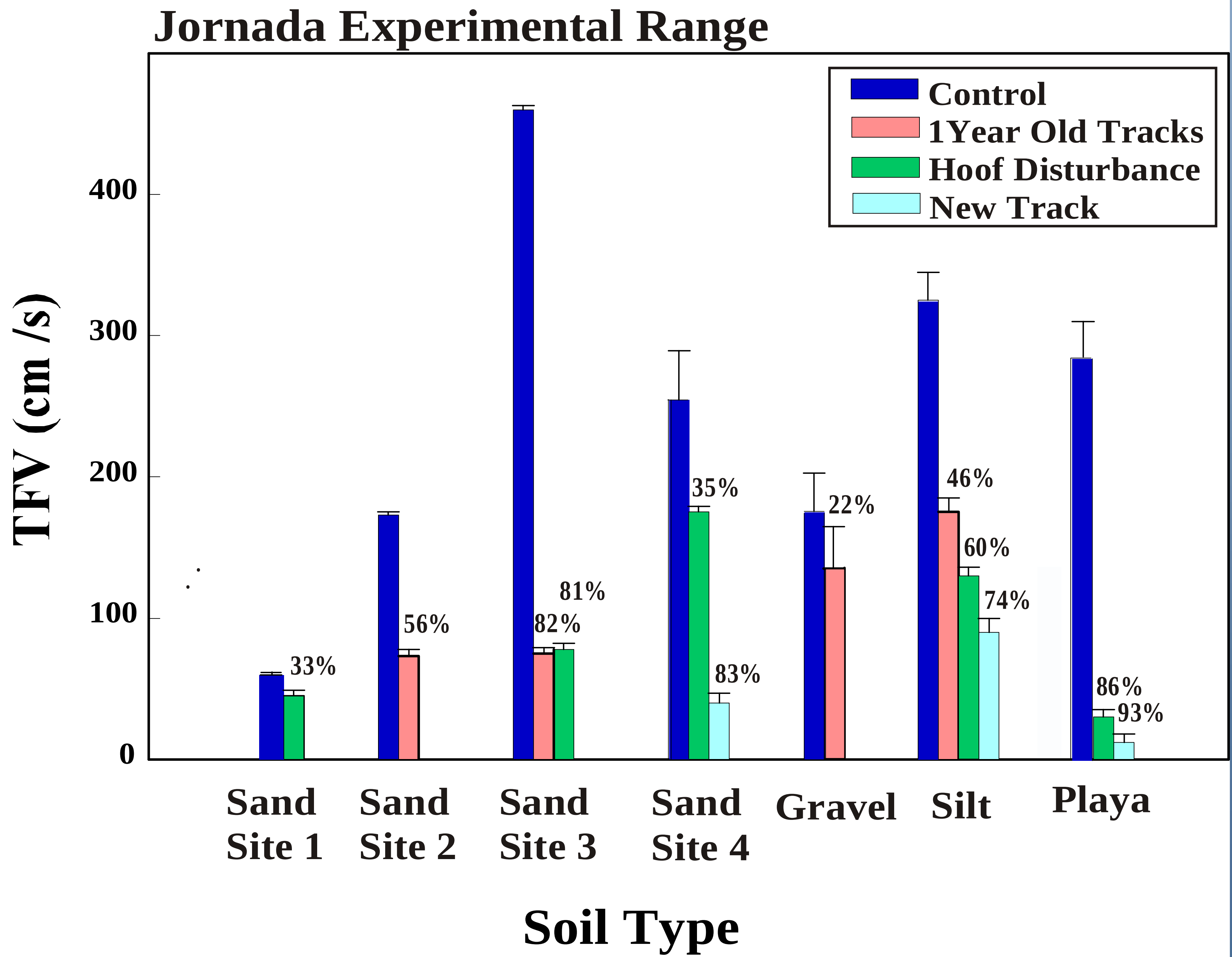
**Sediment = amount of soil blown off the soil surface at high spring wind speed**

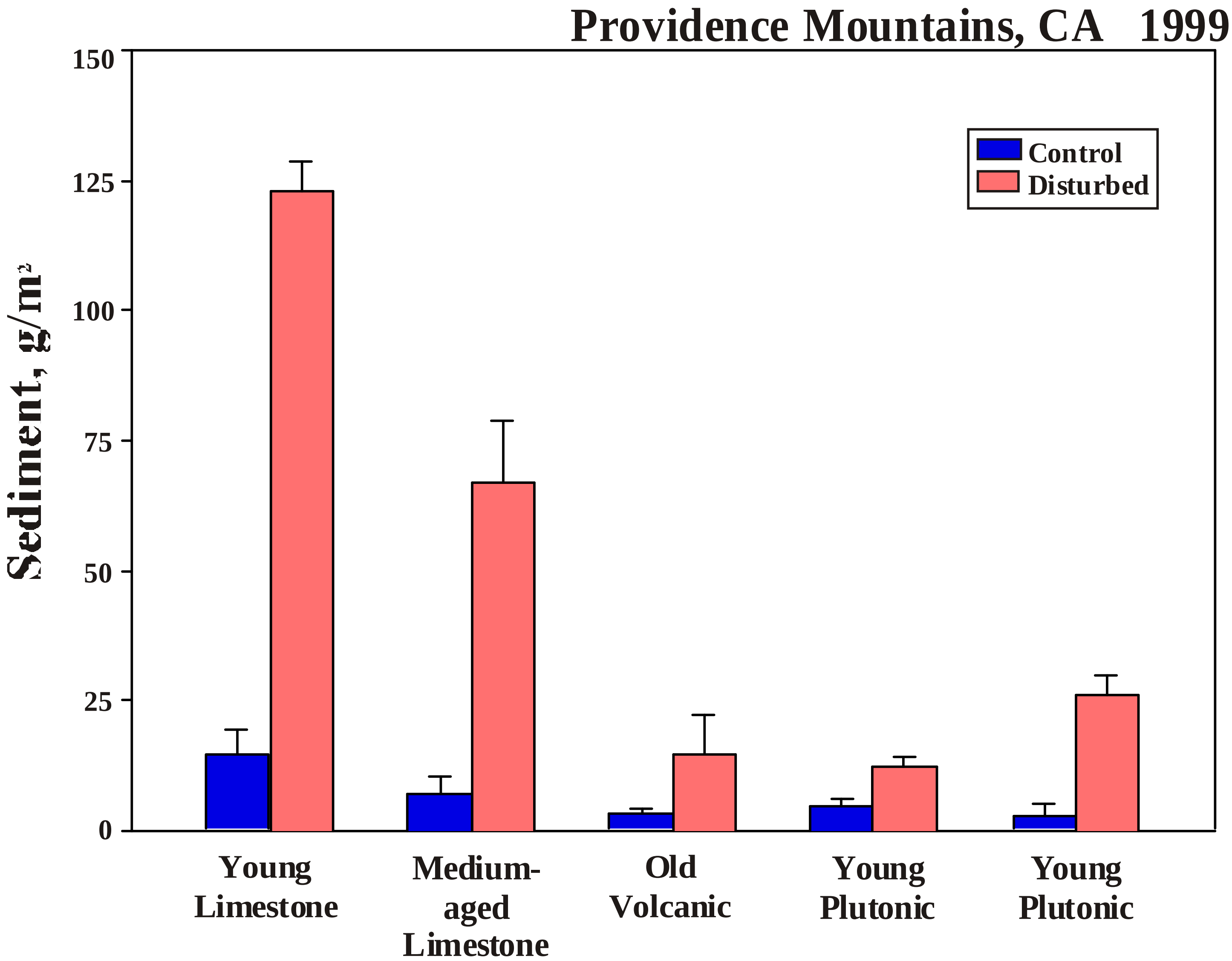


Moab, Utah
TFV, cm/s
500
400
300
200
100
0
> 20 Years
5 Years
1 Year
New
Control
Foot
Tire, 1 pass
Tire, 2 passes
Control
Foot
Tire, 1 pass
Control
Foot
Tire, 1 pass
Sand



Jornada Experimental Range
TFV (cm s-1)
500
450
400
350
300
250
200
150
100
50
0
Sandy, no crust
Sandy, no crust, pebbles
Sandy, very thin cyano.
Sandy, thin cyano. crust
Gravel
Playa
Sandy, thick cyano.
Silt, lichen
Sandy, lichen


Jornada Experimental Range
Control
1Year Old Tracks
Hoof Disturbance
New Track
TFV (cm /s)
400
300
200
100
0
33%
56%
82%
81%
35%
83%
22%
46%
60%
74%
86%
93%
Sand Site 1
Sand Site 2
Sand Site 3
Sand Site 4
Gravel
Silt
Playa
Soil Type

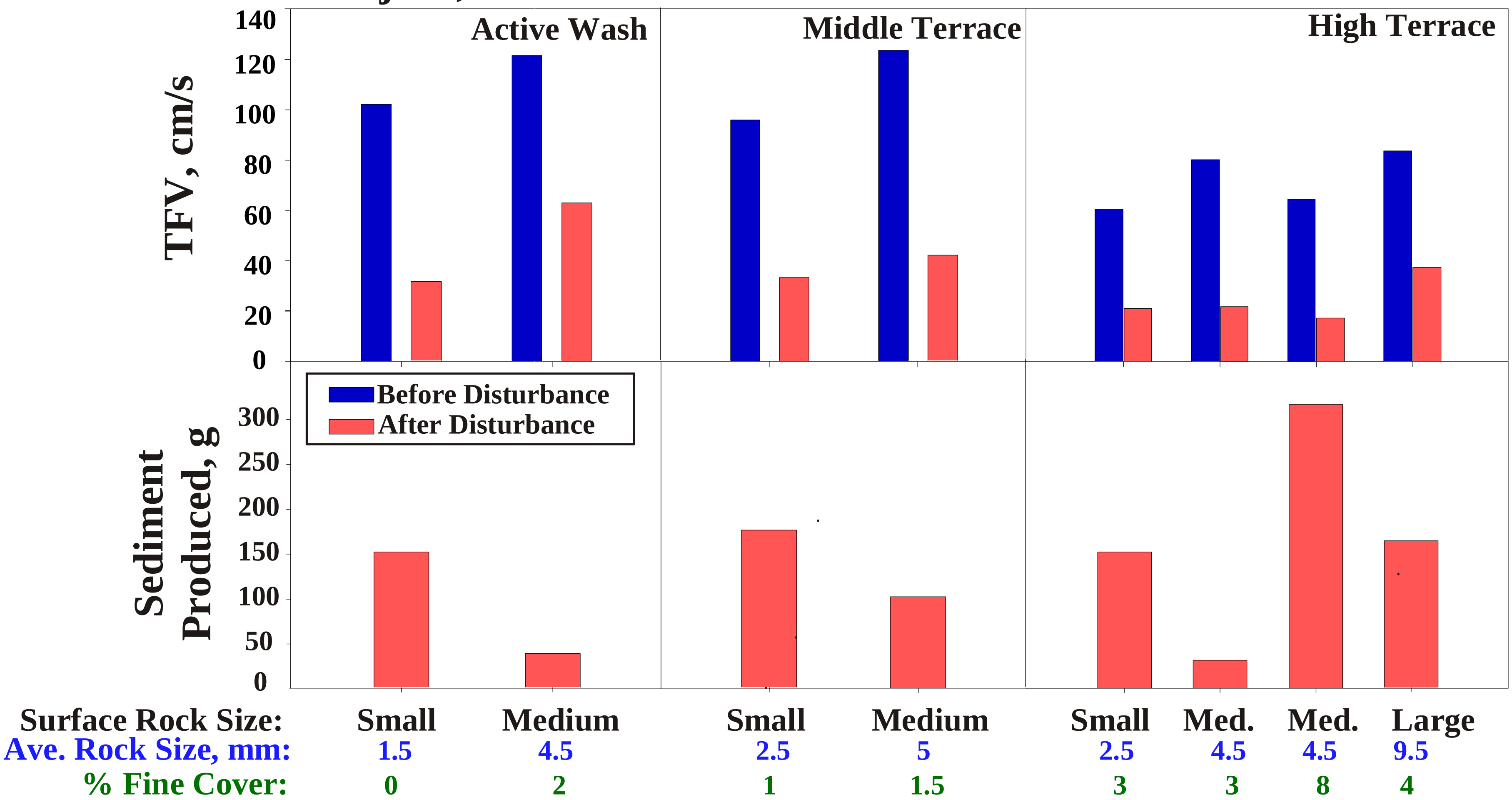



Sites of Different Substrate: Distal Alluvial Fan

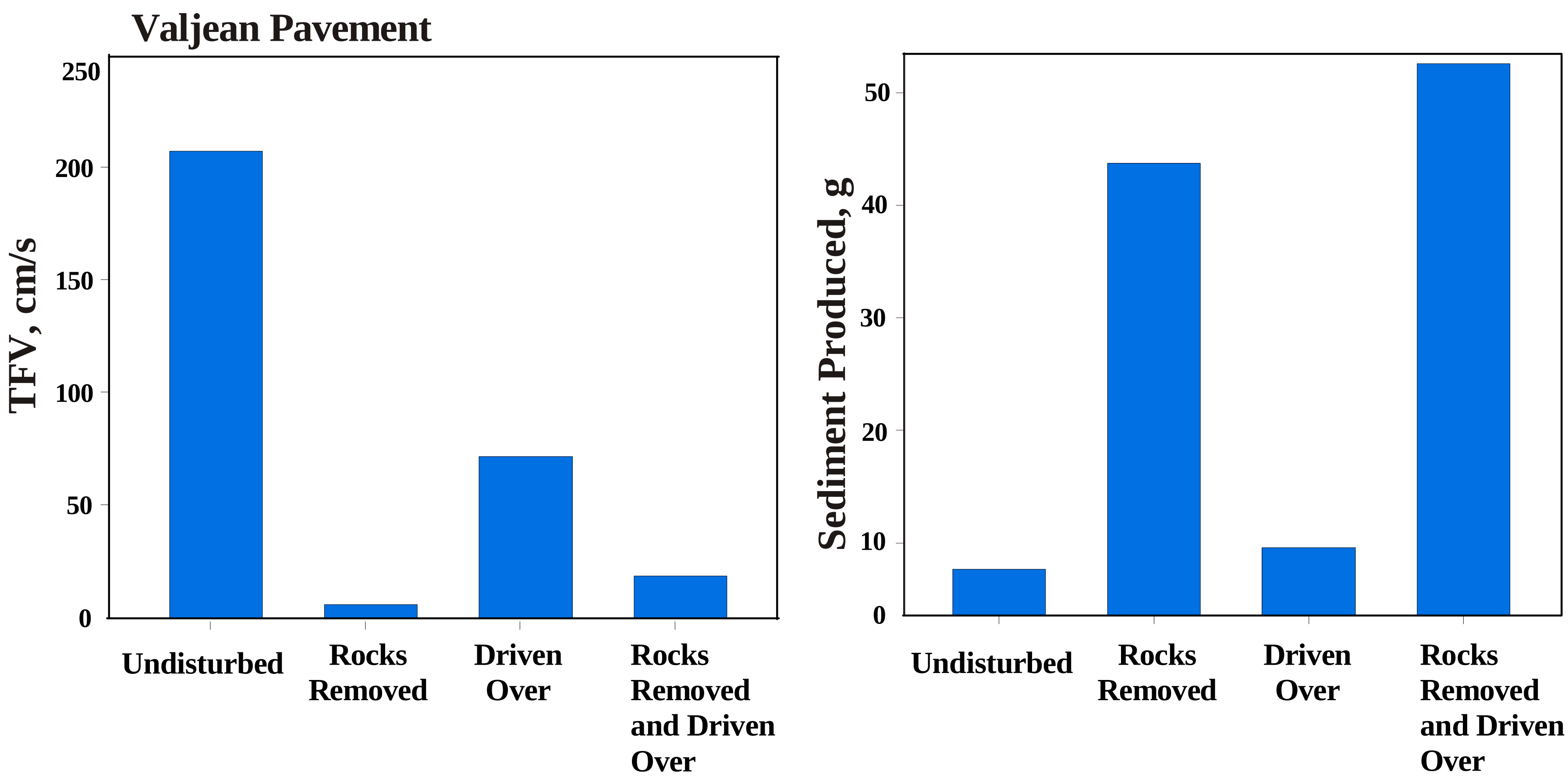
Rock Cover: Control $r^2$=0.86

Disturbed $r^2$=0.97

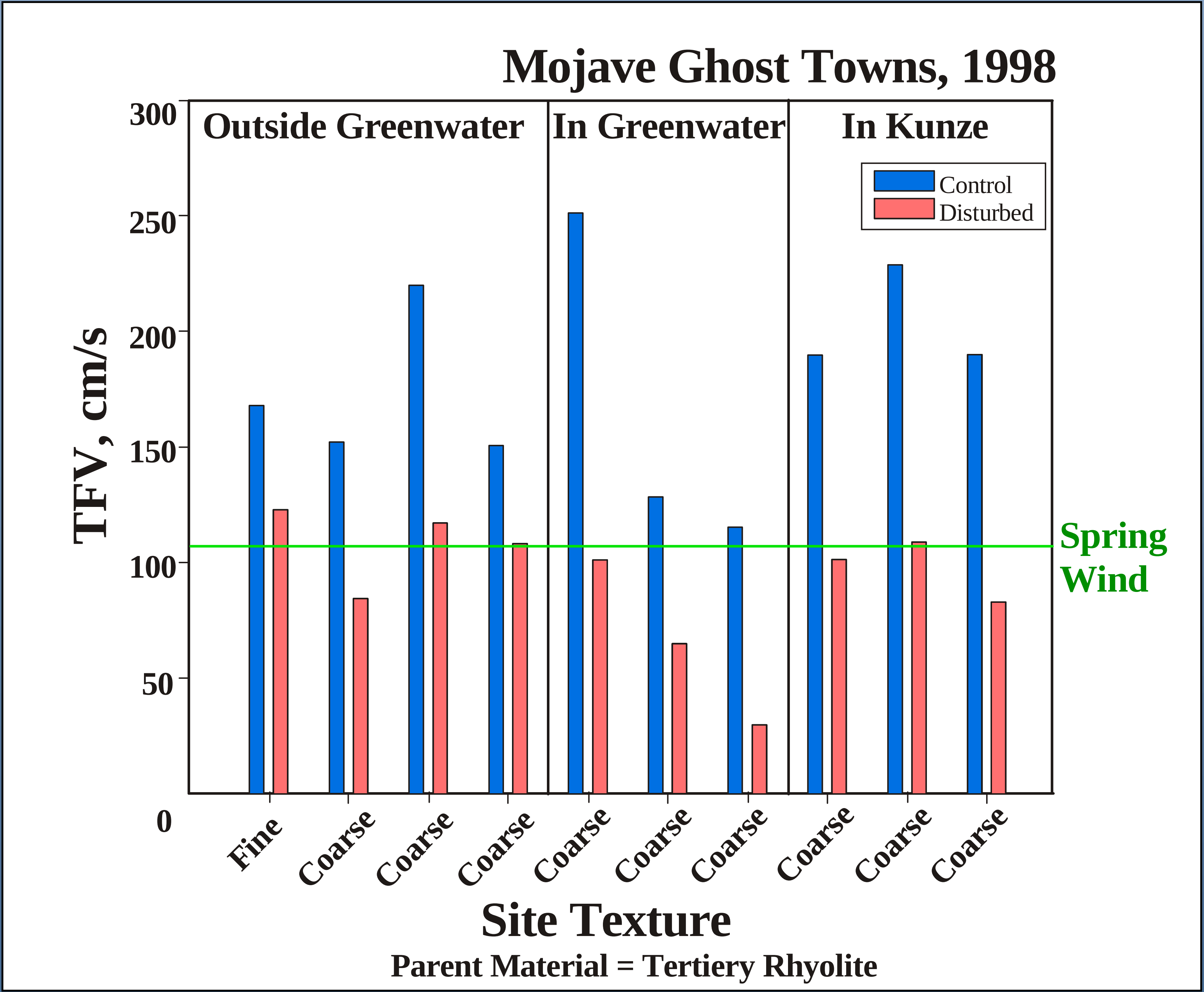
# Valjean, CA



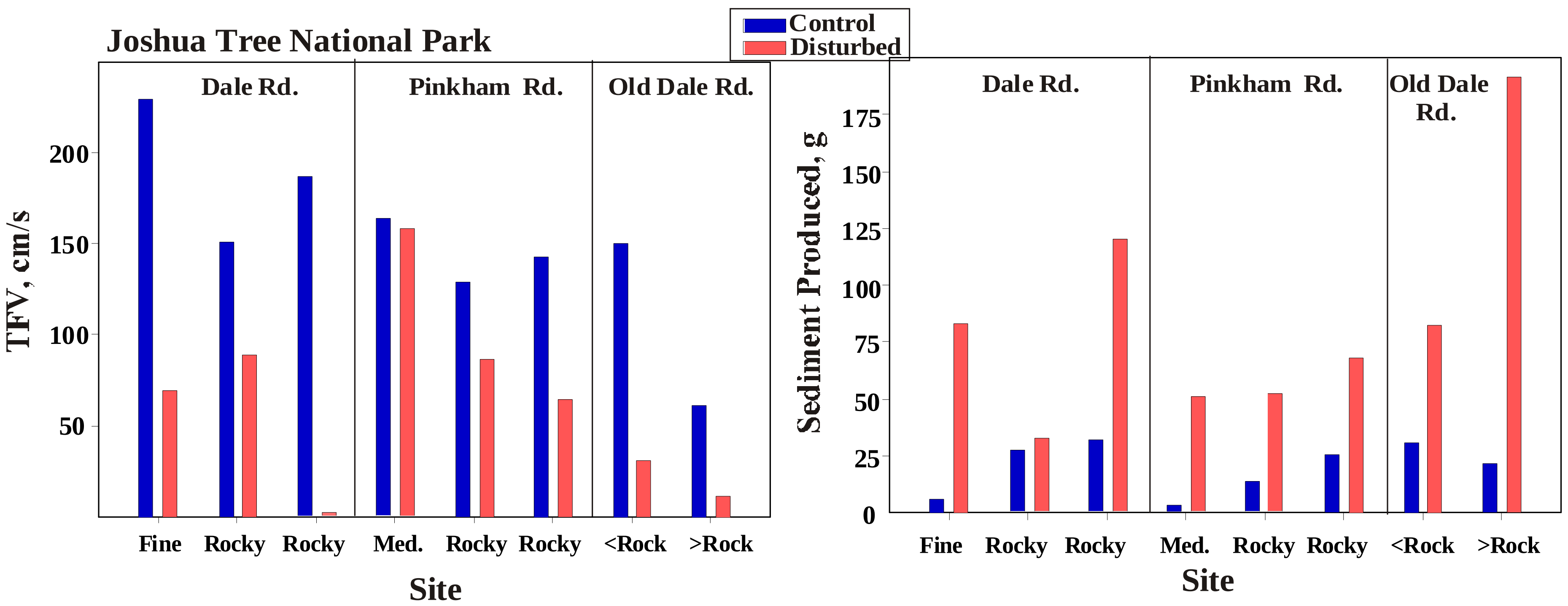
Active Wash
Middle Terrace
High Terrace
TFV, cm/s
140
120
100
80
60
40
20
0
Before Disturbance
After Disturbance
Sediment Produced, g
300
250
200
150
100
50
0
Surface Rock Size: Small Medium Small Medium Small Med. Med. Large
Ave. Rock Size, mm: 1.5 4.5 2.5 5 2.5 4.5 4.5 9.5
% Fine Cover: 0 2 1 1.5 3 3 8 4

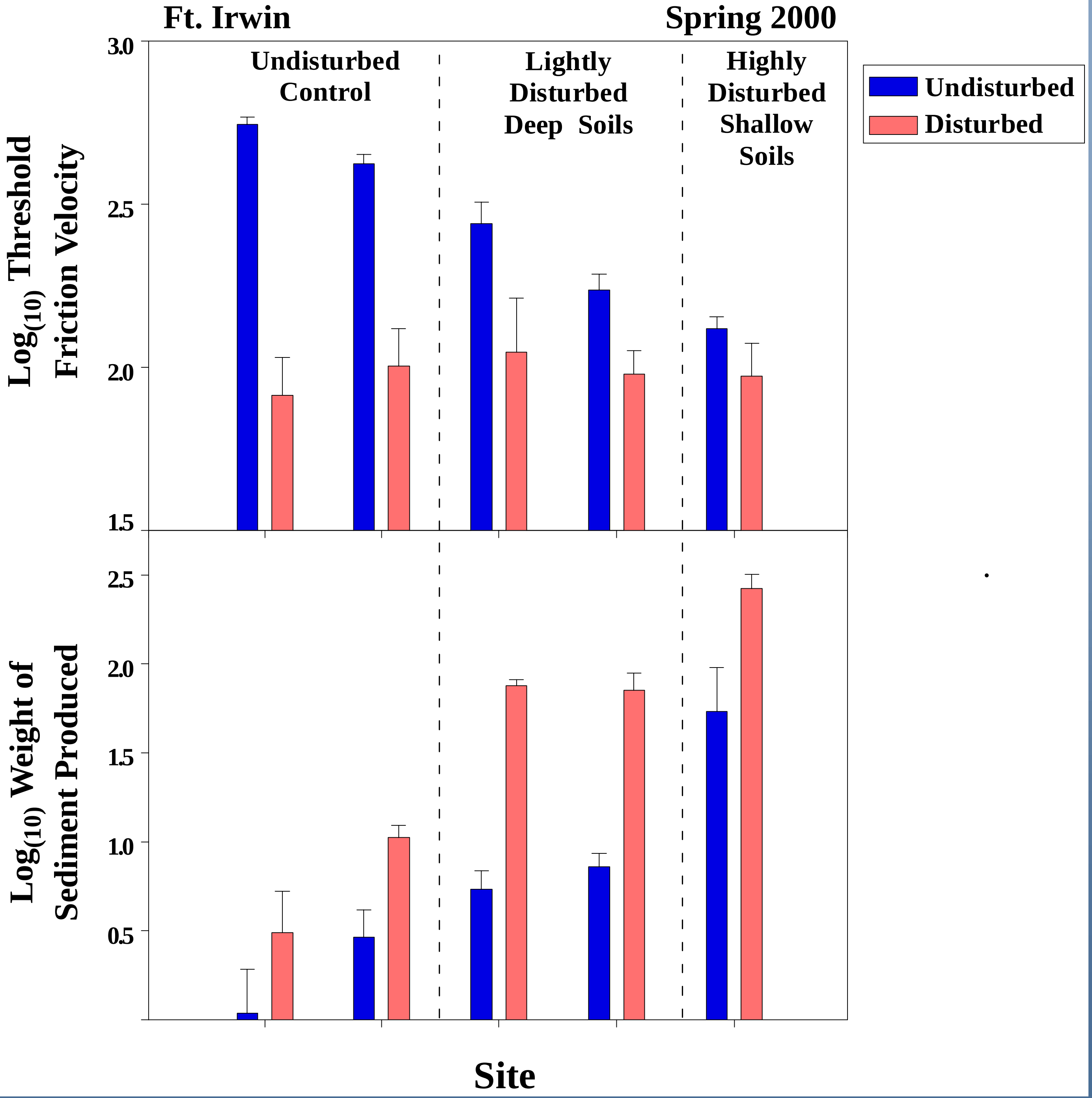


Valjean Pavement
TFV, cm/s
250
200
150
100
50
0
Undisturbed
Rocks Removed
Driven Over
Rocks Removed and Driven Over
Sediment Produced, g
50
40
30
20
10
0
Undisturbed
Rocks Removed
Driven Over
Rocks Removed and Driven Over



Mojave Ghost Towns, 1998
Outside Greenwater
In Greenwater
In Kunze
Control
Disturbed
TFV, cm/s
300
250
200
150
100
50
0
Spring Wind
Fine
Coarse
Coarse
Coarse
Coarse
Coarse
Coarse
Coarse
Coarse
Coarse
Site Texture
Parent Material = Tertiery Rhyolite


Joshua Tree National Park
Control
Disturbed
Dale Rd.
Pinkham Rd.
Old Dale Rd.
TFV, cm/s
200
150
100
50
Fine
Rocky
Rocky
Med.
Rocky
Rocky
<Rock
>Rock
Site
Sediment Produced, g
175
150
125
100
75
50
25
0
Dale Rd.
Pinkham Rd.
Old Dale Rd.
Fine
Rocky
Rocky
Med.
Rocky
Rocky
<Rock
>Rock
Site


Ft. Irwin
Spring 2000
Undisturbed Control
Lightly Disturbed Deep Soils
Highly Disturbed Shallow Soils
Undisturbed
Disturbed
Log(10) Threshold Friction Velocity
3.0
2.5
2.0
1.5
Log(10) Weight of Sediment Produced
2.5
2.0
1.5
1.0
0.5
Site

# Wind Erosion Vulnerability

Location
Altitude
Slope
Aspect
Quarternary Unit
Parent Material
Chemical Weathering Rate
Pavement Formation
Aeolian Sand Inputs
Rockiness Index
Roughness
% Disturbance
Rock Cover (3 Rock Size Classes)
Litter Cover (2 Litter Classes)

Lichen & Moss Cover (by Species)
Lichen &Moss Species Richness
Cyanobacterial Cover
Cyanobacterial Biomass
Shrub Cover
Annual Grass Cover
Perennial Grass Cover
Soil Surface & Subsurface Chemistry (P, K, Zn, Fe, Mn, Cu, Ca, Mg, Na, N, CaCO3)
Soil Texture
Sand Size Fractions
Average Annual Precipitation
Average Annual ET

# Vulnerability to wind erosion

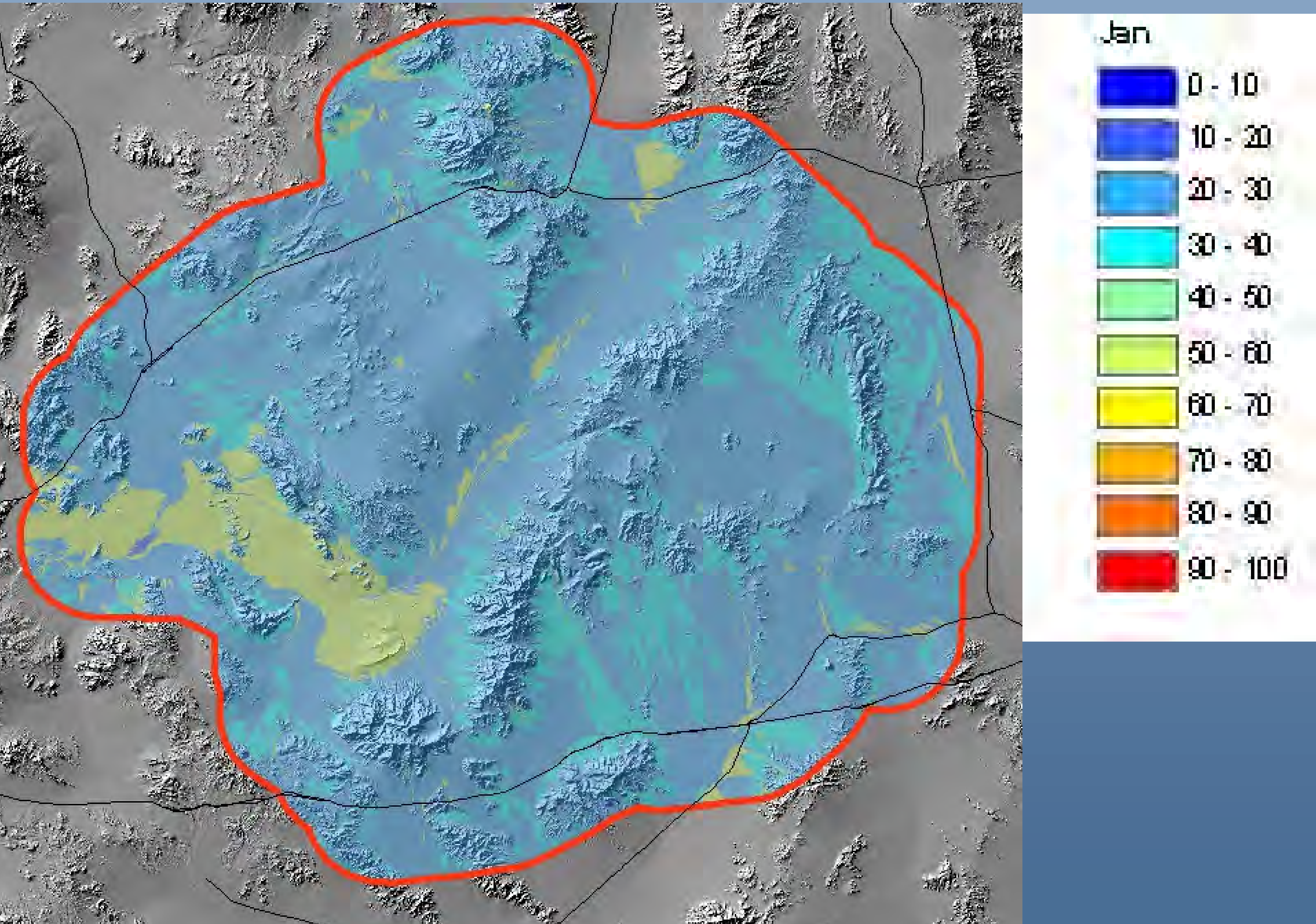
## Soil Surface Characteristics

- Disturbance
- Particle size distributions (med.+fine/silt)
- Surface rockiness
- Salt
- Biological and physical crusts

## Climate

- Hours when soils are dry and winds exceed TFV

# % time per month that a Threshold Friction Velocity is exceeded



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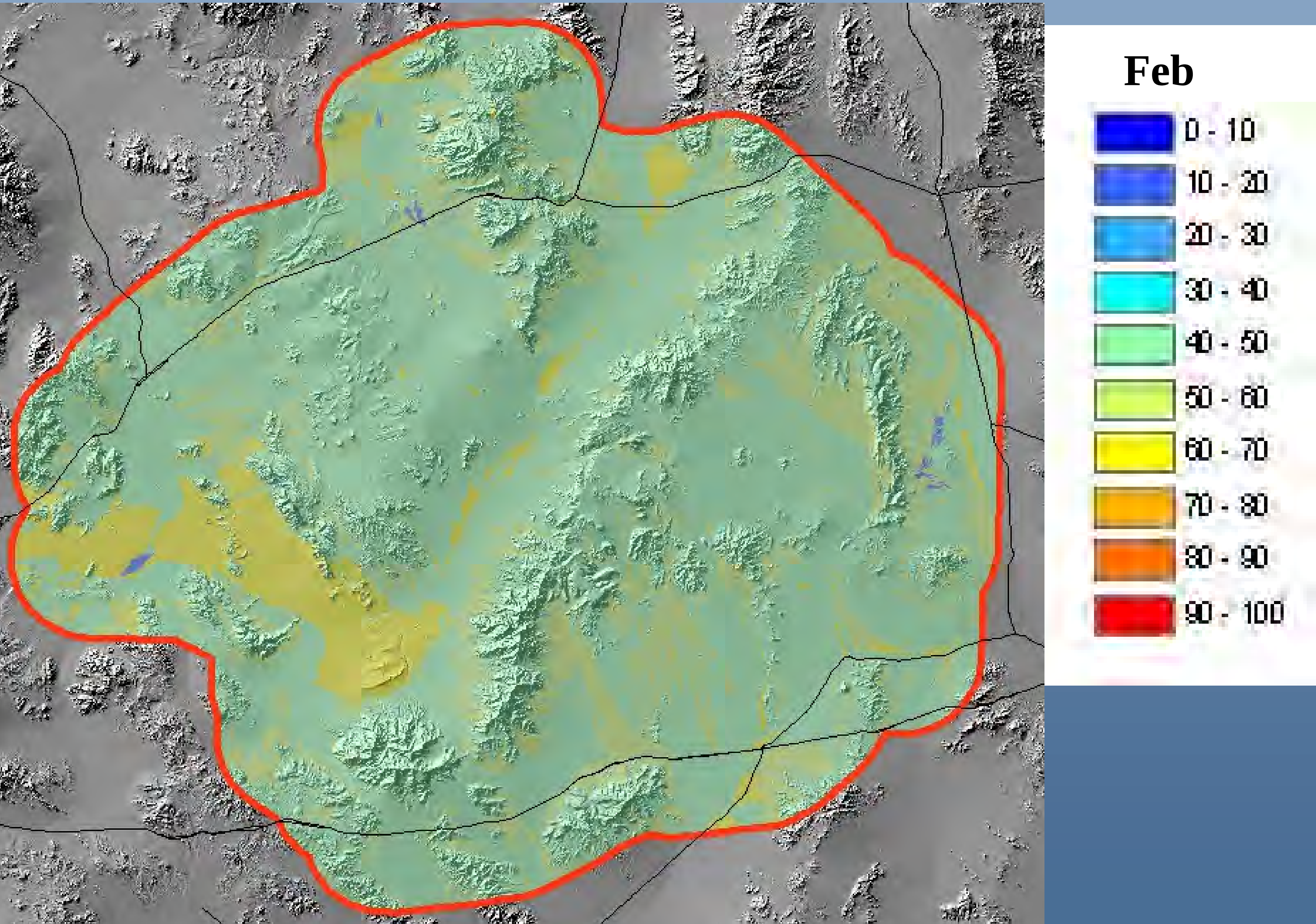

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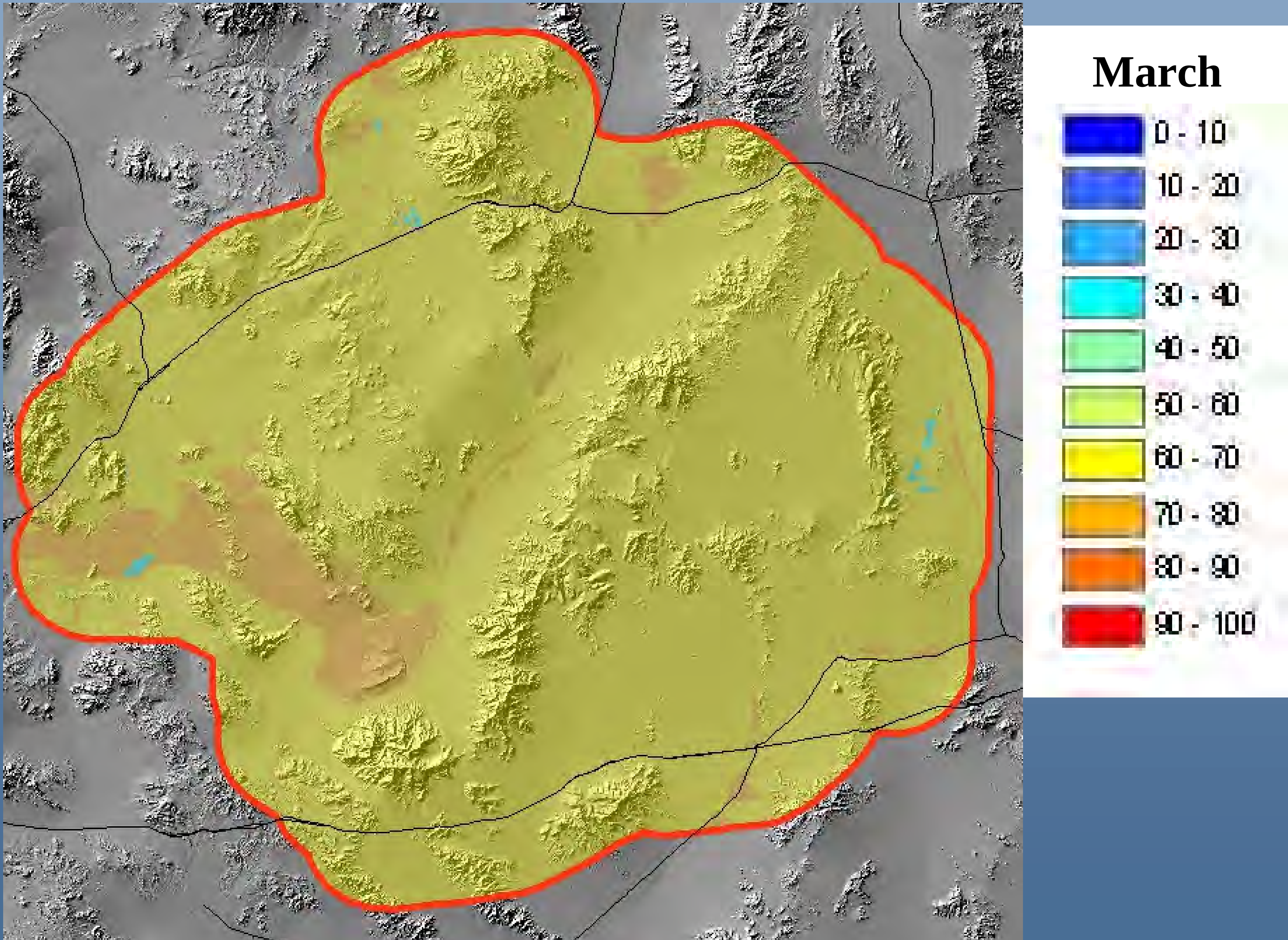

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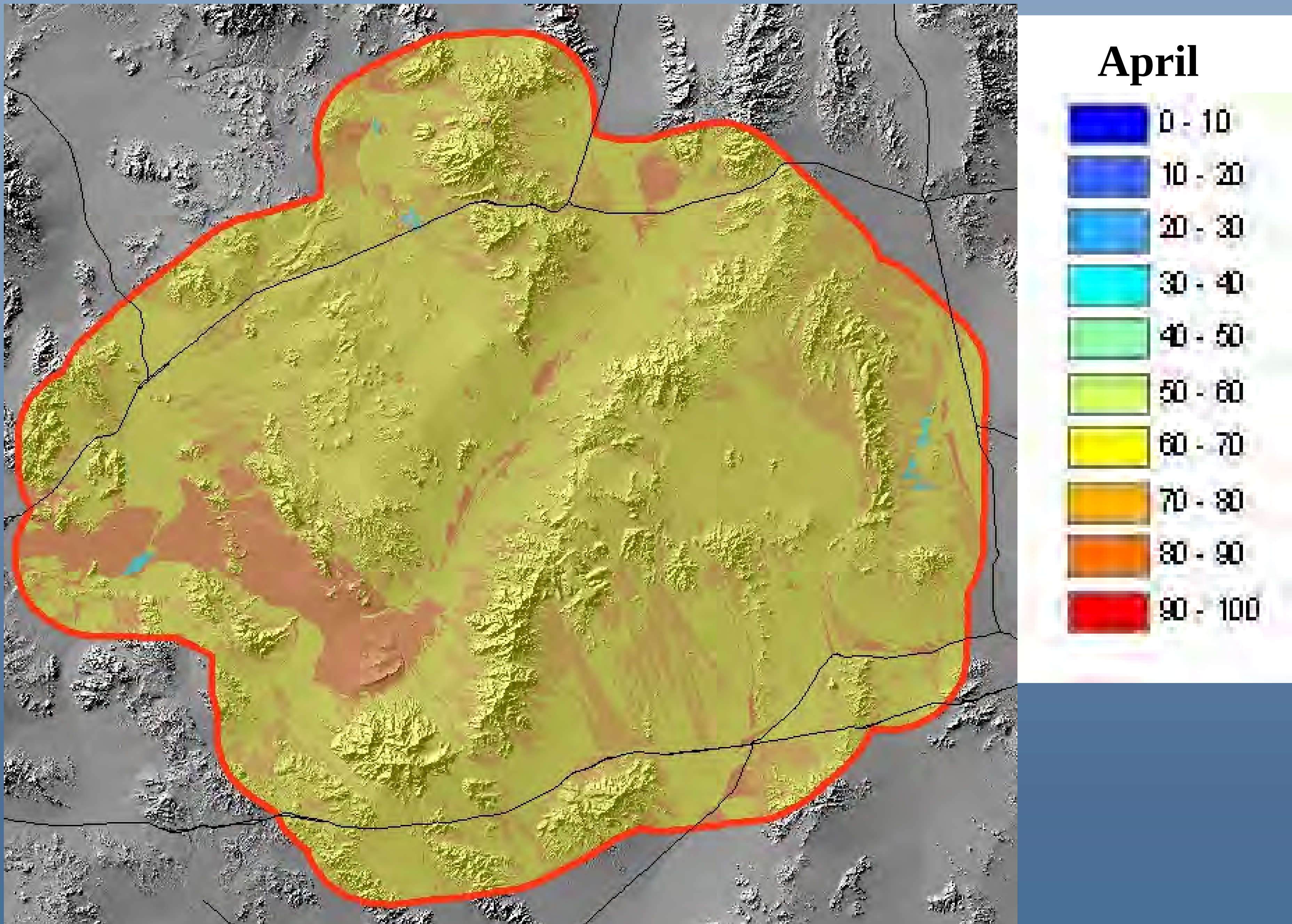

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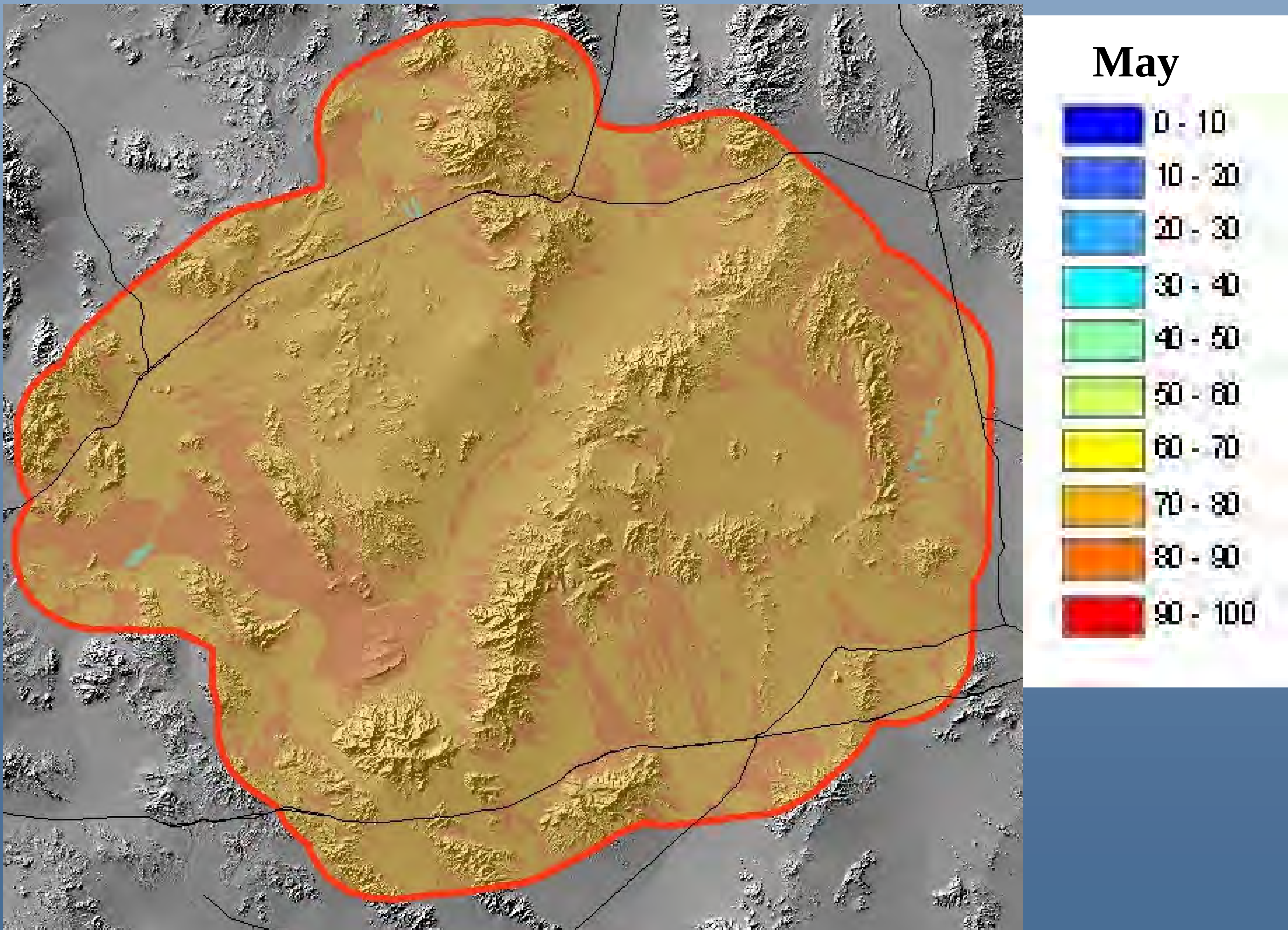

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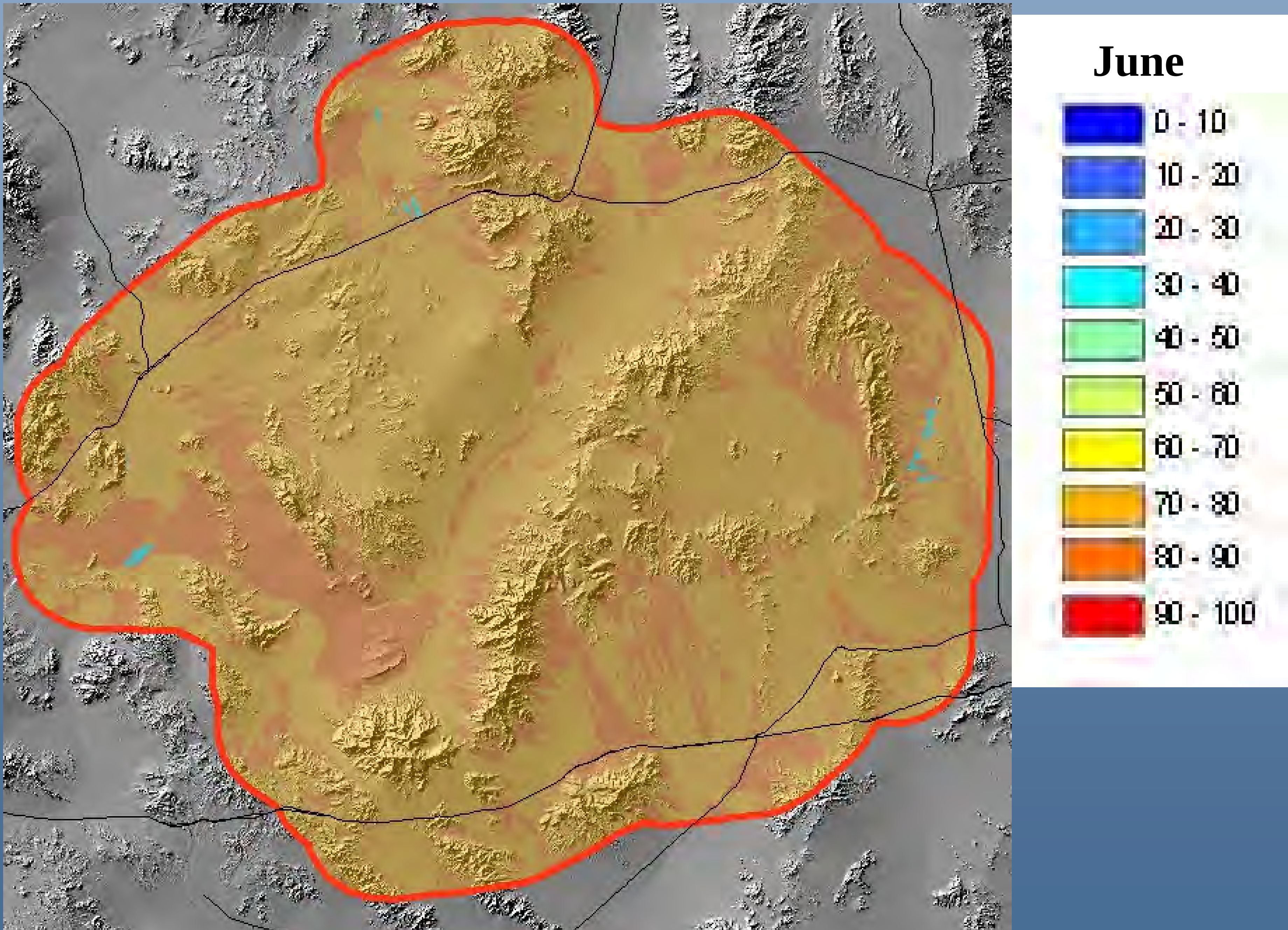

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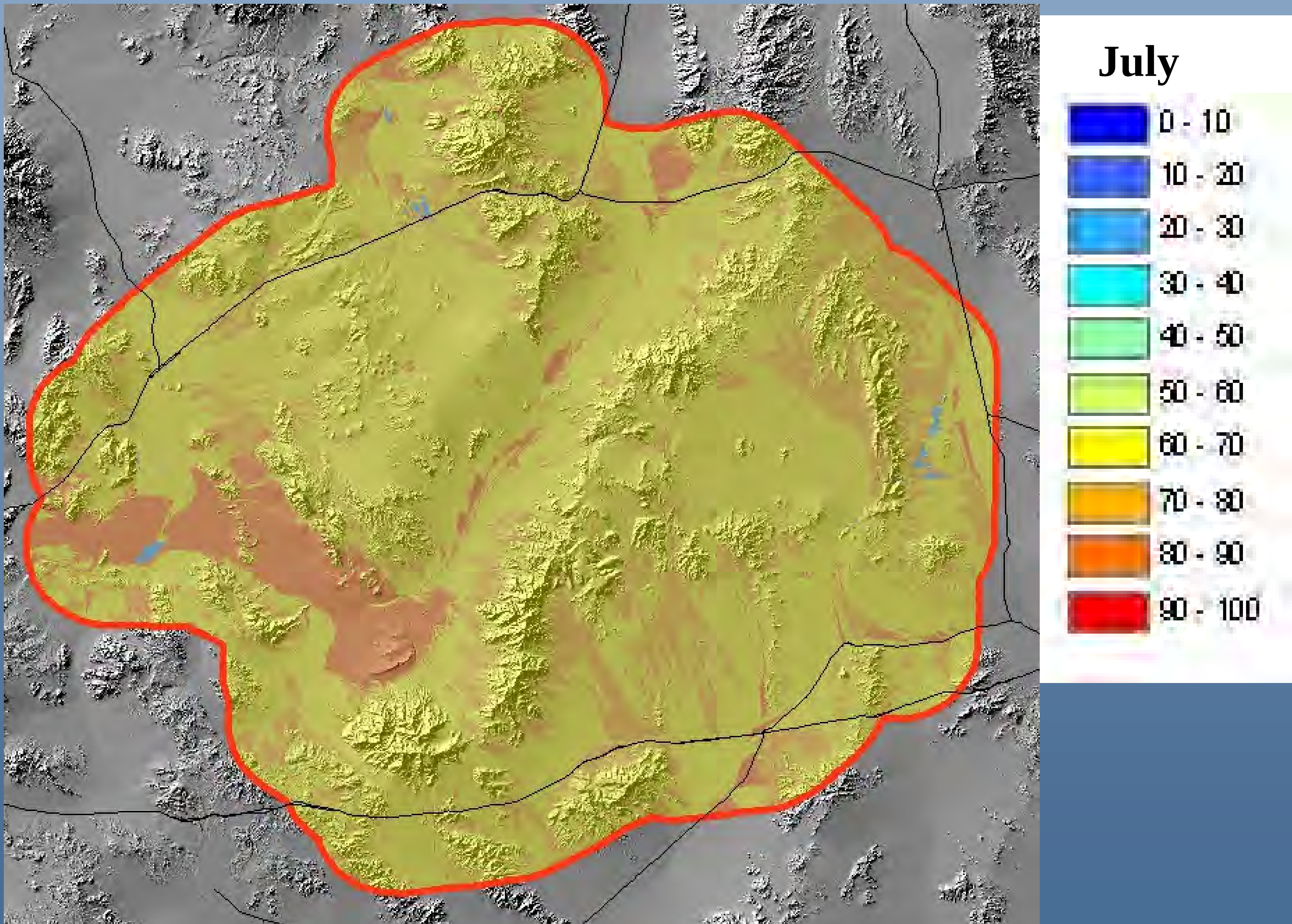

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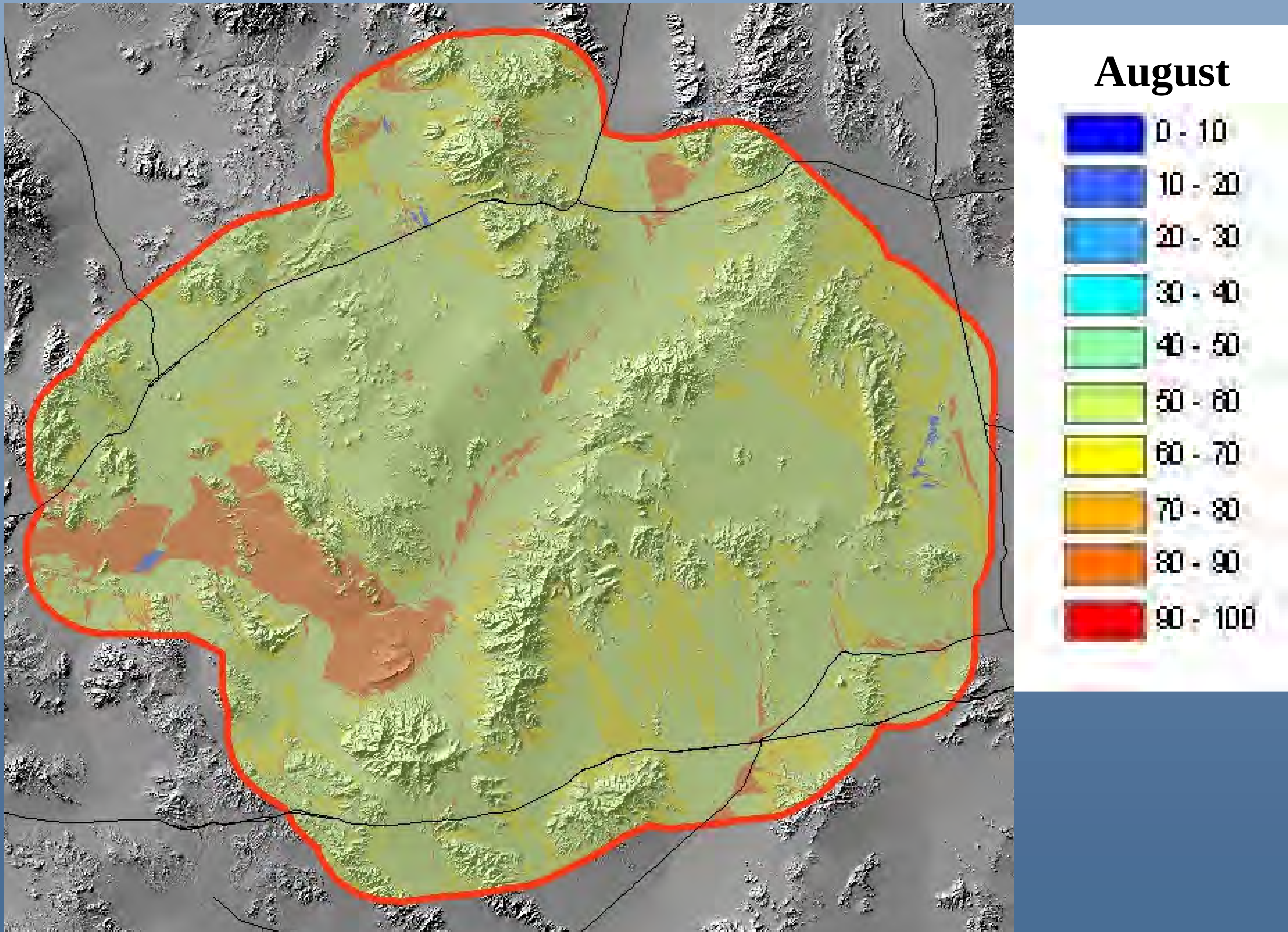

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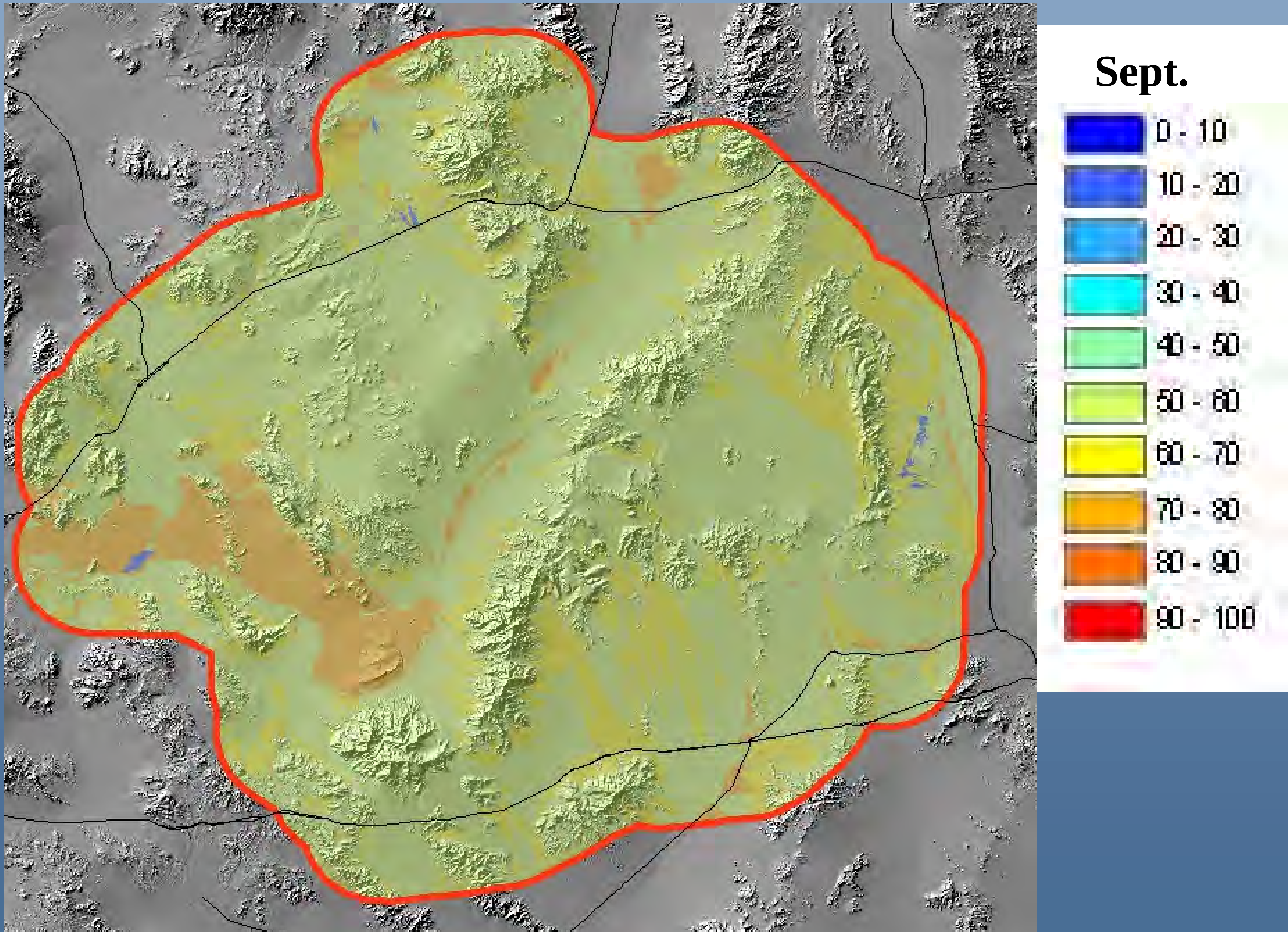

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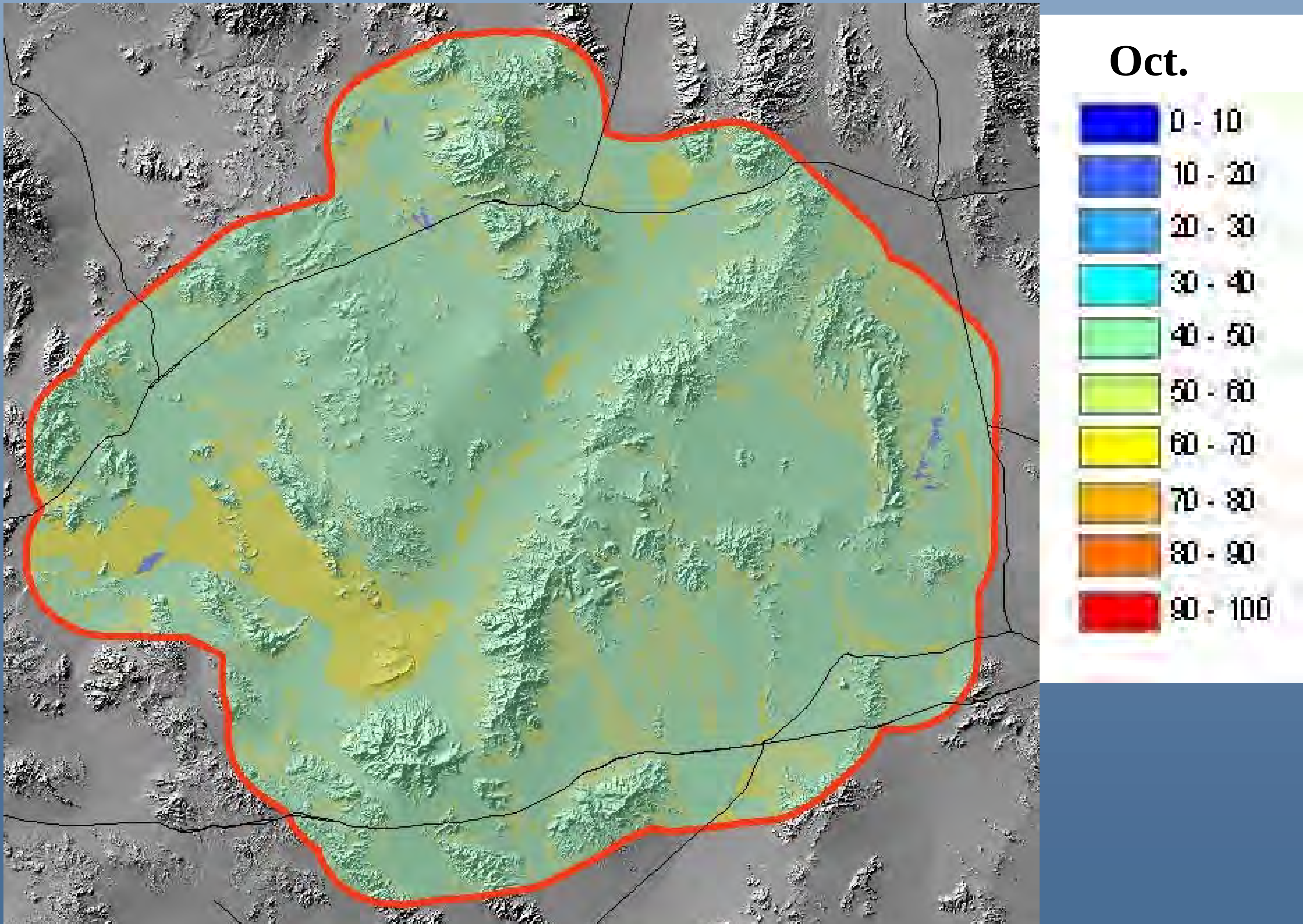

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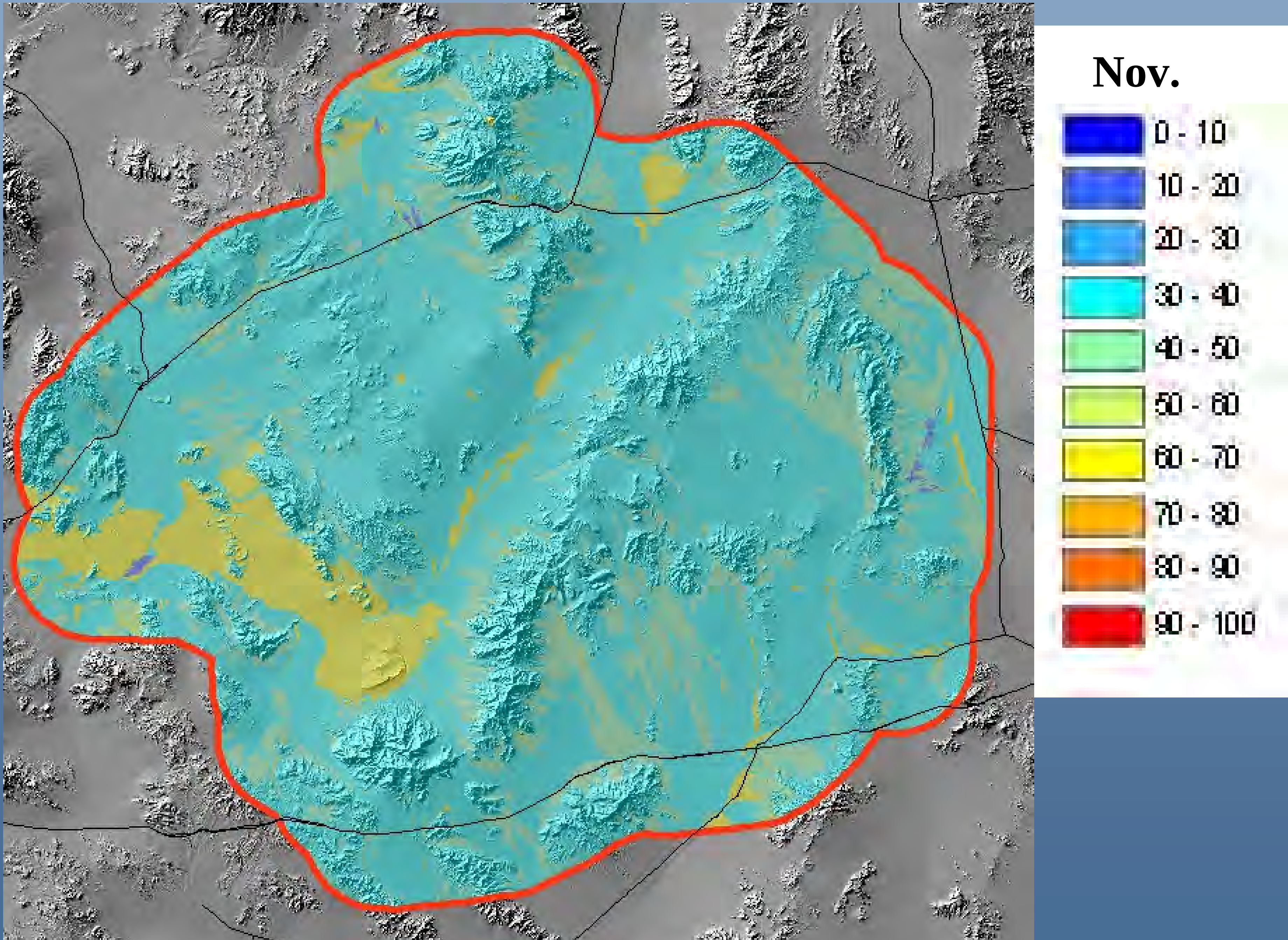

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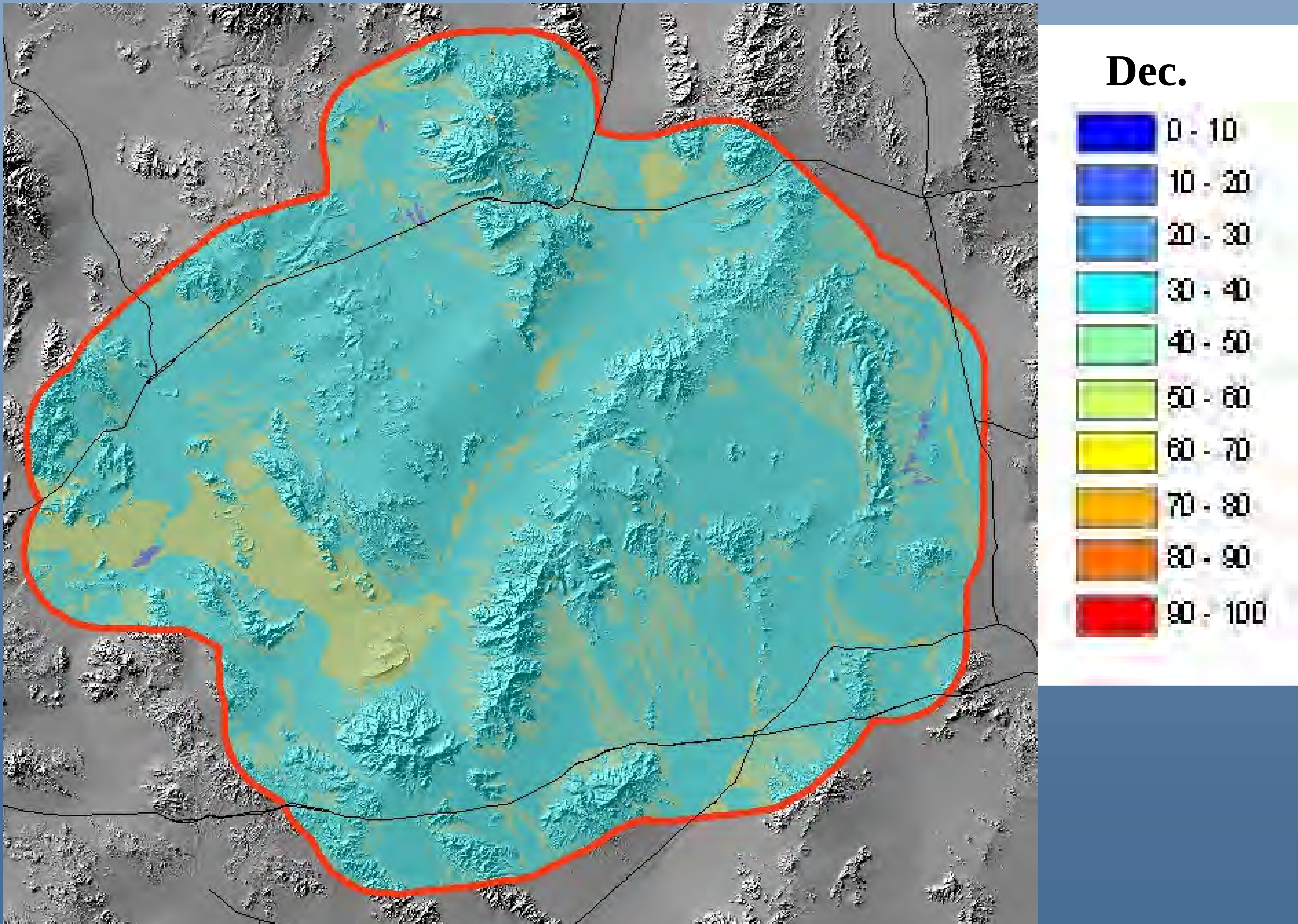
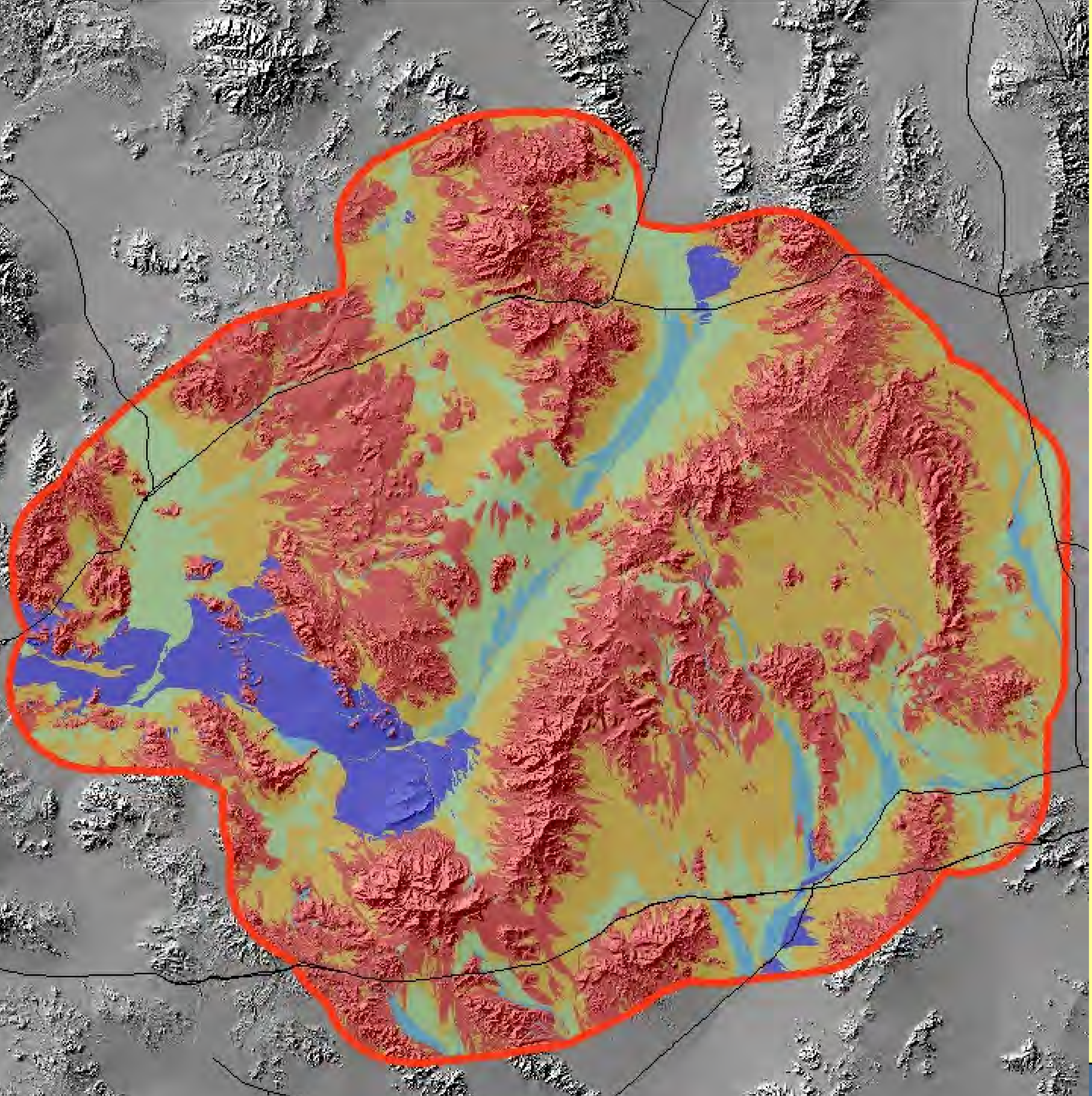


# Preliminary Wind Sediment Production Map for Disturbed Soils in the Mojave Nat'l Preserve



## Legend

Main Road

MOJA border, buffer

Sediment g/m²

Low

Medium

High

# Where from here for Mojave Wind Vulnerability?

- Anemometers
- Repeated disturbances

# CONCLUSIONS

- Potential crust distribution can be predicted and mapped. We need to understand processes behind distribution for greater predictive power.
- Recovery appears to follow a general model, but we need many more dated disturbances
- Explore ways to hasten recovery
- Vulnerability to wind erosion can be predicted and mapped. We need to include repeated disturbance.
- Vulnerability to water erosion has not been tested.

# The California Desert's Role in 30X30: Carbon Sequestration and Biodiversity

February 6, 2024

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**Colin Barrows,** Co-founder, Cactus to Cloud Institute

**Susy Boyd**, MNR. Master of Natural Resources, Forests and Climate Change. Oregon State University

**Pat Flanagan,** B.A. Biology. California State University, Long Beach

**Robin Kobaly,** M.S. Biology and Plant Ecology. University of California, Riverside

**Arch McCulloch,** M.S. Computer Science. Azusa Pacific University. B.S Geology / Computer Science. California State University, Dominguez Hills

**Joan Taylor,** Governing board of the Coachella Valley Mountains Conservancy, and boards of Friends of the Desert Mountains and The Wildlands Conservancy. Chairperson, California Conservation Committee and California/Nevada Desert Committee of Sierra Club

## Author Biography

**Dr. Michael Allen.** Dr. Michael Allen has a Bachelor of Science in Biology from Southwestern College in Kansas, a Master of Science in Botany from the University of Wyoming, and a Ph.D. in Botany from the University of Wyoming, and is currently a Distinguished Professor Emeritus in Microbiology and Plant Pathology at the University of California, Riverside. He has worked on carbon flux and mycorrhizae since his dissertation, served as a program officer at the National Science Foundation where he managed Long-Term Projects, Ecosystems, and Conservation and Restoration Biology. During his tenure, he led discussions for the initiation of the National Ecological Observatory Network (NEON), served as an original member of various NEON boards, led the Biodiversity workshop, led the California bioregion discussions, and designed the soil sensor network that was adopted by NEON to measure soil carbon flux.

**Dr. Cameron Barrows.** Dr. Cameron Barrows worked for The Nature Conservancy (TNC) with his wife Kate, managing the last remaining old growth redwood forest in Mendocino County, CA, and conducting research on Spotted Owls (1980-1986). Dr. Barrows continued working for TNC and other NGO conservation organizations to implement the first-in-the-nation Habitat Conservation Plan in the Coachella Valley and expanding that plan to encompass the full breadth of biodiversity within that valley (1986-2005). Research focused on the Coachella Valley fringe-toed lizard and flat-tailed horned lizard. He worked with the Research Faculty at the University of California Riverside's (UCR) Center for Conservation Biology (2005-2022). Research focused on the response and resilience of desert species to modern climate change. Emeritus Research Faculty at UCR (2022-Retired). Still doing research and still married to Kate (44 years and counting). Their son Colin is carrying the desert conservation torch into the coming decades.

**Colin Barrows.** Colin is a Coachella Valley naturalist and desert advocate who works to promote conservation of natural open spaces and native species. He works with local agencies to advance habitat conservation, recreational trails planning, and education about desert ecosystems. He also serves on the board of the Mt. San Jacinto Natural History Association. Colin currently serves as co-founder of the Cactus to Cloud Institute.

**Susy Boyd.** Susy Boyd completed her MNR [Master of Natural Resources] degree at Oregon State University with an emphasis in Forests and Climate Change. Her research project developed climate change predictions and impacts on Seasonally Dry Tropical Forests in Mexico's Yucatan region. Prior to her studies with OSU, she received a Master of Arts degree in Rhetoric and Communication at UC Davis where she also served as lecturer. She currently works with Mojave Desert Land Trust as Public Policy Coordinator.

**Pat Flanagan.** Pat Flanagan is a naturalist - educator with a BA degree in biology from CSU Long Beach. She was the director of education at the Tijuana River National Estuarine Research Reserve for 10 years. She developed the first bilingual coastal wetland curriculum for bi-national distribution and training. This curriculum was later adapted to the Colorado Desert for the Desert Protective Council. She was a founding member of the Mojave Desert Land Trust where she held various positions. She is on the board of the Morongo Basin Conservation Association (20 years) for whom she has studied and commented extensively on Utility Scale Solar projects in the Mojave Desert. She is an advisor to the Mojave Desert Resource Conservation District and the naturalist at the historic 29 Palms Inn Oasis of Mara.

**Robin Kobaly.** Robin Kobaly holds both BS and MS degrees in Biology and Plant Ecology from the University of California, Riverside. She served as a botanist for the U.S. Bureau of Land Management for 21 years, working on regional conservation plans, habitat management plans, management plans for Areas of Critical Environmental Concern (ACEC), and environmental impact statements. Kobaly served on the Independent Science Panel providing science-based input to the planning process for the Desert Renewable Energy Conservation Plan (DRECP). She currently serves as Executive Director of The SummerTree Institute, an environmental education non-profit.

**Arch McCulloch.** Arch McCulloch has Bachelor of Science degrees in Computer Science and in Geology from California State University at Dominguez Hills, and a Master of Science degree in Computer Science from Azusa Pacific University. He spent 35 years as a software and information assurance engineer in the defense industry. He is currently on the boards of Morongo Basin Conservation Association (MBCA) and the Mojave Desert Chapter of California Native Plant Society (CNPS).

**Joan Taylor.** Joan Taylor has been conserving the California desert for over five decades, including eight years as an appointed stakeholder to DRECP, where she co-authored the joint environmental NGO comments on the CEC energy-acreage calculator. Joan has received numerous awards and acknowledgements for her life-long leadership in desert conservation. Currently, she serves on the governing board of the Coachella Valley Mountains Conservancy, The Wildlands Conservancy, and Friends of the Desert Mountains. Joan also chairs the Sierra Club's California Conservation Committee and its California/Nevada Desert Committee.

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The California Desert Conservation Area

## Executive Summary

Our state's southeast desert region is unlike any other locale of the state. California's desert ecosystem comprises a staggering 25% of state land (approx.26 million acres) and is locally accessible to approximately half of our state's population. The unique beauty of the desert ecosystem has driven visitation to the region, with Joshua Tree National Park recognized as the 8th most visited national park in the country in 2022.

In spite of its rapidly rising popularity, the California desert as an ecosystem remains poorly understood, underfunded, and misperceived. One of the most persistent mischaracterizations is that the California desert is a barren wasteland with low biodiversity and limited capacity for carbon storage. Scientific data refutes these inaccuracies, and this report will demonstrate that the California desert has extremely high biodiversity and is a significant carbon sink with tremendous opportunity to sequester carbon and help our state meet its atmospheric carbon reduction goals.

**There are 2 key takeaway messages from this report:**

1. **The desert's carbon storage process differs significantly from more widely understood sectors such as forests, grasslands, chaparral, and wetlands.**

2. **Because of the distinct carbon storage process found in the desert ecosystem, there is one recommended strategy to maximize the desert sector's contribution to carbon emission reduction: intact desert lands need to be left undisturbed.**

## REPORT OVERVIEW

## I. Introduction.

California's goal of carbon neutrality seeks to balance the net flux of greenhouse gas emissions (GHG) from all sources and sinks.

> California's non-forest habitats play an unappreciated but critical role [in carbon sequestration] …. As with forests, non-forest habitats can store carbon by keeping it from being released and sequester it by removing it from the atmosphere. Habitats in arid and semi-arid regions — including shrublands, grasslands, and deserts — have been found to store significant amounts of carbon while being resilient to drought and increased atmospheric carbon (Yap et al., 2023).

As reported by Yap et al., globally, scientists estimate that deserts store 999 – 1,899 petagrams [Pg] of carbon. In the United States, southwest deserts sequester 50 teragrams [Tg] of carbon annually (equal to 0.05 Pg). And in California's northern Mojave Desert, field experiments demonstrated that $CO_2$ exchange plays a larger role in global carbon cycling than what scientists and policy makers have long assumed. The desert ecosystem, unlike other sectors, is largely unmanaged with the exception of some restoration projects. Additionally, the desert's recovery from alterations of any kind takes place on a time scale at a much slower rate relative to other ecosystem types, up to thousands of years.

The desert's function as a significant global carbon sink is an emerging and exciting scientific territory that merits a central place in any endeavor to meet climate change goals.

Center for Biological Diversity, Yap, T., Prabhala, A., & Anderson, I. (2023). *Hidden in Plain Sight: California's Native Habitats are Valuable Carbon Sinks* (W. Leung, Ed.).

## II. Maximizing Carbon Sequestration and Biodiversity Protections

***Maximizing carbon sequestration and concurrent protection of high biodiversity in the California desert ecosystem is achieved by conserving 100% of undisturbed public lands.***

Arch McCulloch, MS
Board Member, Morongo Basin Conservation Association / Mojave Desert Chapter of CNPS

It is axiomatic that disturbances in the desert take a long time to heal. Scars in terrain altered by General Patton's World War II training exercises remain visible today, and areas grazed by cattle still, over 60 years later, support vegetation assemblages that indicate a history of grazing and associated fires (Sawyer et al. 2009). Deliberate disturbances, such as the desert intaglios near Blythe, can last for many centuries.

Many desert perennials are long-lived: Joshua trees (*Yucca brevifolia*) can live over 100 years and Mojave yuccas (*Yucca schidigera*) can live over 1,000 years; desert ironwood (*Olneya tesota*) may live a thousand or more (Rymer 2023). Creosote bush (*Larrea tridentata*) clonal rings over 10,000 years old are still living in parts of the Mojave Desert (Porter 2012). Blackbrush (*Coleogyne ramosissima*) may take over 60 years to re-establish on sites where it has been removed (Anderson 2001). Obviously, restoration of disturbed sites is complicated by these time scales.

In desert soils, restoration is even more complicated due to very deep and expansive root systems and to the complex soil biota that has co-evolved with plants on particular sites over millennia. After removal of perennial plants, the re-establishment of this deep soil biota, even more than the extremely slow growth rates of desert perennials, means there is no practical way to restore lands where this relationship has been disrupted.

Photovoltaic solar (PV) is rightly seen as a core energy resource to reduce our carbon footprint. The issue is where to place it to best attain this goal. There is great risk of unintended consequences when Southern California deserts are narrowly assumed to be the primary locale for utility scale solar, as we discuss in the following sections. Photovoltaic efficiency is highest on cool, sunny days, which maximizes the electric potential of the solar cell. Since cloud cover and high ambient temperatures both reduce PV efficiency, cooler areas with higher cloud covers will have PV efficiency comparable to hot areas with lower cloud cover. Locating solar panels as close as practicable to load will reduce resistance losses. The success of PV generation in Germany shows that acceptable efficiency is achievable with these strategies.

Given the ability of undisturbed desert land to bind and hold carbon on a scale of millennia, and the difficulty of restoring disturbed desert lands to anything approaching this capability, we believe that any solar project proposed for the desert should be sited on the vast areas that have already been disturbed by urban, agricultural, and industrial installations (and by the ruins, both physical and biological, of former installations).

In sum, any calculation of equivalent carbon savings by a desert solar installation must, if it is honest, subtract carbon no longer sequestered by the destroyed vegetation, as well as carbon being released to the atmosphere by soil now exposed to weathering. It must also account for replacing an ecosystem service (that, if undisturbed, would continue to operate independently and indefinitely), with an industrial service requiring near-constant maintenance and complete equipment replacement every few decades.

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**Characterizing Disturbed Lands**

Susy Boyd, MNR. Master of Natural Resources, Forests and Climate Change, Oregon State University
Public Policy Coordinator, Mojave Desert Land Trust

Disturbed lands are those areas where infrastructure development has been or may be encouraged. The state of California as a whole has much to offer in terms of disturbed lands suitable for utility infrastructure as we transition to clean energy and meet our state's impressive climate change mitigation goals.

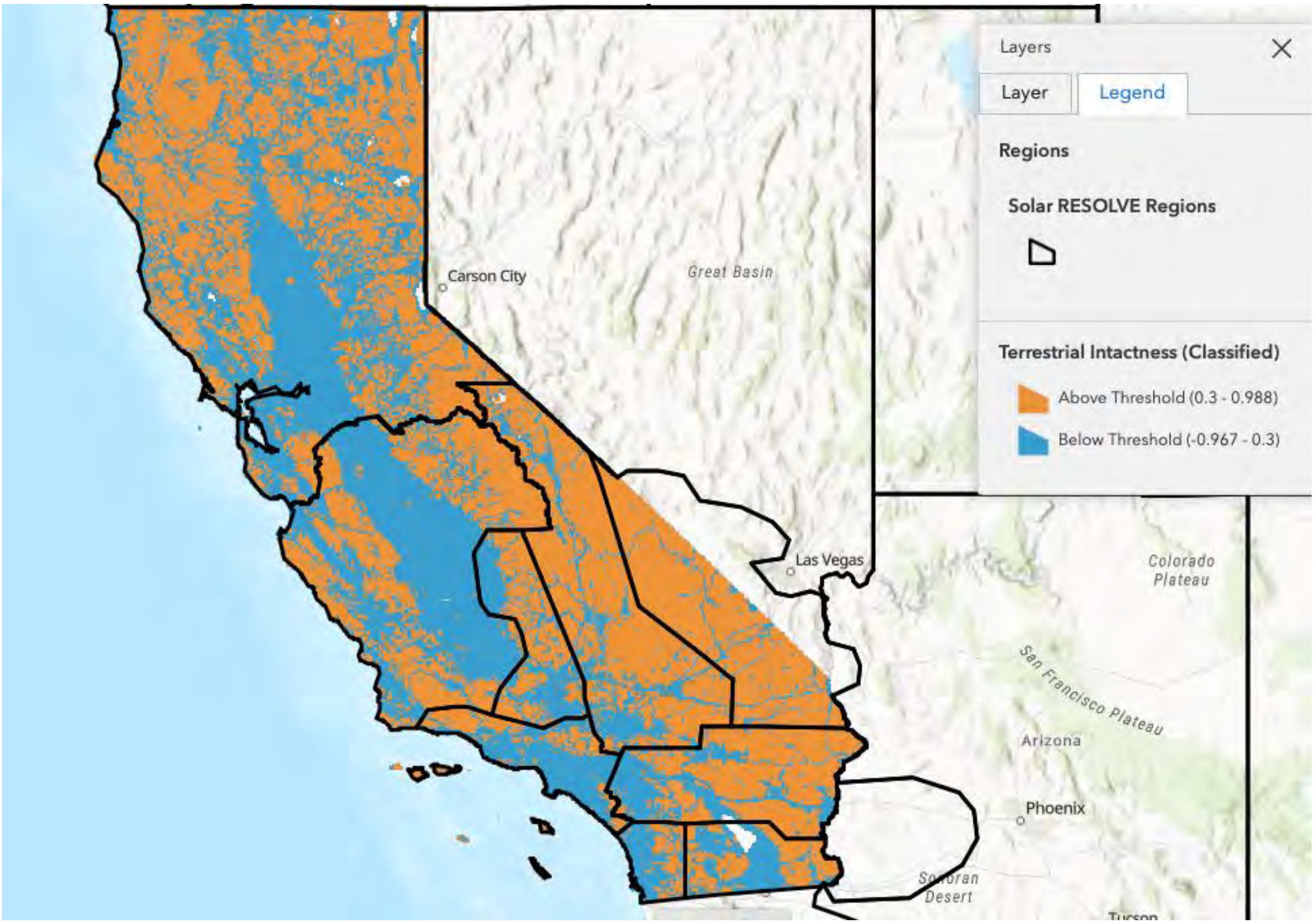
Landscape-scale disturbance falls across a continuum. A pristine desert ecosystem characterizes one end of the spectrum, and worst-case scenario characterized by loss of ecosystem function represents the other end of the spectrum (C. Barrows Ph.D., personal communication, September 14, 2023). A functioning desert ecosystem provides ecosystem services beyond carbon sequestration including habitat for desert organisms. So long as perennial woody vegetation remains intact, the landscape can be considered a functioning ecosystem, even with presence of non-native grasses and mustard that have ephemeral impacts based on water availability. Other examples of undisturbed lands subject to minor impacts include areas with light or well-managed grazing, lands affected by wildfire (with root zone left undisturbed), and lands impacted by flooding with no expected continuing disturbance.

Examples of landscapes that have lost most of their functionality would be abandoned building sites, fallow agricultural lands, and large-scale mining operations; degraded OHV playgrounds; parking lots; and rights-of-way for transmission lines and canals. Residential and commercial developments are also regions where ecosystem function has been reduced to nonfunctional status.

In 2023, the California Energy Commission [CEC] released a staff report entitled, “Land-Use Screens for Electric System Planning.” Land use screens are high level land use evaluation tools that identify favorable sitings for renewable energy after considering technical and economic criteria; legal restrictions; and planning considerations for biodiversity, crop production, climate resilience, and landscape intactness. The 2023 report provides descriptors for landscape intactness:

> Terrestrial landscape intactness: ***A measure of landscape condition based on the extent to which human impacts such as agriculture, urban development, natural resource extraction, and invasive species have disrupted the landscape across California.*** The Conservation Biology Institute (CBI) has created a multicriteria evaluation model using more than 30 data layers, or variables…. The CEC staff partitions this dataset at the mean to create two categories: areas that are already disturbed and have degraded ecosystem function and areas where development would impair the landscape and cause new disturbance. In this analysis, areas of low landscape intactness are most suited for exploration of renewable resource potential, whereas areas of high intactness are better suited for conservation. Therefore, the higher category of landscape intactness values is used to remove technical resource potential from the state.

Lands with degraded ecosystem function are shown in blue (below the mean) in the following map and areas with high intactness value (above the mean) are displayed in orange. Areas with high landscape intactness (orange) indicate areas with low priority for infrastructure development in order to preserve ecosystem function, biodiversity, and carbon sequestration capacity. Intact landscape characterizes much of the California desert region, though large tracts of disturbed land across the state remain highly viable options for renewable energy development. More thorough analysis of disturbed desert lands is needed for planning purposes. Future industrial scale solar projects should be sited on disturbed lands that already exhibit low intactness.




Source: Hossainzadeh, S. et al. 2023.

**Landscape Intactness as calculated by CBI is partitioned into high and low categories based on the mean.**
**Orange = High intactness [Undisturbed]**
**Blue = Low intactness [Disturbed]**

### Reference

Hossainzadeh, Saffia, Erica Brand, Travis David, and Gabriel Blossom. 2023. Land-Use Screens for Electric System Planning: Using Geographic Information Systems to Model Opportunities and Constraints for Renewable Resource Technical Potential in California. California Energy Commission. Publication Number: CEC-700-2022-006-F.

## Why desert restoration is not an effective means to achieve atmospheric carbon reduction goals

Robin Kobaly, M.S. Biology and Plant Ecology, University of California, Riverside
Executive Director, The Summertree Institute

The rate and success of restoration efforts or recovery of disturbed ecosystems is largely dependent upon water availability. When an impacted ecosystem has ample water available for seed germination, root establishment, and growth of new foliage, recovery can be fairly rapid, ushering back the community of insects, reptiles, birds, mammals, and microbes that depend upon plants in the ecosystem. However, if a disturbed ecosystem has limited rainfall and low soil nutrient content, recovery either naturally or through restoration efforts takes much longer and may not always succeed. Recovery from disturbance by temperate ecosystems is much faster than in arid ecosystems, with both infrequent, unpredictable precipitation and low soil nutrients contributing to the slower recovery of arid ecosystems such as those in the California deserts.

Recovery and restoration in forest ecosystems requires about 40 years, but recovery and restoration in desert ecosystems can take centuries longer. Research suggests that removal of desert vegetation and disturbance of the topsoil requires about 30 years before the pre-existing plant community begins to grow back, over two centuries before even partial recovery of species composition occurs, 50 – 300 years for recovery of plants to pre-disturbance cover and biomass, and up to 3,000 years before the disturbed area returns to the ecosystem function it had before disturbance. Disturbance is defined here as a physical force (e.g., road building, plowing for agriculture, construction of industrial-scale solar fields, etc.) that removes most or all the plant biomass.

Research indicates that the older the plant community, the longer the recovery time. Desert ecosystems are known for the longevity of their perennial plant community, with many shrubs living hundreds (blackbrush, Mormon tea, galleta grass, pinyon, etc.) to thousands of years (creosote, Mojave yucca, California juniper, nolina, desert ironwood, etc.). Data show that protecting deserts from disturbance is critical for sustaining old communities, valuable for their generational contributions to ecosystem stability. The desert's ancient plants sustain their community through centuries of drought episodes, excessive heat waves, frosts that kill younger plants, and attacks by diseases and pests that compromise younger plants struggling to become established.

Some scientists have hypothesized that if disturbed, the oldest communities may not actually recover, even with restoration efforts, and they could be replaced by an alternative community. The reasoning is that climate and other conditions (e.g., invasion by exotic species, climate extremes, anthropogenic nitrogen deposition) have changed so much since the communities developed hundreds to thousands of years ago, restoration attempts may not be successful in recreating the original ecosystem, and a different community may become established instead of the original community.

Active revegetation in southwestern deserts has generally been confined to small areas because of its expense, the unpredictable weather that makes restoration effectiveness uncertain, and logistical challenges associated with implementing treatments across large desert areas.

Since disturbances can leave scars in the desert visible for multiple human generations and because restoration is so difficult, costly, and not guaranteed, great care should be exercised before disturbing the desert, not simply for ecosystem health, but also to preserve visual aesthetics, air quality, human health, ecotourism viability, biodiversity, and carbon sequestration capacity. For these reasons, conservation of intact desert lands should be prioritized over restoration of land not already scheduled for disturbance by infrastructure projects.

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## III. The Critical Relationship Between Undisturbed California Desert Lands and Carbon Sequestration

Michael F. Allen, Ph.D.
Distinguished Professor Emeritus, Department of Microbiology and Plant Pathology, University of California, Riverside.

*A microphyll woodland that was later denuded for a utility-scale solar energy facility. While individual trees and shrubs are small aboveground, belowground their roots expand horizontally and vertically, filling the interspaces and reaching to depths of tens of meters. These deep-rooted plants are also very long-lived, sequestering carbon for hundreds to thousands of years. One clonal creosote shrub was measured as 22 by 8 meters across, and was over 11 thousand years old*.

- Carbon fixation and allocation in microphyll woodlands and creosote shrubland is relatively insensitive to local precipitation due to the access that these vegetation types have to two alternate sources of water: moisture from large rain events even miles away that saturate the soil, and access to groundwater by deep roots. These factors allow plants in microphyll woodlands and creosote bajadas to photosynthesize and sequester carbon throughout the seasons even without local precipitation. Although highly variable annually, measurements of net ecosystem exchange [NEE] in mesquite stands through a growing season can exceed 200 kilograms of carbon per hectare per year (kgC/ha/y) and net ecosystem exchange of creosote bajada scrub can exceed 1,000 kgC/ha/y. Our back-of-the-envelope conservative estimates suggest that these two vegetation types could sequester an average of 1.5 million tons of C per year. [By comparison, NEE during a wet year in Baja California was 520 kgC/ha/y with a sky island coniferous forest above southern California desert at 300 kgC/ha/y, a 100-year-old chaparral during a wet year of 520 kgC/ha/y, and drought year of 180 kgC/ha/y, the La Selva tropical rainforest of 1,000 kgC/ha/y (dry year)/3,000 kgC/ha/y (average)/5,000 kgC/ha/y (wet year), and a boreal forest 780 kgC/ha/y]. In deserts, the organic carbon of the ecosystem turns over on an average of 38 years, with soil and sediments turning over on a 200-year average. This contrasts with a temperate forest of 25 and 55 years, respectively; a cropland turnover of 22 and 40 years, respectively; and a perennial grassland turnover of 36 and 100 years, respectively. Desert organic carbon once fixed stays in the system longer than in other ecosystems, releasing back to the atmosphere slowly.

However, unlike the large storage of organic C in most ecosystems, much of the desert total carbon is stored as calcites, generated by respiration.

- Calcites, layered into caliche, form from autotrophic respiration from deep roots and symbiotic microbes, and from heterotrophic respiration of the transferred organic matter. If buried and undisturbed, this carbon can remain sequestered for millennia. We estimate that more than 262 million tons of C could be stored in California deserts as calcites.
- Importantly, buried calcites are dissolved upon exposure to air and water. Upon exposure, the $CO_2$ in calcium carbonates can be released from disturbed soils up to 2.4 gC/m$^2$/day, or 24 kgC/ha/day following a precipitation event.
- We suggest a new C sequestration modeling approach to validate and close the desert carbon budgets using an ecohydrology approach, incorporating deeper water use and using normalized difference vegetative index {NDVI} rather than precipitation as a driver of $CO_2$ fixation, and linking the NEE to deep C sequestration.

***Conclusion***

- Large-scale disturbance of deserts, particularly within critical ecosystems such as creosote bajadas and microphyll woodlands, has the potential to reduce not only California's biodiversity, but also a source of long-term carbon sequestration, releasing calcite carbon stored for millennia.

## IV. Overview of Carbon Sequestration Process in Desert Ecosystems

Robin Kobaly, M.S. Biology and Plant Ecology, University of California, Riverside
Executive Director, The Summertree Institute

### What drives carbon capture and storage in deserts?

The combination of a hot, dry climate, and dynamic plant adaptations to that extreme climate has created a unique pathway for the capture and storage of carbon (carbon sequestration) in deserts. Sparse rainfall has resulted in desert soils that are abundant in minerals such as calcium, but low in nutrients like nitrogen necessary for plant growth. That sparse rainfall, combined with hot, dry surface soils, has enticed many desert plants to grow exceptionally long roots to reach deep soils that still hold moisture from rain events from years past and possibly from miles away, or even deep enough to reach down to groundwater.

Root partners like fungi and bacteria living on or within those deep-rooted desert plants absorb and share resources with their plant host, helping their plant partners overcome the minimal presence of water and nutrients. These pressures, adaptations, and partnerships all work together to create an unexpected mechanism for extremely long-term carbon storage – and carbon capture that can continue even when we least expect it: when rainfall is just a memory across the desert.

**How does the desert capture and store carbon?**

While desert plants do capture and store carbon aboveground in foliage and woody tissue, they store much of their captured carbon deep underground in a massive network of connected roots and fungal root-partners, unlike forests which store most of their carbon aboveground or near the soil surface. Some of this carbon is stored in the tiny but numerous filaments of root-partnering fungi, called mycorrhizal fungi, that live in partnership with plant roots. The filaments, or mycelia, of one large group of these mycorrhizal fungi are coated with a "sealant" called glomalin made from carbon that was captured aboveground by the plant host. Because there can be so many miles of fungal hyphae (covered with glomalin) in each cubic foot of desert soil, glomalin is attributed with storing one-third of the world's soil organic carbon.

Much of the carbon these plants capture aboveground from the air and convert into sugar is eventually turned into inorganic carbon underground.  When the long roots breathe out (respire) carbon dioxide deep into dark moist soil, this carbon dioxide combines with the abundant calcium in our arid soils to create mineralized deposits called calcite (calcium carbonate), or "caliche" when it forms into layers. These deposits start as tiny crystals but eventually grow to large crystals, then chunks, and into layers of caliche that can start at the soil surface or form at various depths underground. These calcite/caliche deposits can store captured carbon in this inorganic form for hundreds, to thousands, to even hundreds of thousands of years…if not disturbed.

**Where does carbon sequestration occur in deserts?**

Historically, much of the desert's "soil organic carbon" has been missed by soil scientists, because many soil studies conclude at "plow-line depth," or between 6 and 12 inches. These studies aren't of much relevance in the desert because most of the carbon that desert plants capture is stored extremely deep in the soil. Roots of most (non-succulent) desert plants grow incredibly deep, up to ten times longer than the plant is tall in their critical quest to find soil moisture, and the subterranean biomass of this network of deep roots is filled with organic carbon. A veritable inverted "forest" of root mass holds carbon deep underground in desert soils. These deep roots and their connected fungal root partners continuously breathe out carbon dioxide from just below the soil surface down to as much as 150 feet (over 40 meters), or down to groundwater. That exhaled carbon, in contact with calcium and moisture, is eventually converted underground into calcium carbonate (calcite) crystals which can form into layers of caliche, capable of storing that carbon for millennia.

**When does carbon sequestration happen in deserts?**

Carbon is captured wherever desert plants grow, but the level and timing of that capture varies with the types and distribution of those plants across the landscape. Desert grasslands and areas with *shallow*-rooted shrubs and cacti capture carbon in response to rain events; in these habitats, carbon accumulation after precipitation can be as high as in wetter ecosystems. Habitats with *deep*-rooted plants, such as microphyll woodlands (dry washes with small-leaved trees like palo verde, mesquite, and ironwood), as well as creosote bajada scrub (broad alluvial slopes with creosote bushes) can continue to photosynthesize and capture carbon long after rain events. Because of their long roots that reach to deep, percolated water from previous rain events (possibly occurring miles away), or even reaching down to groundwater, these stands of desert plants can extend their carbon fixation long into drought cycles. These factors allow plants in microphyll woodlands and creosote bajadas to photosynthesize and sequester carbon throughout the seasons even without local precipitation.

**How much carbon is captured and stored in the desert?**

Scientists are currently working on ways to measure deeply buried carbon across vast landscapes like the California Desert that are highly diverse in topography, soils, climate, and vegetation. Carbon-storing calcite/caliche deposits are distributed in patches in some places and in vast layers in others. Also, these deposits are distributed at varying soil levels depending upon rainfall and the depth of desert plant roots that can deposit carbon all the way down to groundwater. Arriving at a total value for stored underground carbon in a diverse desert is much more challenging than for other more homogeneous landscape types. However, we do have data that measures how much carbon is accumulated by plants in some specific desert habitats, and can compare capture rates to other ecosystems around the planet.

The primary gauge of an ecosystem's carbon sink potential is the net exchange of carbon between the ecosystem and the atmosphere, i.e., the carbon balance of the land, or how much carbon comes in versus how much carbon goes out. This measurement is called "net ecosystem exchange," or NEE. By comparing the carbon balance of diverse ecosystems, we can get an idea of the relative strength of each ecosystem's carbon sink capacity. Dr. Michael Allen has summarized NEE measured within various ecosystems worldwide. He compared them to those measured across two vegetation types thought to sequester significant amounts of carbon in the California desert (microphyll woodlands, which can contain mesquite, and creosote bajada scrub). As shown in the table below, the carbon sink capacity of creosote bajada scrub rivals that of a tropical rainforest or boreal forest. Even microphyll woodlands are in the range of coniferous forests in southern California. **The combined two desert vegetation types, microphyll woodland and creosote bajada scrub (just two of many vegetation types in the California desert), could sequester an average of 1.5 million tons of carbon per year.**

| Net Ecosystem Exchange Rate | kilograms Carbon per hectare per year |
|---|---|
| Sky island coniferous forest in southern California desert | 300 |
| 100-year-old chaparral during a wet year | 520 |
| 100-year-old chaparral during a drought year | 180 |
| La Selva tropical rainforest (wet year) | 5000 |
| La Selva tropical rainforest (dry year) | 1000 |
| Boreal forest | 780 |
| Mesquite stands (microphyll woodland) in California desert | 200+ |
| Creosote bajada scrub in California desert | 1000+ |

**What happens to stored carbon if we disturb desert soils?**

Despite its long-term storage capacity, caliche releases its sequestered carbon when vegetation is removed and soils are disturbed and exposed to erosion. As caliche degrades in disturbed soils, its calcium and carbon molecules are uncoupled, releasing the carbon to reenter the atmosphere as carbon dioxide.

**Why care?**

We risk losing massive accumulations of carbon stored underground as calcite/caliche if the desert soil surface is disturbed. This carbon capture and storage system is functioning now and will continue to capture and store carbon if soils are not disturbed. Most of the caliche in our desert soils was actually formed during the Pleistocene when the climate supported more dense and productive vegetation**. In fact, Dr. Michael Allen at the UCR Center for Conservation Biology commented on the desert's capacity to store large amounts of carbon dioxide as caliche, noting that, "The amount of carbon in caliche, when accounted globally, may be equal to the entire amount of carbon as carbon dioxide in the atmosphere."**

Removal of carbon from our atmosphere is now being considered an important component of fighting climate change. The synthetic conversion of excess atmospheric carbon dioxide to calcite and storing it underground is gaining much attention and funding (although with major technical difficulties). Our deserts are performing this conversion every day, automatically, without any input from humans, and it will continue that unaided sequestration and long-term storage if simply left undisturbed.

## V. Quantification of Carbon Sequestration in the Desert

**Carbon and California Deserts: June 2023.**

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Arid lands worldwide have sequestered carbon (C) for millennia. Human–caused perturbations of deserts alter this balance and risk releasing significant amounts of $CO_2$ to the atmosphere, exacerbating global warming. **Although the net primary production in California Desert Ecosystems is generally low, there remains a net positive carbon sequestration in wildland ecosystems, particularly across desert bajadas and microphyll woodlands.**

**There *remains a view* that, because of low precipitation, high temperatures, and sparse vegetation, hot deserts of southern California are of limited value to carbon sequestration. However, our deserts contain a very large carbon sink.** Laid down over thousands of years, desert C is more dynamic and sensitive to disturbance than is often acknowledged. As Martin and colleagues (Martin et al. 2021) noted:

> "Although equilibrium is often assumed between soil carbon dioxide and groundwater, disequilibrium may result from heterogeneous distributions of recharge, flow paths, and respiration often seen in the carbonate critical zone. Understanding the controls of this disequilibrium, which drives carbon dioxide dissolution or evasion and alters pH, weathering reactions, and carbonate mineral dissolution or precipitation, is critical in linking the carbonate critical zone to the global climate system."

Below, I outline the basis for our concerns with the loss in natural wildland deserts because of its importance in the global atmospheric carbon budget as well as the associated loss of biodiversity (Hernandez et al. 2015).

**$CO_2$ fixation**. Due to the low leaf area, one assumption made by large-scale ecosystem models is that deserts fix carbon at relatively low rates. But when water is available, leaves of desert plants photosynthesize at the same rates as in other ecosystems, and leaves can grow rapidly with soil moisture. Broadly, and especially during drought, rates of flux, net ecosystem exchange (NEE), across scales measured by techniques such as eddy flux, are often low but highly variable. At Deep Canyon during a series of dry years, our NEE was slightly positive. Alternatively, from the desert free air $CO_2$ enrichment (FACE) research project, under ambient $CO_2$ conditions, NEE was estimated up to 1.27 metric tons of carbon per hectare per year (MTC/ha/y) (Jasoni et al. 2005). The standing crop mass was 11 kg of carbon per hectare (kgC/ha), 80% of which was soil organic carbon (SOC) and sensitive to atmospheric $CO_2$ levels, largely deposited as soil C (Evans et al. 2014). For the Sonoran desert ecosystem, NEE was estimated as ranging from 120 kg·of carbon per hectare during a dry season to 360 kg·of carbon per hectare during a wet season (Huxman et al. 2004). [By comparison, NEE for a wet year in a desert in Baja California was up to 520 kgC/ha/y, a sky island above southern California desert at 200 to 300 kgC/ha/y, a 100 year old Chaparral of 520 kgC/ha/y, and drought year of 180 kgC/ha/y, the La Selva tropical rainforest of 1,000 kgC/ha/y (dry year)/3,000 kgC/ha/y (average)/5,000 kgC/ha/y (wet year), and a boreal forest 780 kgC/ha/y].

From these desert NEE measurements, where is the additional carbon in deserts? Likely deep in the profile (see discussion in C sequestration). Desert grasslands and areas with shallow-rooted shrubs and cacti are coupled to precipitation and carbon accumulation depending on local precipitation. However, large pulses in precipitation provide groundwater that extends the length of active photosynthesis of deeply-rooted shrubs (greater than 50m) such as creosote and mesquite (*Prosopis)* (Huxman et al. 2004) and utilization of deep groundwater from storms generated far upstream can extend the carbon fixation of stands into drought cycles in deserts (Scott et al. 2006) and in the uplands such as the montane sky islands (Kitajima et al. 2013). Plants with shallow roots in deeper pools and in groundwater can access many sources of water in which to undertake photosynthesis and carbon accumulation (Querejeta et al. 2007, Querejeta et al. 2009). Reynolds and colleagues (Reynolds et al. 2004) challenged the simple "pulse-reserve" complex showing that in deserts, sequences of pulses are more important than individual events, and Weiss and colleagues (Weiss et al. 2004) found that Normalized Difference Vegetation Index (NDVI), using satellite imagery that visualizes greenness, showed that water from distant sources (groundwater) can extend photosynthetic activity (Bisigato et al. 2013, Rohde et al. 2021).

*What is clear is that simple precipitation models are inadequate for assessing carbon sequestration in arid lands, riparian corridors, or any areas that have underground sources of water. Understanding and modeling Carbon requires a complex approach that integrates ecohydrology and plant morphologies (Gutiérrez-Jurado et al. 2006).*

**Where does the fixed $CO_2$ go?** Groundwater originates at higher elevations in complex terrain, traveling in subsurface flows to lower bajadas, providing moisture to creosote and microphyll woodlands. At these lower elevations, plants have very deep rooting systems from several meters down at least to 53m [174'] in the case of honey mesquite, *Prosopis juliflora*, (Canadell et al. 1996) and down into the caliche layer in the case of creosote, *Larrea tridentata* (Barbour 1969), sometimes growing through cracks and extending below the caliche layers and affecting water fluxes and soil development (Gutiérrez-Jurado et al. 2006). Because they can utilize the deep groundwater, shrub photosynthesis extends beyond the local precipitation season (Ávila-Lovera et al. 2017). Isotopic signature data from my group at Deep Canyon showed that the deep-rooted shrubs acquired between 69% and 87% of their water for photosynthesis from groundwater (M. Allen unpublished data). Others (Ogle et al. 2004) have shown that the water through the stem could well be used to model water uptake profiles, and thereby provide estimates of stored soil water use, and thereby assess the SOC buried deep in the profile.

*This deeper C is the reason for some of the slow turnover of SOC and for the formation of calcites (discussed below).*

**C sequestration**. In terrestrial ecosystems, there are three forms of sequestered C to be considered. The first is easier to estimate and model, and that is aboveground herbaceous and woody tissue, with some estimates providing belowground tissue C as well. At the global scale, current aboveground biomass is 349 Pg, belowground 92 Pg, totaling 441 Pg C (Walker et al. 2022). The second is the soil organic carbon (SOC), globally equaling 3,037 Pg C, or more than 8 times the estimated aboveground carbon, and nearly 7 times the total standing crop biomass.

If we use a NEE figure of 200 kgC/h/y (see $CO_2$ fixation section) for creosote and for microphyll woodlands, we can begin to estimate at least the C accumulation for desert ecosystems. There are 2.47 acres per ha. Using the CA 4th Climate Change Assessment for the Inland Desert Area, there are 489,423 acres of microphyll woodland and 17,466,886 of creosote. Using this estimate, that would amount to an average of 1.5 million tons of carbon accumulated by these two vegetation types annually. Using the EPA Level III Ecoregions map, that would amount to 1.88 million tons of carbon. These estimates are in the range for coniferous forests or oak woodlands in southern California.

There are large gaps, such as between the NEE of Jasoni and Huxman. If 80% of the carbon (C) is allocated belowground to a meter in depth (Evans et al. 2014), and a large fraction is transported deep, then the overall carbon accumulation will be underestimated. In isotopic studies, soil calcite values show evidence of C recycling in soil (Schlesinger 1985, Allen et al. 2013) above the caliche layers, suggesting extensive C recycling. C is transferred downward via roots deep into the profile (sometimes more than 50m). Respiration of roots and symbiotic microbes (autotrophic respiration) and decomposers (heterotrophic respiration) produces $CO_2$. Add water (ground water or surface precipitation) and calcium (Ca)-derived upslope from basalts, limestone, marble or dolomite -- and some of that $CO_2$ is bound into calcites, the most stable of which is $CaCO_3$. Because the process is a dynamic equilibrium, add water again, and exposed calcite can be re-solubilized. Some of the $CO_2$ is volatilized back to the atmosphere and the Ca moves downward with the water. That Ca rebinds with newly respired $CO_2$ in the deeper layer, again forming calcite. The deeper the process occurs, the higher the $CO_2$ concentration. The process continually repeats itself to the maximum depth that water travels (forming a caliche layer), or to groundwater. Surface measurements, such as from eddy covariance techniques, are highly variable as the environmental conditions are fickle even within the footprint of the sensors, and for sensitivity to assumptions regarding fetch and topography. Most comprehensive soil carbon measurements (from soil cores) to date are constrained to the top meter of the soil.

Further, to understand sequestration, we must also incorporate carbon turnover. For example, despite enormous production, tropical rainforests have fast rates of decomposition resulting in a rapid turnover, thereby returning the fixed carbon back to the atmosphere. In wet tropics, the average turnover for vegetation is 15 years, and soil organic carbon (SOC) 27 years. Temperate forests vegetation turns over on average every 25 years, and the SOC in 55 years (Reichle 2020). Desert vegetation turns over every 38 years, but the SOC turns over on a 200-year span. Moreover, carbonates, when buried, can remain for millennia, but upon exposure, will volatilize releasing $CO_2$ to the atmosphere.

The soil carbon component is complex, but there are indicators that deserts may sequester SOC in many complex forms. As an initial example, in the Mojave Desert under Creosote (*Larrea tridentata)* canopy, the arbuscular mycorrhizal fungal standing crop was 423 kgC/ha (and 635 kgC/ha under elevated $CO_2$). It is very challenging to determine the hyphal lifespan, critical to estimating C sequestration, as literature values range from 5 days (Staddon et al. 2003) to 145 days (Treseder et al. 2010). Currently other efforts to estimate turnover are being undertaken by Allen from image data already collected. Much of the variation is probably due to responsiveness of fungal hyphae to individual precipitation events at daily to seasonal scales (Hernandez and Allen 2013). An example is glomalin, a glycoprotein complex produced largely by arbuscular mycorrhizal fungi, that has a long retention span (Rillig et al. 1999, Allen 2022). Glomalin is known to accumulate due to a slow turnover, (measured using immunoreactive soil protein

(IRSP), and can be as much as 40 µg/g soil (Clark et al. 2009). Using a 2m rooting depth, this means that there may be 2 metric tons of glomalin protein per ha across the extensive creosote shrubland soils, representing a significant pool of SOC.

**Calcites/Caliche Carbon**. Carbonates may be relatively unimportant to the global C cycle over a time scale of millions of years, as precipitation and dissolution is continuous. However, at time scales of decades to centuries, the inorganic carbon ($C_i$), is often in disequilibrium and can dramatically impact the carbon cycle (Martin 2017). At a global scale, as much as 940 Pg $C_i$ is sequestered as soil calcium carbonate (or calcite) with as much as 1404 Pg C as bicarbonate in groundwater, more than all the soil organic C (1530 Pg C), and well more than the 594 Pg C of standing plant biomass (Monger et al. 2015). Chuckwalla, Gunsight and Cherioni soils contain extensive layering of calcites, and even Carsitas soils have carbonate coatings on the surface of rocks. In the Chuckwalla Valley, for example, estimates ranged from 36 metric tons of carbon/hectare to 82 metric tons of carbon/hectare. Using the smaller figure, and assuming that calcites underlie much of the creosote and microphyll woodlands (14.6 tons of carbon/acre), then a conservative estimate is that there could be as much as 262 million tons of carbon stored deep in desert soils.

Moreover, produced at approximately 4 kgC/ha/y, the buried calcite-C becomes relatively stable. Schlesinger (1985) estimated that the $CaCO_3$ in the Chuckwalla Valley was formed during the Pleistocene, between 15,000 and 20,000 years ago, and an 85,000-year residence time appears to be relatively accurate. However, upon disturbance, loss rate appears to be significant over annual to decadal time scales, as much as 10 kgC/ha/wet day (Swanson 2017).

The conversion of $CO_2$ to calcite is considered important enough that considerable effort is being undertaken to synthetically convert atmospheric $CO_2$ to calcite (Pogge von Strandmann et al. 2019), the process that desert plants undertake every day.

*The **Mechanism** in deserts*. Both roots and microorganisms respire $CO_2$: then $CO_2$ and $H_2O$ (water) combine to form $HCO_3^-$ and an $H^+$ ion, acidifying the soil. Upon encountering $Ca^{2+}$ dissolved in soil water, $HCO_3^-$ binds to the Ca to form $CaCO_3$, a large fraction of which precipitates to form calcite (limestone, $CaCO_3$), or upon layering, caliche.

*Accessing groundwater acquired by deep roots of specialized desert plants.* Roots can go down tens of meters to acquire water (Canadell et al. 1996, Jackson et al. 1999). At the interface of the water table, microbial activity may dramatically increase. Just above the water table, arbuscular mycorrhizae search for phosphorus and other nutrients, in part to sustain dinitrogen fixation (with high respiration rates) occurring in the groundwater (anaerobic) by associated bacteria that provides the nitrogen for these ecosystems (Virginia et al. 1986). Mycorrhizae increase respiration of $CO_2$ (Knight et al. 1989) as well as sequestering organic C (Rillig et al. 1999).

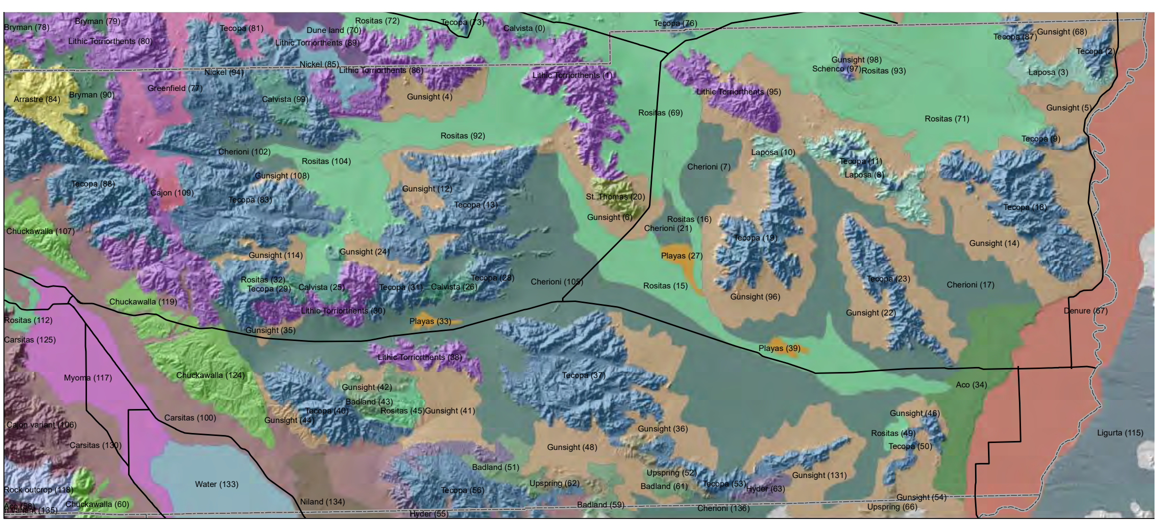
Groundwater in western deserts is notorious for being hard, that is, having high concentrations of $CaCO_3$. As it is pumped up for use, $CaCO_3$ dissociates, releasing $CO_2$ (Wood and Hyndman 2017). They estimated that groundwater depletion could account for a measurable fraction of annual $CO_2$ emission. As caliche is exposed to the atmosphere, caliche degrades releasing $CO_2$ (Hirmas and Allen 2007). One assumption is that because $Ca^{2+}$ remains in the soil, re-association with $HCO_3^-$ will occur (Mills et al. 2020). This certainly will be the case in a closed system (such as a laboratory beaker). But in an open ecosystem, equilibrium remains an open question and is in need of further examination (Leij et al. 1999, Martin 2017, Gallagher and Breecker 2020, Martin et al. 2021). On the surface, $CaCO_3$ equilibrates with $CO_2$ at ~400 ppm, the current atmospheric $CO_2$ level (Hirmas et al. 2010), but soil $CO_2$ where most exchange occurs can range up to 3,000 ppm (Allen et al. 2013), likely accounting for deposition of caliche beds (Schlesinger 1985). Rhizosphere $CO_2$ levels (in the soil rooting zone) can exceed 3,000 ppm in undisturbed soil, but drop in devegetated lands, only increasing $CO_2$ loss from $CaCO_3$ dissolution (Allen et al. 2013). Deep in groundwater, $CO_2$ bound as $CaCO_3$ can exceed 190 mg/L (DeSimone et al. 2009), degassing as it is pumped out (Wood and Hyndman 2017). Surface isotopic values of caliche show that there is a fractionation in the caliche C, indicating that exchange (losses or gains in caliche C) is occurring (Allen et al. 2013, Mills et al. 2020). The conversion of land to agriculture and tree production is resulting in a shallowing of rooting depths nationwide along with a loss of deep root functioning (Billings et al. 2018).

**Summary: Concerns**.

Adding the dynamics of calcites to the slow SOC turnover demonstrates why the overall C cycling becomes extremely challenging to quantify, especially across long time scales and an area as diverse and large as the California desert. Loss of NEE from California deserts would amount to a significant loss of carbon in addition to loss in California's biodiversity.

**But our largest concern is the risk of losing massive accumulations of carbon, stored underground as calcite-C. This C capture and storage system is functioning now and will continue to capture and store C for long time periods if soils are not disturbed.** In the Chuckwalla Valley of the California deserts, C as $CaCO_3$ was 8 kgC/m$^2$, within the top 1.35 m of soil (Schlesinger 1985) in one profile and 3.5 kgC/m$^2$ in a second. $CaCO_3$ can be found across the valley. Assuming an average of 6 kgC/m$^2$, there could be 60 metric tons of C per ha of microphyll woodland/creosote bush in the surface soils. A large fraction of the Chuckwalla Valley creosote bush and microphyll woodland has already been stripped of vegetation for a single solar development.

It is always challenging to extrapolate beyond the actual locations of measurements. However, existing datasets support this concern. Schlesinger (1985) raised the issue that disturbance of desert caliche C was of concern to C budgets. When we examine soils maps, the bajadas and microphyll woodlands have high concentrations of soil $CaCO_3$, across Chuckwalla, Gunsight and Cherioni soils. These soils are alluvial soils, often with a calcic horizon ranging from 25 cm to more than a meter deep, and often with creosote scrub vegetation fingering into microphyll woodlands. These soils extend from almost every mountain range in the California deserts. So, this is our best estimate.




US Soil Map for East Riverside County

0 10 20 30 40 50 Miles

0 10 20 30 40 50 60 70 80 Kilometers

| compname | id# | caco3_l | caco3_r | caco3_h |
|---|---|---|---|---|
| Rositas | 15 | - | - | - |
| Cherioni | 17 | 0 | 3 | 5 |
| Gunsight | 36 | 4 | 6 | 8 |
| Gunsight | 96 | 4 | 6 | 8 |
| Cherioni | 105 | 0 | 3 | 5 |

Quantity of Carbonate (CO3) in the soil expressed as CaCO3.
Weight percentage of the less than 2 mm size fraction

Other maps, such as the SSURGO Soil data for Coachella Valley show high calcite concentrations in the bajadas and in the desert washes north of the Salton Sea, but south of the Salton Sea, where agriculture predominates, that calcite is largely gone, except for some upper edges.

Our final concern is that with increasing disturbance of desert soils by utility-scale solar energy [USSE] there will be a loss of the high biodiversity of California's deserts. We are especially concerned with a direct loss in microphyll woodlands and desert bajadas, and in a potential for the decrease in the linkages between these vegetation types and the uplands where Ca and water inputs occur. Both biodiversity and regulation of carbon cycling will be impacted, to date with unpredictable consequences. The more we learn and apply understanding of the soil carbonate dynamics (Martin et al. 2021) to managing for biodiversity and carbon cycling, the better we will be able to manage desert lands to reduce greenhouse gas production and sustain our biodiversity (Allen and Mishler 2022).

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## VI. Modeling Carbon Sequestration in Our Deserts

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Many modeling efforts purporting to describe C sequestration in deserts are problematic. They underestimate C accumulation, as they use precipitation drivers at the location of production. However, desert plants use water over longer terms from single large events, and uplift groundwater precipitated in mountains well away from the locations of primary production. We agree with others who have critiqued the California Air Resources Board [CARB] modeling as dramatically underestimating the C sequestration potential by ignoring large parts of the C cycle (CarbonCycleInstitute 2022). Currently, destruction of large wildland deserts for agriculture, mining, or for Utility-Scale Solar Energy (USSE) development is on-going or proposed for California deserts.

We know that traditional precipitation-based modeling for C sequestration is inadequate. However, is there a more useful approach? We argue that there is a more promising direction based on existing modeling approaches.

First, Normalized Difference Vegetation Index (NDVI) should be used to identify the land areas with photosynthetic activity and the duration of that activity (Rohde et al. 2021), not local precipitation. From the greenness activity, it should be feasible to estimate C fixation, replacing the precipitation driver for wet periods in models such as DAYCENT (Parton et al. 1998).

Second, an ECOHYDROLOGY model (Gutiérrez-Jurado et al. 2006) allows for estimating water transport and coupling soil properties (including calcite horizons) building on HYDRUS (Šimůnek et al. 2005). HYDRUS can also be used with the equations described by Kitajima and colleagues (Kitajima et al. 2013) to quantify the additional timeframes for C gain using intermediate depth- and ground-water sources.

Third, the SLIC model (Hirmas et al. 2010) evaluates the transitions between $Ca + CO_2 + H_2O \leftrightarrow CaCO_3$.

Fourth, once the water sources and time frames are identified, NEE measurements coupled with soil respiration measurements could provide spot-checks on modeled values.

This modeling approach can provide a comprehensive overview to help close the carbon cycle in the deserts. It is important that the confirmation measurements are based on a long-term dataset, and that, given $CO_2$ and global temperature changes, two or more longer-term C cycling instrument facilities be deployed. The model as developed by the National Ecological Observatory Network (NEON), could serve as a model, and could be installed at field stations such as the NRS stations at the Granite Mountains and Boyd Deep Canyon, or the CSU Zzyzx station.

**References: Please see previous section V.**

## VII. Mapping and Identifying Prioritized Areas of our Desert to Achieve Carbon Reduction Goals

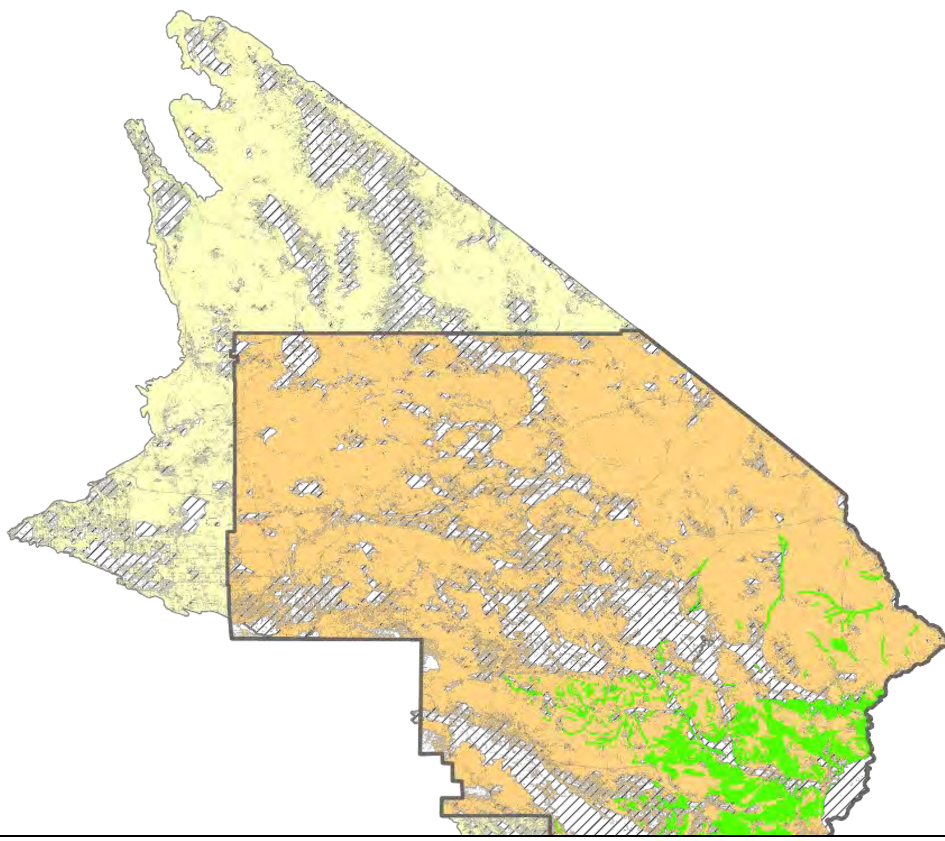
### *Microphyll woodlands/Creosote*

Colin Barrows. Co-founder, Cactus to Cloud Institute

In sections IV, V and VI above, Kobaly and Allen indicated the importance of two specific desert vegetation types in the desert region’s impressive capacity to store carbon. Kobaly notes the combined carbon sequestration capacity of **microphyll woodland** and **creosote bajada scrub** could sequester an average of 1.5 million tons of carbon per year. Allen reports that these two vegetation types create a net positive carbon sequestration value within California's desert ecosystem.

Section VI discussion around the relationship between groundwater and underground caliche formation (carbon sequestration) plays out across these two vegetation types. With the groundwater originating at higher elevations, it traverses in subsurface flows to lower elevations such as those where the creosote bajadas and microphyll woodlands are found. The vegetation types here have rooting systems that can run over 53m [174'] deep. Root systems of creosote can grow into the caliche layer and beyond to reach groundwater sources.

The dynamics of these two vegetation types are of particular interest in demonstrating high capacity for carbon sequestration, though they are not the only vegetation types nor the only means by which carbon may be sequestered within the desert ecosystem. But microphyll woodlands and creosote are of high interest in discussion of carbon sequestration in the desert, and this section identifies and quantifies which desert regions warrant high prioritization for conservation.



EPAIII CA Deserts boundary (DRECP) [Exterior Boundary]

CA Climate Assessment inland desert boundary (30x30) [Interior Boundary]

Shrub/Scrub land cover for both areas in **orange (30x30)** and **yellow (DRECP)**

Microphyll woodland in **green.**

Small areas of lighter green outside the 30x30 area.

**SUMMARY**

| Boundary Area | Desert Vegetation Type | Acres |
|---|---|---|
| CA 4th Climate Change Assessment Inland Desert Area [30X30] Boundary | Shrub Scrub Land Cover | **13,300,107** |
| EPA Level III Ecoregions, Mojave and Colorado CA Desert Area | Shrub Scrub Land Cover | **18,715,754** |

**Recommended acreage of conserved desert land for vegetation cover types microphyll woodlands and creosote bajadas.**

It should be noted that these identified lands represent those areas recognized to be highest conservation priority for carbon sequestration function. These acreages represent only a partial opportunity to maximize carbon sequestration and protect biodiversity.

## VIII. Additional benefits

### *Biodiversity in California's deserts*

Cameron Barrows, PhD. Conservation Ecologist, Emeritus. Center for Conservation Biology, University of California, Riverside

Pat Flanagan, B.A. Biology. California State University, Long Beach
Board Member, Morongo Basin Conservation Association

California is by far the most biologically diverse of the United States' contiguous 48 states, with deserts comprising roughly one third of California's land surface. And yet California's deserts, as well as deserts worldwide, tend to be overlooked in discussions of biodiversity. The dictionary definition of "desert" reflects the prevailing bias: "a large area of land that has very little water and very few plants growing on it". Other descriptors include "wasteland," "barren," and "lifeless." *Desert* is often used as a euphemism for a place where little or no life, food, or culture exists. Other than being arid, none of these perceptions is accurate.

One can test the hypothesis that California deserts are biologically depauperate. Covering one third of California, if species were randomly distributed, then we would expect about 33% of California's plant and animal species to live in deserts. Values significantly less than 33% would support a belief that our deserts are, compared to elsewhere in California, lacking living things. On the other hand, if values are greater than 33%, then the assumption of our deserts being a barren wasteland would be categorically false.

While exact numbers will vary with shifting taxonomic classifications,

> **California is the home of almost 2300 native annual herbaceous plants, over 3600 native perennial herbaceous (not woody) plants, over 1300 species of native shrubs, and just under 240 native tree species** (using Calflora's Consortium of Herbaria database).

Combining California's three main deserts—the Great Basin, the Mojave, and the Colorado— along with the "sky island" mountains that are within or border those deserts, it was found:

**55% of those native California annual herbaceous plants, 53% of perennial herbaceous plants, 60% species of shrubs, and 53% of those native tree species live in the California deserts**.

Of the three deserts,

**The Mojave has the highest plant species richness, with 49% of those native annual herbaceous plants, 44% of perennial herbaceous plants, 52% of shrub species, and 45% of those native California tree species.**

Since this species richness is well above 33% in each of those plant categories, we can reject the hypothesis that California deserts have low biodiversity.

**In the categories of annual herbaceous plants and shrubs, California deserts have more species than any other ecological region in California.**

Our desert "wastelands" are not only richer from a vegetation standpoint, but they also appear to be incubators of speciation, with many species occurring nowhere else on earth. A recently published study, Pillay et al. (2022, *Frontiers in Ecology and the Environment*, vol. 20, issue 1) looked at patterns of vertebrate animal species richness across our planet. As expected,

**They found that the tropics ranked number one. However, deserts were the next most species-rich biome when it came to mammals, birds, and reptiles, higher than temperate forests, shrublands, and grasslands.**

In California, reptile species richness is especially high in our deserts.

**California has 40 species of native lizards that call our state home. Ninety percent of those can be found in our deserts, again**, well above the expected 33% of lizards that were randomly distributed across California. **At least six of those lizards are found nowhere else.**

Some areas are especially species rich. Along with colleagues from the U.S. and Mexico, we looked at lizard species richness across North America and found nowhere else that compared to deserts in the number of species that occur together.

**The top spot was the Coachella Valley at the edge of the Colorado and Mojave Deserts which has 33 lizard species within a 50 km [31.07 miles] radius circle. Of the 34 species of snakes found in California, 76% are found within desert habitats.**

We do not have similar data sets for insects. However:

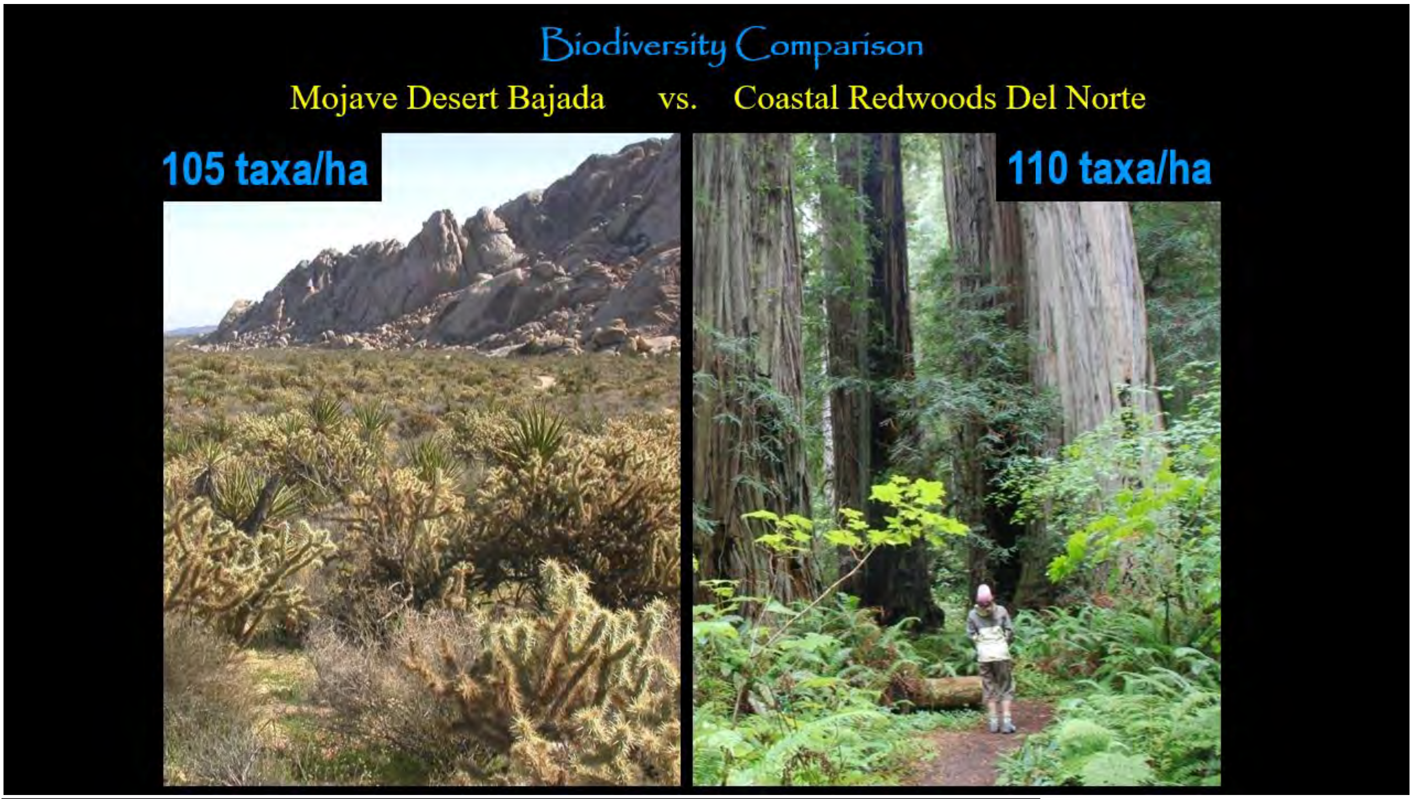
**Native bee pollinators in the Joshua Tree National Park area are estimated to include more than 600 species representing 40 genera in 6 families.**

And some insect families, such as darkling beetles (Tenebrionidae), specialize in living in arid habitats. Darkling beetles are the clean-up crews in deserts. Technically detritivores, they eat dead matter, replacing the job fungi and bacteria do in moist environments. Several years ago**,**

**[Dr. C. Barrows] conducted a survey of darkling beetles living on the remaining sand dunes of the Coachella Valley. Across those dune fragments [Dr. C. Barrows] found 34 different darkling beetle species. Try to put that into perspective: Imagine finding a lake with 34 resident species of ducks, or a forest with 34 species of warblers, or a mountain range with 34 species of deer.**

Beyond biodiversity, people also put value on superlatives such as the antiquity of individual plants or animals. In the Pacific Northwest, redwood trees can reach the advanced age of 3200 years. In the central Sierra Nevada range, giant sequoias can reach 2700 years of age, and in the White Mountains, bristlecone pines can be up to 4800 years old. That's impressive. But even more impressive is the oldest creosote bush, the most widely distributed desert shrub:

> **The King Clone creosote is 11,700 years old, an extreme superlative. There are also desert tortoises who can approach nearly 100 years of age.**




Courtesy of James M. Andre. Sweeney Granite Mountains Desert Research Center. gmdrc@ucr.edu

### *Economic benefits*

Susy Boyd, MNR, Master of Natural Resources, Oregon State University
Public Policy Coordinator, Mojave Desert Land Trust

Land that is set aside for conservation holds potentially high economic value as a driver of tourism and recreation. The good news is that recreational use of public lands allows the land to remain largely undisturbed *and* continue to sequester carbon, thus fulfilling a dual mission while generating local business and tax revenue.

A 2014 report [ECONorthwest] noted economic contributions of Quiet Recreation Visits within 50 miles of recreation sites on BLM-managed lands within California. Total Direct Spending was $243,938,853. In inflation-adjusted dollars for 2023, that amount today would be $314,392,148.

Visit California's Economic Impact of Travel report for 2021 indicated Local Tax Revenue of $293,000 for the state's Desert Region, supporting community benefits such as safety, fire, recreation, and library services.

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***Biocrusts in the desert***

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Executive Director, The Summertree Institute

**Overview:**

~ Microscopic organisms living at and near the surface of arid soils produce glue-like substances that hold undisturbed desert soils together and prevent soil erosion

~ These living soils, called biocrusts, create and store valuable fertilizing nutrients for the surrounding plant community

~ Biocrusts, when kept intact, hold otherwise dangerous PM10 and PM2.5 particles and spores, such as Valley Fever, in the soil and out of the air, protecting people from breathing in these health-impacting pollutants

A thin surface crust forms across arid soils on or within the top few centimeters of the soil surface. Surprisingly, these crusts are not made up simply of encrusted, excess soil minerals as often thought, but are created by microscopic and somewhat larger macroscopic organisms that live together in an unseen but profound world.

The microbes that make up this living "biocrust" live only near the top few centimeters of the soil because they need sunlight to make their own food. As some of these organisms travel through the soil, their network of mucilaginous, hollow tunnels between soil grains records a history of their movements and leaves a legacy of soil cohesion.

These and other tiny microbes living between desert soil grains create and store scarce, valuable, fertilizing nutrients like phosphorus and nitrogen at and below the surface, and they share these building blocks for life with all the plants in the surrounding community. If not disturbed by vehicle wheels or bulldozer blades, this soil cement and the community that produced it can persist for many thousands of years—or more.

Biological soil crusts keep soils intact and prevent dust storms…unless soils are disturbed. The dried, glue-like threads of microbes in biocrusts form a resistant seal across the soil surface, keeping dust, particulate matter, and harmful fungal spores like valley fever from being blown up into the air wherever the soil has not been disturbed.

These living soil crusts take hundreds of years to develop into effective soil "sealants." When they are allowed to remain intact, they will hold back wind and water erosion, supply nutrients to neighboring plants, improve water infiltration, prevent particulate matter from entering the air, and help keep our air clean and healthy. When living soil crusts are disturbed, choking dust storms occur. Dust storms blow harmful particulate matter into the air – and we breathe it in. The smaller particulate matter (smaller than 10 microns, or PM 10 particles) when inhaled into our lungs cause health impacts ranging from coughing and wheezing to asthma attacks and bronchitis, as well as high blood pressure, heart attacks, strokes, and premature death in people with heart and lung disease.

Keeping desert biocrusts intact protects the health of people living near the soil disturbance as well as people living many hundreds of miles from the point of disturbance.

### ***Health benefits***

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Maximizing the desert region's carbon sequestration potential by conserving undisturbed non-military land provides the additional benefit of bolstering public health. Dust, particularly [Particulate Matter] $PM_{10}$, is an important outcome of disturbance in desert wildlands (Pointing and Belnap, 2014; Frie et al., 2019). Desert dust erosion resulting from disturbance of desert soils is a source of significant health issues (Lwin et al., 2023) ranging from respiratory particles to local sources of heavy metals including Aluminum, Arsenic, Selenium, Cadmium, Lead, Uranium and Thorium (Frie et al., 2019). Numerous studies have noted evidence of associations between desert and sandstorm dust, and morbidity/mortality rates. Particle size is believed to be one of the key factors implicated in health risk. Large-sized particles can cause damage to external organs causing skin, eye, and ear irritation. But small size particles are capable of entering the respiratory tract and causing disorders within that system. The smaller size particles may penetrate the respiratory tract and damage cardiovascular, cerebral, cerebrovascular, blood and immune systems.

The high incidence of childhood asthma surrounding the Salton Sea (at a rate over 20%) is among the highest in California. In on-going studies, mice models found that the dust collected from these disturbed desert areas triggered a significant neutrophil inflammatory response that is distinct from the known immune allergic response, causing "asthma-like symptoms" (Biddle et al., 2023). This tells us that there are unknown new diseases emerging from the increasing disturbances in California's desert.

Desert dust may also cause infectious disease by carrying pathogens. An example is Valley Fever, caused by spores of fungi of species of *Coccidiodes*, which is present in desert soils and triggered upon inhaling dust when surface soils are disturbed (https://www.cdc.gov/fungal/diseases/coccidioidomycosis/index.html). Valley fever is endemic in California desert soils and increasing dust with disturbance and global warming is of concern (Cat et al., 2019; Gorris et al., 2019). In new studies from California deserts, local dust emissions are increasing and releasing novel microbial pathogens (Freund et al., 2022) that we are only now beginning to identify.

At the global scale, it is estimated that 1.7% of lung-cancer and cardio-pulmonary disease deaths can be attributed to chronic exposure to desert dust. In latitudes with extensive deserts such as Africa, the middle East and Asia, the percentage jumps to 15 – 50%. Short-term exposure to dust was documented to be the source of respiratory illness among 70% of Afghan and gulf war veterans deployed between 2003-2004.

Clearly, scientific research demonstrates a concerning link between desert dust and severe public health risk. Disturbance to desert soil is a contributor to desert dust, presenting an additional benefit for leaving desert lands undisturbed.

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## IX. Transition to Clean Energy: Meeting our Clean Energy Goals and Minimizing Disturbance to our Desert Ecosystem

### *Introduction*

There is a growing understanding that a tension exists between the need to conserve desert land, which itself functions as a significant nature-based solution to store carbon emissions – and expansive renewable energy projects that disturb desert lands and in doing so, release carbon back into the atmosphere.

This is a solvable problem that requires coordination between renewable energy developers, conservationists, policy makers, and the handful of experts who have carefully analyzed and evaluated desert lands and crafted detailed maps that consider solar industry needs, cost, and conservation all at once. This is the key work that needs to be done if desert lands are to continue their critical function as grand carbon sinks. Experts agree that the means to successfully navigate the nexus of industrial solar and conservation of carbon-storing natural desert lands lies with thoughtful, advanced planning, and integration of a suite of renewable energy options. If desert lands are perceived as a sacrificial ecosystem in the name of renewable energy, we run the risk of undermining the long-term carbon storage function they have performed for thousands of years and backpedaling on meeting carbon sequestration targets. And unlike other ecosystems, once disturbed, recovery in the desert is so long-term it should be considered as a non-option.

### *Utility Scale Solar and Avoidance of Desert Disturbance*

Joan Taylor. Chairperson, California Conservation Committee and California/Nevada Desert Committee of Sierra Club.

CA Senate Bill 100 established a landmark policy requiring renewable energy and zero-carbon resources to supply 100 percent of electric retail sales to end-use customers by 2045. To meet this goal, the California Energy Commission, California Public Utilities Commission, California Air Resources Board SB 100 Joint Agency Report estimated a need for an additional 70,000 megawatts (MW) of utility-scale solar to come online by 2045 in its Core Scenario (CEC 2021). Notably, the Core Scenario assumed high electrification demand but did not factor in any advances in renewable technology or in tools to manage peak load, so this estimate can properly be considered conservative.

Based on the most recently approved large utility-scale solar project in California, 5.02 acres are required to develop one megawatt of ground-mount single-axis tracking utility-scale solar with four hours of battery storage, including generation ties and other infrastructure (California Water Boards 2021). This equates to approximately 350,000 acres of land or other surface on which to mount PV panels. Even were one to use the now-outdated number of 7.1 acres per megawatt that was assumed nearly a decade ago by CEC (CEC 2014), the total acreage requirement for utility-scale solar would be less than 500,000 acres. For context, there are over 105 *million* acres in California.

There are numerous feasible options for developing utility-scale solar in California that can deliver the estimated need for new utility-scale solar and provide increased local jobs and other benefits, without disturbing intact desert. Some of these include:

- Water-deprived agricultural lands in the Central Valley estimated to be a minimum of 500,000 acres (Hanak et al, 2019) or as much as 900,000 acres (Escriva-Bou et al, 2023)
- 250,000+ acres of selenium- contaminated land in the Westlands Water District
- 200,000+ acres of parking lots in California (USGS 2019)
- 11,500 MW of capacity on large commercial/industrial rooftops near substations (RETI 2009)
- 4,000 miles of canals and 16,000 miles of highway right of ways
- Agrivoltaics (ie, slightly elevated or spaced photovoltaic panels) on a portion of the 40+ million acres of farm and ranch lands throughout the state (CDFA)

**Examples of appropriate utility-scale solar sites and potential additional renewable capacity**

| Preferred Sites | Acres | Total potential generation |
|---|---|---|
| **Water-deprived Ag Lands Central Valley** | **500,000 – 900,000** | **100,000 MW – 250,000 MW** |
| **Selenium contaminated land, Westlands Water District** | **250,000** | **50,000 MW** |
| **Parking Lots in CA** | **200,000** | **40,000 MW** |
| **Large commercial/industrial rooftops near substations** | **n/a** | **11,500 MW, min (this 2009 estimate is outdated)** |
| **20,000 miles highway & canal right of ways (est 100’ wide)** | **240,000+** | **47,000 MW, min** |
| **TOTAL** | **1,190,000 – 1,590,000** | **248,000 – 398,00 MW** |
| | | |
| **Agrivoltaics on 40+ million acres farm & ranch lands** | **40,000,000+** | **Millions of MW** |

While utility-scale solar that is sited remote from load is dependent on high voltage transmission, utility-scale solar that is generated “In Front of the Meter” on large rooftops and parking lots at load centers is not dependent on the larger grid. Urban and peri-urban solar eliminates the capital costs, delay, average 7%-line energy losses, steep monthly ratepayer charges for new transmission capacity and inherent lack of reliability of electric power that relies on long-distance transmission. Moreover, transmission costs are rising faster than the cost of the energy wheeled, while PV prices are falling (CPUC 2021), making solar sited at load more attractive for ratepayers, not to mention the benefits of local jobs and energy reliability. But if the full estimated need for utility-scale solar cannot be met on the distribution grid, the alternative of siting solar on water-deprived or contaminated lands and/or utilizing agrivoltaics on a small fraction of the state’s 40 million acres of farm and ranch lands can easily absorb the balance in a win-win for landowners as well as the environment (DOE 2023).

The potential solar capacity of the above options far exceeds the energy agencies' projected need for an additional 70,000 MW of new utility scale solar to meet the state's 2045 decarbonization goal. Clearly, the above options are the preferred resources to avoid land-use impacts and societal costs of developing transmission-dependent solar on intact desert lands in the California desert.

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## X. Policy Strategies and Tools to Maximize Carbon Sequestration and Conservation Values

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Public Policy Coordinator, Mojave Desert Land Trust

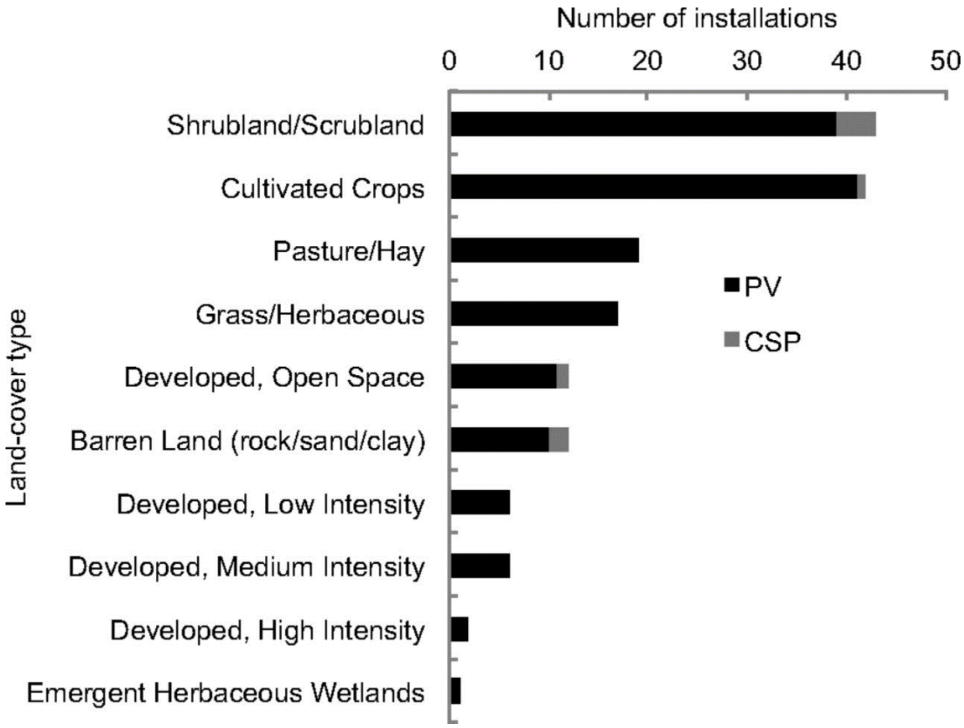
The state of California has long been recognized for its leadership in transitioning towards new, clean energy sources to reduce $CO_2$ atmospheric emissions. There are, however, two aspects to emissions reductions work.

The first is "what". This piece is on track. The state has diligently passed legislation and dedicated millions of dollars towards reducing carbon emissions through technological innovation and utilizing our natural and working lands to reach net zero.

The second aspect of carbon emissions work is "how." While the state has rolled out dozens of utility scale solar energy projects (USSE's) at an accelerating pace across desert lands, this has taken place at the expense of disturbance of intact desert lands, which counterproductively serve as significant carbon sinks. The irony is that we are releasing carbon into the atmosphere by disturbing desert lands and their long-term sequestered carbon while building infrastructure intended to reduce atmospheric carbon. On this front, California has not yet realized fully its leadership potential. How these transitions are carried out is based on siting decisions made in advance. For instance, China has directed their energy transition efforts towards utility-scale, ground-mounted PV [photovoltaic] panels, whereas Germany has achieved about 90% of its transition development within a built environment.

Several studies have revealed that regulations and policies in California have deemphasized solar growth and development within the built environment close to final destinations to meet demand, and instead favored development within shrublands and scrublands. Hernandez et al. (2015) note that carbon sequestration, among other ecosystem services including groundwater depletion and movement corridors for wildlife, may be adversely impacted globally by land cover conversion of shrubland and scrubland ecosystems.

Shrublands and scrublands have borne the brunt of land use conversion in our state's efforts to pursue USSE's on a massive scale, while developed regions remain largely underutilized.



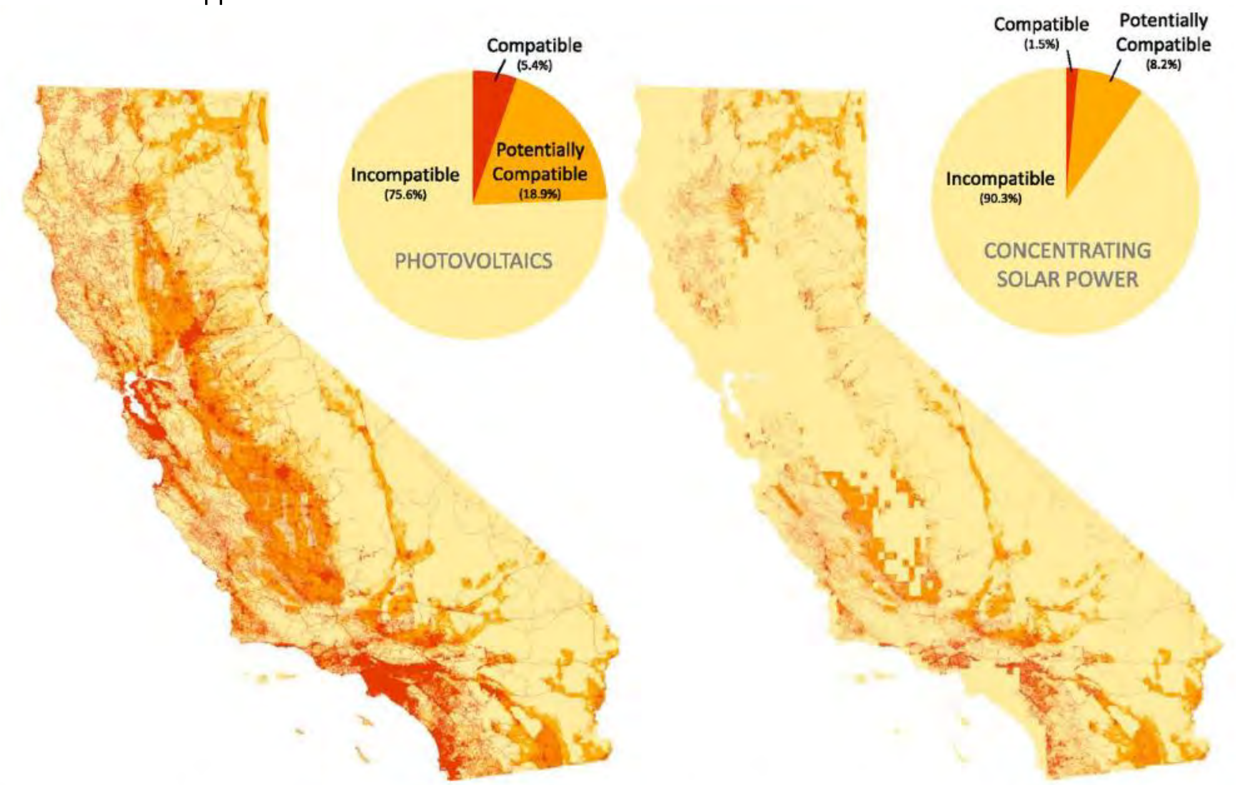

**Hernandez et. al. 2015.**

*Number of photovoltaic (PV) and concentrating solar power (CSP) installations (planned, under construction, operating) by land cover type in California; represented in order of most installations to least for both technologies.*

**How do we, as policy and decision-makers, carry out the task of addressing the "how" aspect of transition to clean energy so that the desert's carbon sinks remain undisturbed and intact?**

There are **planning tools** currently available that allow decision makers the opportunity to simultaneously develop solar installations on desert lands, while protecting conservation values including carbon sequestration all at once. This is the kind of pioneering work that establishes California as an environmental leader.

One such tool is the **Carnegie Energy and Environmental Compatibility [CEEC] model,** a multiple criteria model that quantifies each solar installation based on environmental and technical compatibility. The CEEC model is a decision support tool that develops a spatial environment and technical compatibility index that outputs 3 tiers: Compatible, Potentially Compatible, and Incompatible. The model was designed for use in California and can identify environmentally low-conflict areas based on resource constraints and opportunities.




*The state of California classified according to the CEEC Compatibility Index (Compatible, Potentially Compatible, Incompatible) and area (percentage) within each class for photovoltaic (PV) and concentrating solar power (CSP) technologies.*

Hernandez et.al., 2015

A second tool of interest for decision-makers seeking to integrate the advancement of USSE's with conservation of our desert lands is a framework proposed by a group of researchers led by Dr. Rebecca R. Hernandez of UC Davis. **Techno-ecological synergies [TES]** engineers the mutually beneficial relationships between technological and ecological systems to bolster the sustainability of solar energy across a suite of environments including land, water, and built-up systems. The intent of applying the TES framework to solar energy technologies is an effort for "sustainable engineering" to minimize unintended consequences on nature as we rapidly advance USSE's on our natural and working lands.

The authors propose expansion of solar energy engineering principles to include both economic and ecological systems based on a synergistic relationship between technology and the environment. The outcome of TES produces products relevant to the technology end of development (PV module efficiency and grid reliability) *as well as* support for ecosystem services such as carbon sequestration and storage, water-use efficiency, and wildlife habitat. The research team offers 20 potential TES outcomes and discusses metrics and assessment methods to measure TES flows.

One example of a TES opportunity is optimizing land resources. The most degraded lands sites, for example EPA Superfund sites, could produce about 38% of total US energy consumption (based on 2015 assessment). At the same time, degraded lands function as substitutes, sparing undisturbed land with greater capacity for carbon sequestration. Moreover, the negative effects of land cover change and disturbance such as release of GHG emissions, dust release, and soil-borne pathogens are reduced or eliminated.

Further examples of optimizing land resources include co-location of other renewable energy formats (such as wind turbines) adjacent to solar utility, with benefits compounded when this takes place on already degraded land. The number of potential beneficial outcomes for individual TES's ranges from 6-13; that is, there are substantial benefits to be gained by the synergistic framework proposed by this system.

While the commitments to transition to clean energy are moving rapidly, it may be necessary to make good use of policies to embed solar energy TESs into the economics of planning.

**References**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Parker, S., Cohen, B. D., & Moore, J. E. (2018). Impact of solar and wind development on conservation values in the Mojave Desert. *PLOS ONE*, *13*(12), e0207678. https://doi.org/10.1371/journal.pone.0207678


## XI. Conclusion

To fully realize the value of desert lands as part of our state's efforts to sequester atmospheric carbon, the desert must be recognized as a significant carbon sink -- *and it needs to be left undisturbed*. Unlike other ecosystems, it has a unique time scale that would require hundreds to thousands of years to recover from disturbance. The highest capacity regions for desert carbon storage, including microphyll woodlands and desert bajadas, should be identified as the top priority regions for conservation. And the state must also place high importance on the "how" part of transitioning to clean energy by careful pre-planning and siting of renewables on already disturbed desert lands and developments. We only get to do this once, so it needs to be done right.

**USGS**
*science for a changing world*

# Assessing the geology and geography of large-footprint energy installations in the Mojave Desert, California and Nevada

David R Bedford and David M Miller
U.S. Geological Survey, 345 Middlefield Road, MS-973, Menlo Park, CA 94025

## Abstract

Large-footprint energy installations such as solar and wind farms are proposed for wide areas of drylands that are publicly owned. These installations impact areas of 400 to 2000 hectares each, requiring land-use assessments that are novel compared to past decisions for relatively small installations such as mine sites and roadways. Solar installations require low-gradient smooth topography, areas for which we have several data sets that can help with evaluations.

We use topography (30 m DEMs) and surficial geology (1:100,000 scale) for an area of 40,400 km2 stretching from Lancaster and Mojave on the west to Jean, NV, and Goffs, CA, on the east to evaluate potential lands for solar energy installations. The geology was mapped using uniform methods across the northern Mojave Desert so that a consistent database is available for analytical purposes. We use slope categories, surficial geology attributes, and land ownership to describe this area in a series of maps.

About 48% of the entire area is less than 5% slope, and 8.3% is less than 1% slope, the favored slope category. For this lowest-slope category, deposits underlying about 98% of the area are either mixed eolian-alluvial origin or are fine-grained alluvial deposits, and thus are susceptible to eolian dust and sand transport, especially after disturbance. In addition, in this low-slope category, 89% of the area is susceptible to flooding, based on the age and geomorphology of alluvial deposits. These maps are examples of several we present for decision-making with respect to hazards and ecological attributes in the face of climate change.

## Overview

The Mojave Desert have been identified as an area with ample space and many of the resources needed for alternative energy development. Responding to recent interests in alternative energy, the BLM has received thousands of applications for large, utility-scale alternative energy developments. To assess the impacts of alternative (predominately solar and wind power) energy, the BLM has established Programmatic Environmental Impact Statement (PEIS) study sites. These sites will be used to develop management plans for the currently identified areas as well as other areas that may be potentially permitted for large energy developments.

These facilities typically require flat to very gently sloping topography and have a large footprint of disturbance. The goal of this poster is to identify how surficial geologic information can help guide site placement and anticipate mitigation requirements.


Area of analysis in the three-state Mojave Desert region. BLM-designated PEIS sites are also shown

## Geologic Mapping

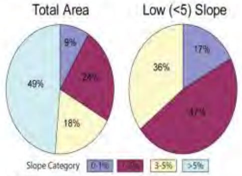
USGS collected and organized surficial geology data for the 8-quadrangle area we analyzed. The database was collected at scales more detailed than 1:100,000, and generalized to that scale. This scale roughly corresponds to the 30-m DEM and Landsat resolution. The effort was organized so that resulting 8 databases are uniform and robust, resulting in a geospatial database covering a broad tract of the Mojave Desert Ecoregion. An example of a published data base is Bedford et al. (2010). Surficial geology attributes include parent material, thickness, grain size, soil development, age, and geomorphic process of deposition (or erosion). These attributes allow the database to be used for many applications such as soil hydrology, susceptibility to erosion, estimations of plant cover and plant species composition, and susceptibility to flooding (Miller et al., 2009). The database also includes point measurements of a number of soil and geomorphic properties that were not used in this study.

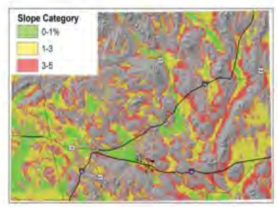
This database contains information similar to the detailed NRCS soil maps, but in addition carries geomorphic process information. The process information is powerful for applying the database to several uses. For instance, the knowledge that a polygon is typified by active alluvial fan channels carries information about recency and frequency of flooding and when combined with topography, defines "downstream" directions that will be modified if the channels are disturbed by construction.

**Surficial Geologic Map of the Study Area**

## Slope Analysis

We analyzed a 30-meter Digital Elevation Model (DEM) for areas of suitable slope. Solar energy facilities need to be sited on less than 5% slopes. To capture broad areas of similar slope, we smoothed the slope map calculated from the DEM using a 9x9 moving window. We then broke the slope map into 3 categories where facilities could be sited (0-1%, 1-3%, 3-5%) and a single category for unsuitable slopes larger than 5%.




**Findings:**

- About half the area is <5% slope, but only 9% is <1% slope, the favored category for installations.
- Of the <5% low-slope fraction, about half is 1-3% slope and one-third is 3-5%.
- The 0-1% slope area mainly occurs in and near playas and in the Mojave River plain.
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We then wanted to know who owned the land across the study area. It is well known that much of the land is "off limits" for energy development (e.g. National Parks). We intersected an ownership map with the slope categories.

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Example conclusion: The most suitable areas determined by slope (0-1%) make up only 9 percent of the study area. Within that area, 76% of the area could potentially be developed based on ownership.

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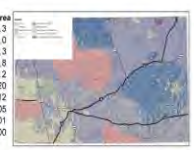

**Ownership by slope category**
Top number: percent of total area
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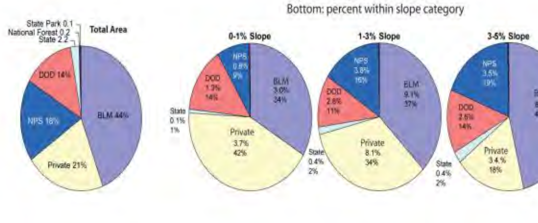


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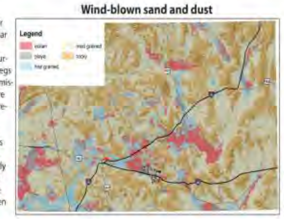
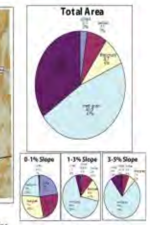
We reclassified our geologic map into a few broad categories that are likely to be important to assess the impacts and functioning of alternative energy facilities.

**Wind-blown sand and dust**

Wind-blown (eolian) sand and dust is a major hazard in arid regions and interferes with solar energy production and can greatly increase water (for cleaning) needs. Disturbance of surface biocrusts and plants, as well as pebble regs and pavements, exacerbate dust and sand emissions during storms; siting installations where eolian emissions are minimized should be preferred.

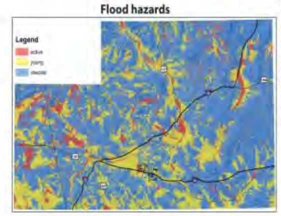
Our "eolian" category represents areas with modern or past eolian sand in the deposit; its disturbance can rapidly destabilize the soils. Playas are very fine grained and intermittently flooded, resulting in chemical crusts that are easily disrupted. Fine-grained deposits have potential for emissions of dust and sand when disturbed; lesser potential is probable for medium and rocky categories.




Susceptibility for **High** Eolian hazard: 75% 28% 12%

**Flood hazards**




Flood hazards on alluvial fans can be estimated with a knowledge of age of deposit, channel characteristics, and topography (House, 2005; Robins et al., 2008). Areas with active channels and deposits are intermittently active, whereas those with young deposits flood less frequently, during only the most extreme precipitation events or if channel hydrology is disturbed.

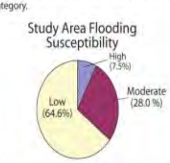
**Results:**

- Surficial geology with high flooding potential makes up only 6% of the total area with <5% slopes
- High flooding potential characterizes 25% of the area with 0-1% slope.
- High flooding potential characterizes 10% of the area with 1-3% slope.

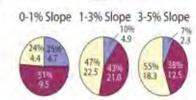
Results:

- Much of the area we identified as having favorable ownership and slopes have rocky to medium grained soils, which have low susceptibility to eolian hazard.
- A large proportion of the 0-1% slope category is composed of active and former eolian deposits, playa deposits, and fine-grained deposits. These three substrate types are the most susceptible to eolian emissions that affect the installations and downwind locations.
- The 1-3% slope category has much lower susceptibility to eolian hazards than the lowest slope category.

Study Area Flooding Susceptibility




0-1% Slope 1-3% Slope 3-5% Slope




## Integration of Geologic Analyses

We investigated the geology of the areas with highest susceptibility for hazards. Spatial correspondence of flood hazard and eolian hazards in the lowest slope categories is striking result. These areas correspond with two main landforms: 1) valley bottoms, and 2) big-river flood plains. Valley bottoms are sites of playas, playa-fringe deposits of mixed origins, eolian sand deposits, and distal alluvial fan deposits. These deposits have in common a fine grain size and lack of rocky cover; as a result they are among the most unstable landforms in arid regions. Big-river flood plains are broad, generally fine-grained flats that may be rocky in a few places. Floodplains typically are valued for a wide variety of commercial and residential uses.

High hazard values (both eolian and flooding) are evident for large proportions of the lowest slope category. In contrast, the high hazard values for the 1-3% slope category applies to much less of the area: 28% is high eolian hazard and 10% high flood hazard. Similar decreases in the proportion of the steepest slope category that is susceptible to hazards are evident.

## Implications for Climate Change

Increased mean temperature, extreme temperatures, and climate variability are forecast for this region. Uncertainty for forecasts of summer (monsoon) precipitation and total precipitation remain. Higher temperatures will reduce soil moisture and increase aridity, which along with increased extreme conditions, will increase emissions during extreme wind events. As vegetation responds to climate shifts there also is a likelihood for more sediment to become destabilized and made available to wind and water transport. If monsoon conditions increase in frequency and intensity due to warmer Gulf of California, increased flooding may result (Miller et al., 2010). These scenarios indicate that current assessments of the vulnerability to erosion from wind and water may need to be re-evaluated and that more of the Mojave Desert may be susceptible to these impacts. Species adapted to playa-margin environments may be especially vulnerable to climate change.

## Conclusions

Although very low slope (0-1%) areas, the favored sites for solar installations, constitute less than 10% of the Mojave Desert region, they represent a disproportionately large percentage of substrate that is susceptible to flooding and to eolian sand and dust emissions. Private ownership of these low-slope lands exceeds BLM ownership; with greater road access and other features of private ownership, these lands may warrant more consideration for development. Steeper slopes (1-3%) characterize more of the desert (24%); these lands have less susceptibility to flood and eolian hazards. These steeper lands deserve greater consideration in efforts to tradeoff less suitable building land with decreased susceptibility for hazards. Future studies will add plants and animals to this study of geology and topography. Such a study could strengthen conclusions and permit forecasts in the face of climate change. Geomorphology and surficial geology allow some aspects of energy installation to be described and used for decision-making.

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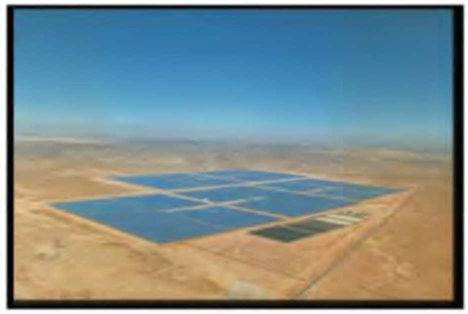

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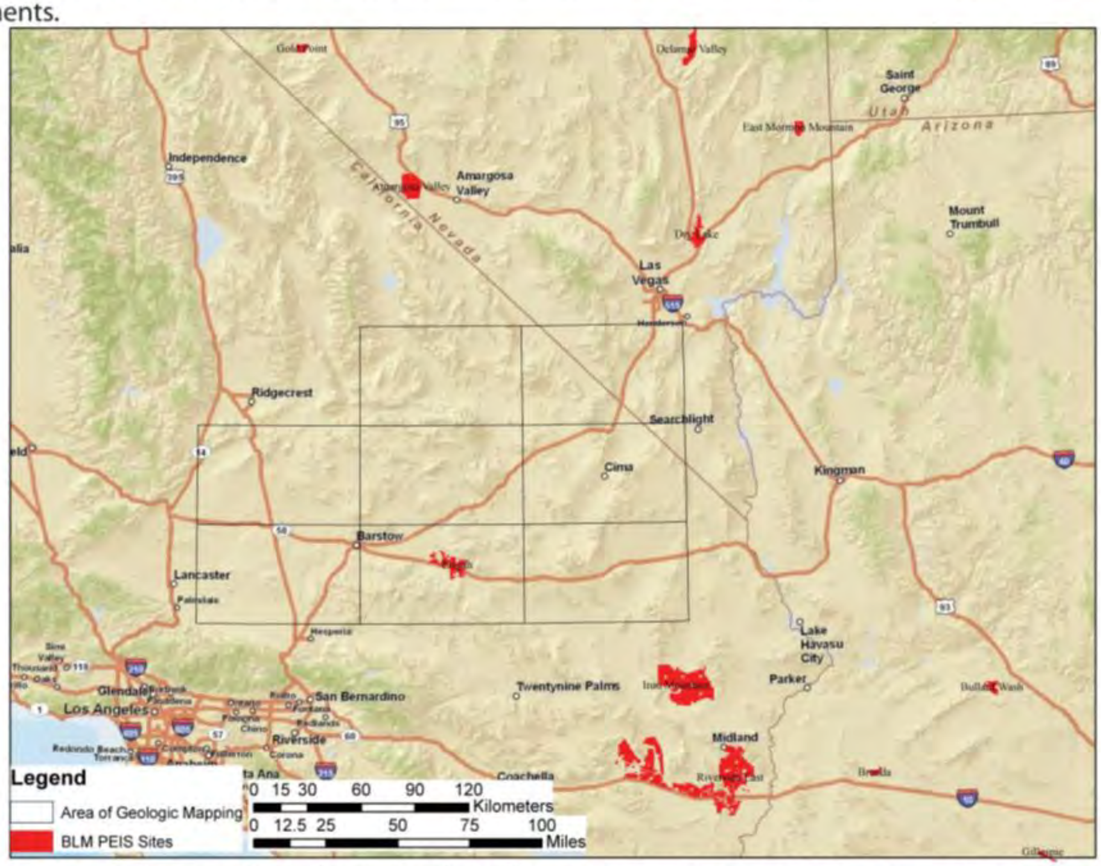


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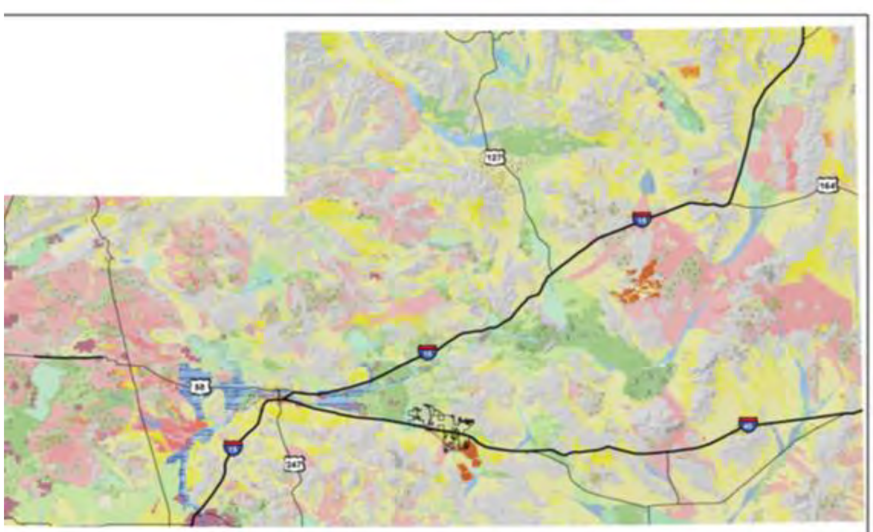

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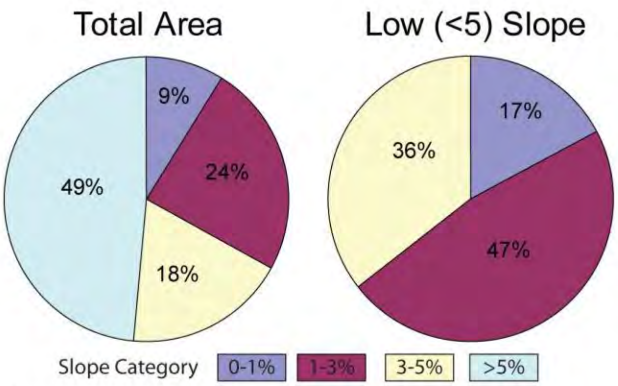


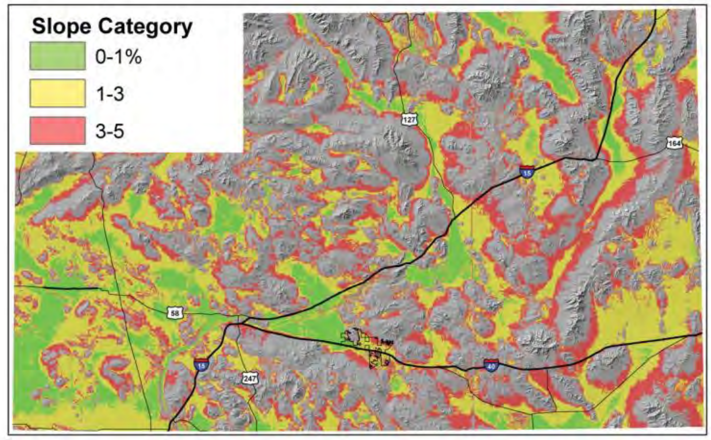


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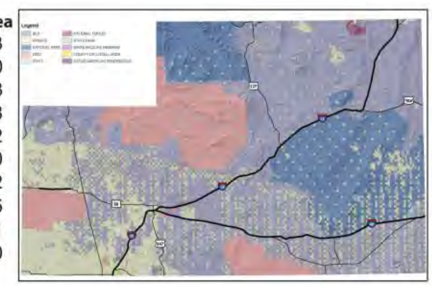

**Ownership by slope category**

Top number: percent of total area

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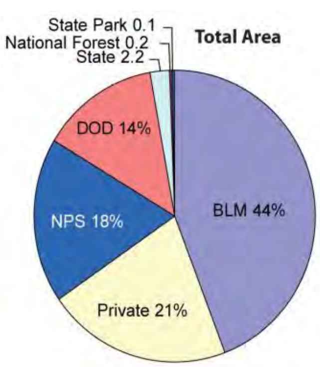


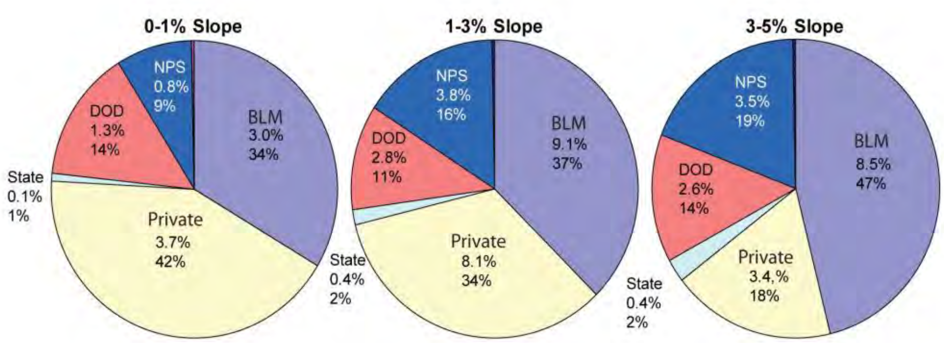

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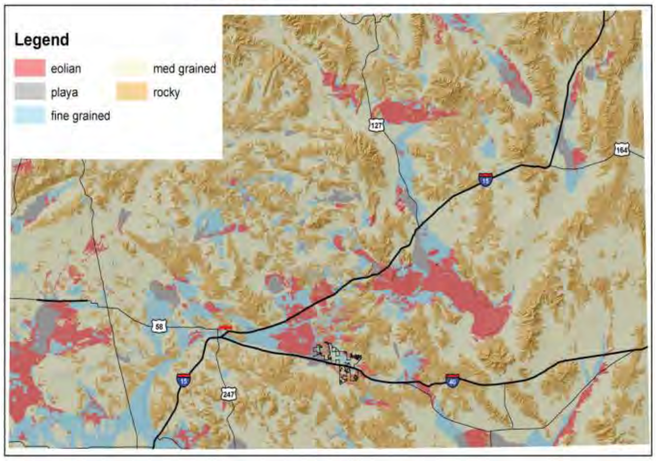
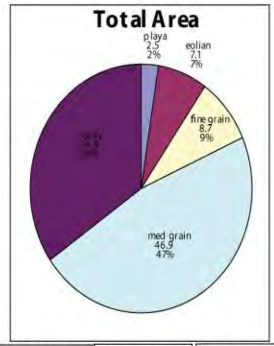
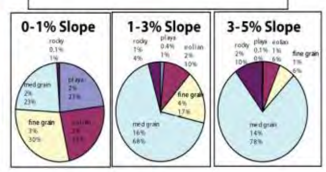


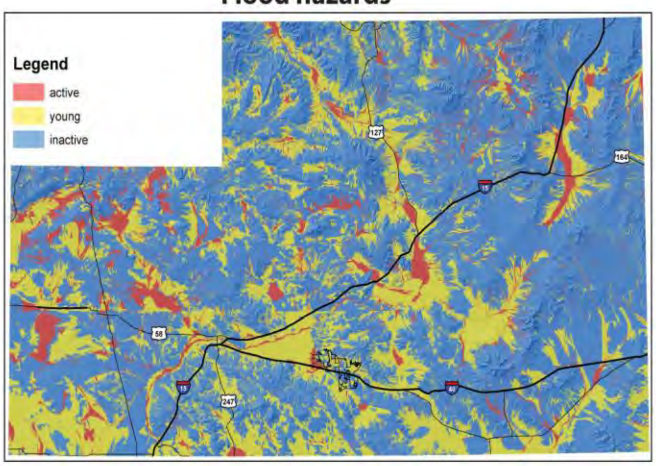




| Susceptibility for **High** Eolian hazard | 75% | 28% | 12% |
|---|---|---|---|

Results:

- Much of the area we identified as having favorable ownership and slopes have rocky to medium grained soils, which have low susceptibility to eolian hazard.
- A large proportion of the 0-1% slope category is composed of active and former eolian deposits, playa deposits, and fine-grained deposits. These three substrate types are the most susceptible to eolian emissions that affect the installations and downwind locations.
- The 1-3% slope category has much lower susceptibility to eolian hazards than the lowest slope category.

## Flood hazards

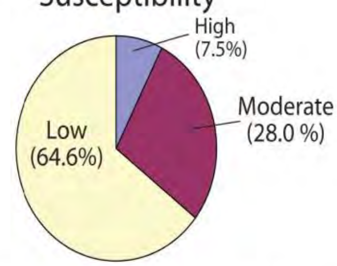


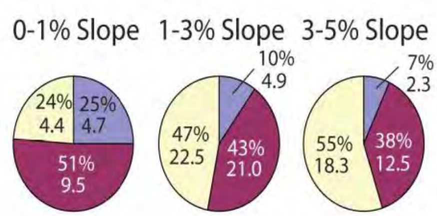

Flood hazards on alluvial fans can be estimated with a knowledge of age of deposit, channel characteristics, and topography (House, 2005; Robins et al., 2008). Areas with active channels and deposits are intermittently active, whereas those with young deposits flood less frequently, during only the most extreme precipitation events or if channel hydrology is disturbed.

**Results**:

- Surficial geology with high flooding potential makes up only 6% of the total area with <5% slopes
- High flooding potential characterizes 25% of the area with 0-1% slope.
- High flooding potential characterizes 10% of the area with 1-3% slope.

### Study Area Flooding Susceptibility



## Integration of Geologic Analyses

We investigated the geology of the areas with highest susceptibility for hazards. Spatial correspondence of flood hazard and eolian hazards in the lowest slope categories is striking result. These areas correspond with two main landforms: 1) valley bottoms, and 2) big-river flood plains. Valley bottoms are sites of playas, playa-fringe deposits of mixed origins, eolian sand deposits, and distal alluvial fan deposits. These deposits have in common a fine grain size and lack of rocky cover; as a result they are among the most unstable landforms in arid regions. Big-river flood plains are broad, generally fine-grained flats that may be rocky in a few places. Floodplains typically are valued for a wide variety of commercial and residential uses.

High hazard values (both eolian and flooding) are evident for large proportions of the lowest slope category. In contrast, the high hazard values for the 1-3% slope category applies to much less of the area: 28% is high eolian hazard and 10% high flood hazard. Similar decreases in the proportion of the steepest slope category that is susceptible to hazards are evident.

## Implications for Climate Change

Increased mean temperature, extreme temperatures, and climate variability are forecast for this region. Uncertainty for forecasts of summer (monsoon) precipitation and total precipitation remain. Higher temperatures will reduce soil moisture and increase aridity, which along with increased extreme conditions, will increase emissions during extreme wind events. As vegetation responds to climate shifts there also is a likelihood for more sediment to become destabilized and made available to wind and water transport. If monsoon conditions increase in frequency and intensity due to warmer Gulf of California, increased flooding may result (Miller et al., 2010). These scenarios indicate that current assessments of the vulnerability to erosion from wind and water may need to be re-evaluated and that more of the Mojave Desert may be susceptible to these impacts. Species adapted to playa-margin environments may be especially vulnerable to climate change.

## Conclusions

Although very low slope (0-1%) areas, the favored sites for solar installations, constitute less than 10% of the Mojave Desert region, they represent a disproportionately large percentage of substrate that is susceptible to flooding and to eolian sand and dust emissions. Private ownership of these low-slope lands exceeds BLM ownership; with greater road access and other features of private ownership, these lands may warrant more consideration for development. Steeper slopes (1-3%) characterize more of the desert (24%); these lands have less susceptibility to flood and eolian hazards. These steeper lands deserve greater consideration in efforts to tradeoff less suitable building land with decreased susceptibility for hazards. Future studies will add plants and animals to this study of geology and topography. Such a study could strengthen conclusions and permit forecasts in the face of climate change. Geomorphology and surficial geology allow some aspects of energy installation to be described and used for decision-making.

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# Vulnerability of desert biological soil crusts to wind erosion: the influences of crust development, soil texture, and disturbance

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Biological soil crusts, consisting of cyanobacteria, green algae, lichens, and mosses, are important in stabilizing soils in semi-arid and arid lands. Integrity of these crusts is compromised by compressional disturbances such as foot, vehicle, or livestock traffic. Using a portable wind tunnel, we found threshold friction velocities (TFVs) of undisturbed crusts well above wind forces experienced at these sites; consequently, these soils are not vulnerable to wind erosion. However, recently disturbed soils or soils with less well-developed crusts frequently experience wind speeds that exceed the stability thresholds of the crusts. Crustal biomass is concentrated in the top 3 mm of soils. Sandblasting by wind can quickly remove this material, thereby reducing N and C inputs from these organisms. This loss can result in reduced site productivity, as well as exposure of unprotected subsurface sediments to wind and water erosion. Actions to reduce impacts to these crusts can include adjustments in type, intensity, and timing of use.



**Keywords:** cryptogamic; microbiotic; microphytic; cyanobacteria; lichens; soil loss; wind erosion; land degradation

## Introduction

Wind is an important erosive force in deserts, where there is little soil surface protection by organic matter or vegetative cover. Dust deposition by wind often exceeds that of fluvial deposition in these drier regions (Goudie, 1978; Williams *et al.*, 1995). Sediment is produced from soil surfaces when wind forces exceed soil threshold friction velocities (the force needed to detach particles from soil surfaces). Since wind erosion is of major concern both in the western United States and worldwide (Dregne, 1983*a*), it is important to understand how soil surface disturbance affects these threshold velocities.

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In hot and cold arid regions of the world where vascular plant cover is absent or restricted, biological soil crusts (also referred to as cryptogamic, cryptobiotic, microbiotic, or microphytic crusts) often dominate the soil surface (Cameron, 1966; Friedmann & Galun, 1974; Friedmann & Ocampo-Paus, 1976; Harper & Marble, 1988; West, 1990). Depending on soil characteristics and disturbance regimes, soil crust components generally include cyanobacteria, green algae, lichens, mosses, and/or microfungi. In arid soils that are more alkaline, cyanobacteria generally dominate (Friedmann *et al.*, 1967; Belnap & Gardner, 1993; Johansen, 1993; Belnap, 1995).

Sheath material extruded by cyanobacteria entrap and bind soil particles together, acting to reduce both wind and water erosion (Belnap, 1993; Williams *et al.*, 1995; McKenna-Neuman *et al.*, 1996; Belnap & Gillette, 1997). Cyanobacteria appear better able than green algae to protect soil surfaces from wind erosion in the laboratory (McKenna-Neuman *et al.*, 1996). Field studies in Utah cold deserts show that well-developed crusts, containing both lichens and mosses, offer more protection than cyanobacteria alone (Belnap & Gillette, 1997). These studies also showed that any vehicle or foot traffic over well-developed or previously disturbed crusts drastically decreased soil surface resistance to wind erosion in the sandy loam soils tested.

Garcia-Pichel & Belnap (1996) showed that biomass and activity in biological soil crusts were concentrated within 3 mm of the soil surface. This distribution has important implications for studies on soil surface vulnerability to wind erosion, as very little soil loss can result in the removal of most soil surface organisms. Cyanobacteria and cyanobacterial-containing soil lichens are an important source of both fixed carbon and nitrogen for many desert ecosystems (Beymer & Klopatek, 1991; Evans & Ehleringer, 1993; Belnap, 1995), and can increase macronutrient concentrations in vascular plant tissue (Belnap & Harper, 1995). Removal of these organisms therefore reduces site productivity and exposes unprotected subsurface soils to both wind and water erosion. In addition, loss of fine soil particles to which nutrients are bound also reduces site productivity. Reduced fertility of systems is one of the most definitive and problematic aspects of desertification (Dregne, 1983*b*).

This study further expands field tests of arid land soil vulnerability to wind erosion. Here we examined the surface resistance of four warm desert soils in southern New Mexico with different levels of biological soil crust development. We then examined soils for the effects of hoof and vehicle disturbance and compared results to those obtained with similar experiments from the cold deserts of southern Utah.

## Materials and methods

### *Study sites*

This study was conducted at the USDA-ARS Jornada Experimental Range (JER) at the north end of the Chihuahuan Desert in south-central New Mexico, where annual precipitation averages 247 mm. Daily average temperature maxima range from 13°C in December to 36°C in June. The elevation of the study sites ranged from 1150 to 1175 m. Wind speeds in this area were estimated using a Geomet station that recorded 6-min wind speed averages at 6·1 m above the soil surface during the previous calendar year.

Sites were located on four soil types within JER: sandy, alluvial silt, gravel, and playa soils. Sandy and playa soils were replicated at four sites, alluvial silt soils at three sites, and gravel soils at two sites. At each site, two runs were performed for TFVs.

Wind tunnel measurements and soil samples were collected in open interspaces between perennial vegetation. Biological crust development was visually assessed by the presence/absence of cyanobacteria, mosses, and lichens. Well-developed crusts were defined as those with lichen and/or moss cover. Poorly developed crusts — those containing only cyanobacteria — varied from sites with very low cyanobacterial biomass to sites with very high cyanobacterial biomass. Cyanobacterial biomass was qualitatively determined by counting the number of filaments that could be seen when soil surfaces were broken.

The sandy site was dominated by mesquite (*Prosopis glandulosa*) and very low cyanobacterial biomass. The gravel sites were dominated by creosotebush (*Larrea tridentata*), 40% rock cover, and low cyanobacterial biomass (on soils between the rocks). The alluvial silty soils were dominated by tarbush (*Flourensia cernua*), high cyanobacterial biomass, and a well-developed lichen soil crust dominated by the soil lichens *Catepyrenium* sp. and *Collema tenax*. The playa soils lacked perennial vegetation and biological soil crust.

Threshold friction velocities (TFV, the force required to detach soil particles from the surface) were determined for each soil type at each of the replicated sites. TFV for surface integrity (SI) was the friction velocity at which large, intact chunks of the surface were detached and blown away. Because wind stress equals the square of friction velocity times the density of air, relative resistances of the different crustal classes to wind erosion are defined as the square of the ratio of threshold friction velocities between the classes being compared. Results are also reported as the per cent decrease in soil resistance to wind erosion.

Once TFVs were determined for the undisturbed soils, disturbance was applied in the form of a cow hoof (applied by hand) or two passes with a four-wheel drive vehicle. TFV for soil within the disturbance was then determined. In addition, TFVs were obtained from experimental vehicle tracks established 1 year previously and fenced to prevent further disturbance. The three crustal classes were compared using a two-way ANOVA and multiple range test. A *t*-test was used to distinguish between disturbance treatments and controls.

### *Wind tunnel*

Detailed methods can be found in Belnap & Gillette (1997). A portable, open-bottomed wind tunnel, 0·15 m $\times$ 0·15 m cross-section by 2·4 m length, was used so that many wind speeds could be created over the desert surface.

TFVs were determined by gradually increasing wind speed in the tunnel until consistent forward soil particle movement was observable across the soil surface. Air-flow velocities were then recorded at the soil surface midway across the end of the working section at 3·2, 6·4, 12·7, 25·4, 38·1, 50·8, 63·5, 76·2, 88·9, and 101·6 mm above the soil surface, yielding wind profiles for the controls (undisturbed soils). For areas receiving hoof or vehicle treatments, TFVs were determined for the undisturbed surface, after which treatments were applied. TFVs are reported in cm $s^{-1}$; the conversion factor for wind speeds in m $s^{-1}$ is 100.

## Results

### *Soil texture and crust development*

Sandy soils had a significantly greater per cent of sand than did the playa or silt soils (72%, 33%, and 30% respectively; Table 1). Per cent sand in the playa and silt soils did not differ significantly. Per cent clay was greatest in the silt soils but did not significantly differ between the playa and sandy soils (29%, 18%, and 13% respectively). Per cent silt was greatest in the playa and silt soils (49% and 41%, respectively), and this percentage differed significantly from that of sandy soils (14%). Gravel and sandy soils had similar textures, with the gravel site having a 40% rock cover.

Biological soil crusts were found at all silty alluvial, sand, and gravel sites. Development of these crusts varied widely. Silty alluvial and sandy sites 2–4 had high cyanobacterial biomass and well-developed lichen soil crusts. No cyanobacteria to medium cyanobacterial biomass was found on the sandy soils at site 1, and very low cyanobacterial biomass was found at the gravel sites. Playa soils had mineral crusts, but no biological crust development was seen.

### *Threshold friction velocities*

TFVs for the different sites are shown in Figs 1–3. Figure 1 shows the SI values for all sites tested. These values ranged widely from 30 to 471 cm $s^{-1}$. TFVs of the soil surface were related to biological crust development and rock cover. Lowest SI values were seen in sandy soils with no crusts (30 cm $s^{-1}$). Soils with very thin and thin cyanobacterial crusts had higher TFVs (40 and 82 cm $s^{-1}$, respectively). Sandy soils with thicker cyanobacterial crusts averaged 260 cm $s^{-1}$, while well-developed lichen crusts on silt and sand showed very high TFVs (323 and 471 cm $s^{-1}$, respectively).

Rock cover and soil mineral crusting also conferred some resistance to wind erosion. Soils with no crusts but 20% rock cover showed an increase of TFVs when compared to similar soils with no crust (30 *vs*. 42 cm $s^{-1}$). Gravel sites, with 40% rock and thin cyanobacterial cover, showed intermediate TFV values (173 cm $s^{-1}$). Playa sites with mineral crusts showed intermediate TFVs as well (185 cm $s^{-1}$).

Applied disturbance decreased the resistance of all soil types to wind erosion at all sites (Figs 2 and 3). In sandy soils, hoof disturbance resulted in a 20–83% decline in TFVs, with the slightly thicker crust showing the greatest per cent decline and the very thin crusts showing the least decline. In silty soils, hoof impacts reduced TFVs by 60%. On playa soils this decline was 86%. Gravel showed the least impact with a 22% decline in TFV.

New disturbance by vehicles in sandy soils resulted in an 83% decline in TFVs. Sites affected by vehicles 1 year previously showed no recovery, with TFVs still reduced by 31–82%. In silty soils new tracks had an impact similar to those in sandy soils, with a decline of 74%. However, 1-year-old tracks showed declines of only 46%. New vehicle tracks in playa soils resulted in a TFV decline of 93%.

**Table 1.** *Soil texture of Jornada Experimental Range sites*

| | % sand | | % silt | | % clay | |
|---|---|---|---|---|---|---|
| | Average | SE | Average | SE | Average | SE |
| Playa | 33·10 | 5·36 | 49·32 | 3·36 | 17·58 | 3·20 |
| Sand | 72·38 | 5·92 | 14·27 | 2·20 | 13·35 | 3·99 |
| Silt | 30·11 | 0·67 | 40·61 | 1·76 | 29·28 | 1·15 |
| Gravel | 68·72 | * | 11·64 | * | 19·64 | * |

*Indicates no standard error because only one sample was taken.

## Discussion

Resistance to wind erosion paralleled biological crust development. Both silt and sandy soils with the greatest TFVs were those with the most well-developed crusts, while less wind resistance was seen at sites with less crustal development. Because cyanobacteria and lichens secrete substances and produce filaments that entangle soil grains (Belnap & Gardner, 1993; McKenna-Neuman *et al*., 1996), this result was expected. Rocks and mineral crusts were also seen to confer some resistance to erosion.

Soil surface disturbances resulted in greatly decreased soil resistance to wind erosion for all soil types, regardless of the disturbance regime. Resistance to wind erosion is the square of measured TFVs. Consequently, disturbance reduced the resistance of the tested soil surfaces from 69% to more than 5200% (Table 2). Hoof print disturbances increased wind erosion susceptibility by 69–5247%, depending on substrate type, while disturbance with a vehicle increased susceptibility by 1372–3399%. Even after a year of recovery, sandy surfaces still showed a 114–2950% increase in susceptibility. As cyanobacteria and lichens are very brittle when dry and crush easily, surface stability conferred by these organisms would be severely compromised after compressional disturbances (Webb & Wilshire, 1983; Belnap & Gardner, 1993; Johansen, 1993; Belnap *et al*., 1994; Belnap, 1996).

Although silty alluvial and sandy soils showed a similar response to new vehicle disturbance (83% *vs*. 74% TFV decline), silty soils showed a faster recovery rate than sandy soils. The partial recovery seen in the silty soils was probably a result of clay particle suspension after rainfall. When rainfall is heavy enough to pool on the soil surface, clay particles can float to the water surface, and upon drying, form a thin mineral crust. Thus thin crust resists wind erosion when dry but does not protect soil

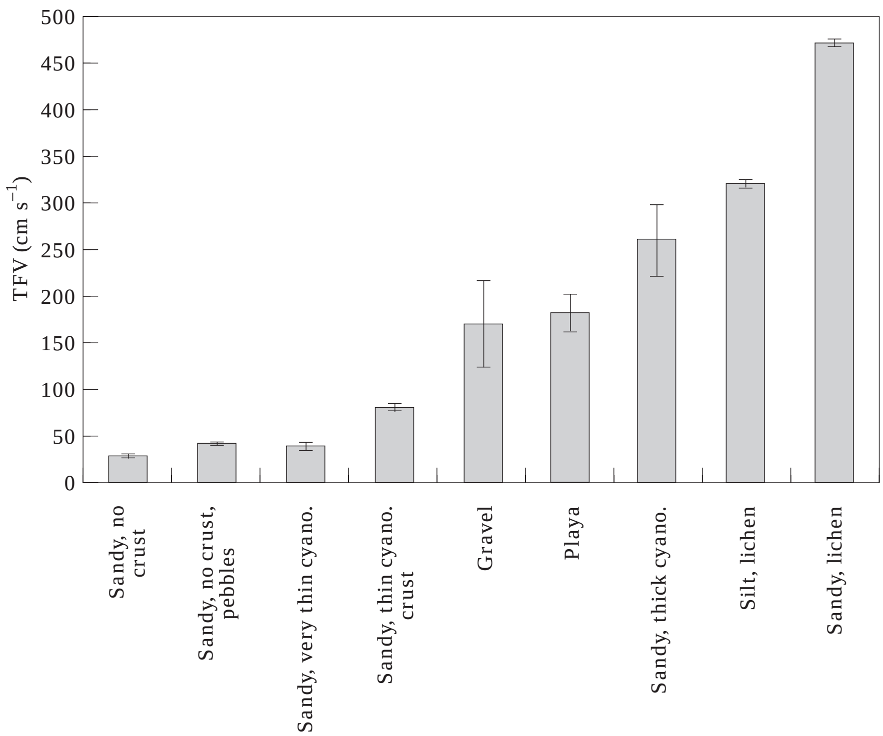


**Figure 1.** Threshold friction velocities (TFV) for all undisturbed sites.

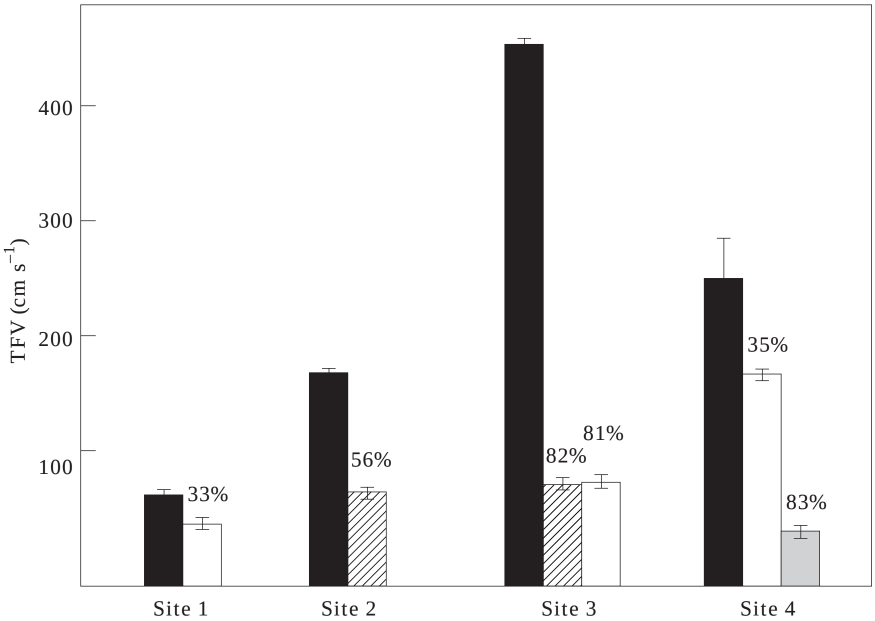


**Figure 2.** Decline in TFV resulting from applied disturbances at four sites in sandy soils. Hoof disturbances were applied by hand; tracks are from two passes of a four-wheel drive vehicle. All disturbances significantly differed from controls and each other ($p < 0{\cdot}01$) except sandy site 3, where the control and treatments significantly differed from each other but the treatments did not significantly differ from each other. (■) = control; (▨) = 1-year-old track; (□) = hoof disturbance; (▒) = new track.

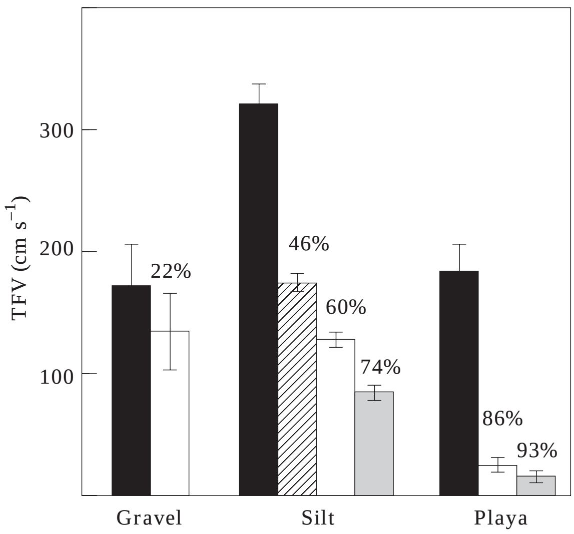


**Figure 3.** TFVs from gravel, silt, and playa sites. All disturbances significantly differed from controls and from each other ($p < 0{\cdot}01$). (■) = control; (▨) = 1-year-old track; (□) = hoof disturbance; (▒) = new track.

surfaces from water erosion when wet. This same phenomenon may occur in the sandy soils but to a lesser degree.

Playa soils showed the greatest impact with disturbance. Silty and sandy soils showed an intermediate response, with gravel soils being the least compromised. Since the playa soils had no biological crust or rocks to increase resistance to wind erosion, crushing of the thin mineral crust left the surface with virtually no protection from wind erosion. In almost all cases, vehicle tracks resulted in greater damage than hoof prints, regardless of soil type. The reason for this is not known.

Wind speeds on the Jornada were continuously recorded by a Geomet station during 1995, the year before this study (Fig. 4), at a height of 6·1 m. The mode was seen at 1·5 m $s^{-1}$ and the maximum at 20 m $s^{-1}$. These measurements were taken well above the surrounding vegetation. For playa sites, which lack vegetation, these wind speeds are a good approximation of ground speed. For vegetated areas, ground wind speeds would be expected to be much less. SI values obtained for sites covered by a well-

**Table 2.** *Per cent reduction of soil resistance to wind erosion. Resistance is calculated by squaring TFV values*

| Site | IS (cm $s^{-1}$) | Hoof (%) | New track (%) | 1-year track (%) |
|---|---|---|---|---|
| Sandy 1 | 54 | 69 | 114 | – |
| Sandy 2 | 180 | – | 517 | – |
| Sandy 3 | 471 | – | 2950 | – |
| Sandy 4 | 264 | 236 | – | 3399 |
| Gravel | 173 | 163 | – | – |
| Silt | 323 | 618 | 337 | 1327 |
| Playa | 185 | 5247 | – | – |

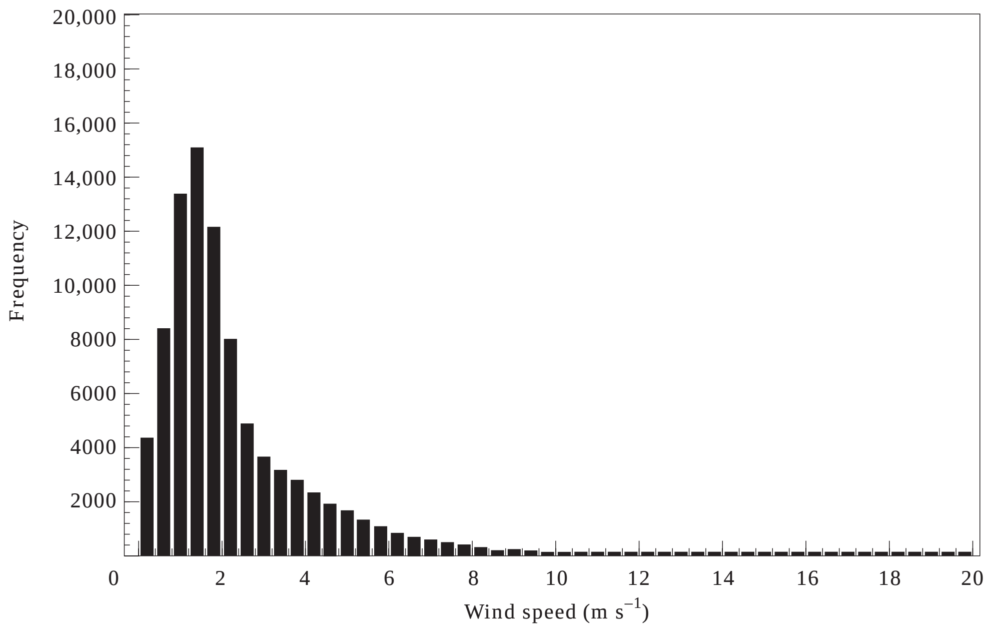


**Figure 4.** Wind speeds at a Geomet station at the Jornada Experimental Range, Las Cruces, NM. Numbers represent 6-min averages throughout 1 year (1995). Measurements were taken 6·1 m above the soil surface.

developed biological soil crust (29–32 m $s^{-1}$) indicate that well-developed crusts can protect soil surfaces from erosion by winds in this region. However, sites with very low or no cyanobacterial biomass and limited or no perennial vegetation would be susceptible to frequent wind erosion events. Both hoof and vehicle disturbance lowered soil resistance significantly on all soil types. Surfaces previously not susceptible to wind erosion (silt and sand) were vulnerable after disturbance.

The results obtained in this study were similar to those seen for previous field studies of wind erosion on biologically crusted surfaces. Belnap & Gillette (1997) found that although sandy soils with well-developed lichen crusts had TFVs well above wind speeds of the region, disturbance by foot or vehicle traffic resulted in TFVs well below commonly occurring wind events. This was true for both new disturbances and those more than 5-years-old. Williams *et al.* (1995) reported TFVs of 200 cm $s^{-1}$ for alluvial soils with fairly high silt-clay contents that had been fenced off from grazing disturbance for 3 years. Gillette (1988) reported a TFV of 290 cm $s^{-1}$ in rain-crusted soils in the Mojave Desert and 20–60 cm $s^{-1}$ for loose sandy soils (Gillette *et al.*, 1980). Gillette *et al.* (1980) also showed increasing fine texture in soils results in increased TFVs.

Decreasing TFVs have been shown to be directly associated with increased sediment movement (Leys, 1990; Williams *et al.*, 1995). Soils are slow to weather from parent material in arid and semi-arid regions. This process has been estimated to take 5000 to 10,000 years (Wilshire, 1983); therefore, soil loss can have long-term consequences. In addition, nearby biological soil crusts can be buried by this sediment, resulting in the death of the photosynthetic organisms (Belnap, 1995, 1996). Garcia-Pichel & Belnap (1996) have shown that in biological soil crusts more than 75% of the photosynthetic biomass, and almost all photosynthetic productivity, is from organisms in the top 3 mm of these soils. Therefore, very small soil losses can dramatically reduce site fertility and further reduce soil surface stability. In addition, many plants have relatively inflexible rooting depths and often cannot adapt to rapidly changing soil depths.

## Conclusions

This study demonstrated that soils with well-developed soil crusts can be highly resistant to wind erosion. However, all types of disturbance on the soil types tested left soil surfaces much more susceptible to wind erosion from commonly occurring wind speeds. Recovery rates varied depending on soil type.

Soil erosion in arid lands is a major threat worldwide. Beasley *et al.* (1984) estimated that 3·6 million ha of western United States rangelands experience some degree of accelerated wind erosion. Relatively undisturbed biological soil crusts can contribute a great deal of stability to these otherwise highly erodible soils. Biological soil crusts are present year round. Unlike vascular plants, their cover is not reduced in drought years. Unlike rain crusts, they do not dissolve when wet. Consequently, over time and in adverse conditions they offer stability that is often lacking in other soil surface protectors.

Ever-increasing recreational and commercial use of semi-arid and arid areas globally threaten the integrity of these crusts and may lead to significant increases in regional and global wind erosion rates. For these reasons, managers of arid and semi-arid regions need to consider the important role these crusts play in soil surface stability and reduce disturbance to these biological crusts whenever possible. Specific actions may include reduction in types and intensites of use as well as adjustments in timing of use.

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