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

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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, 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.

Contact information:

Dr. Michael Allen
mallen@ucr.edu

Dr. Cameron Barrows
cbarrows@ucr.edu

Susy Boyd
susydesert@runbox.com

Pat Flanagan
info@mbconservation.org

Robin Kobaly
robin@summertree.org

Arch McCulloch
info@mbconservation.org

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.

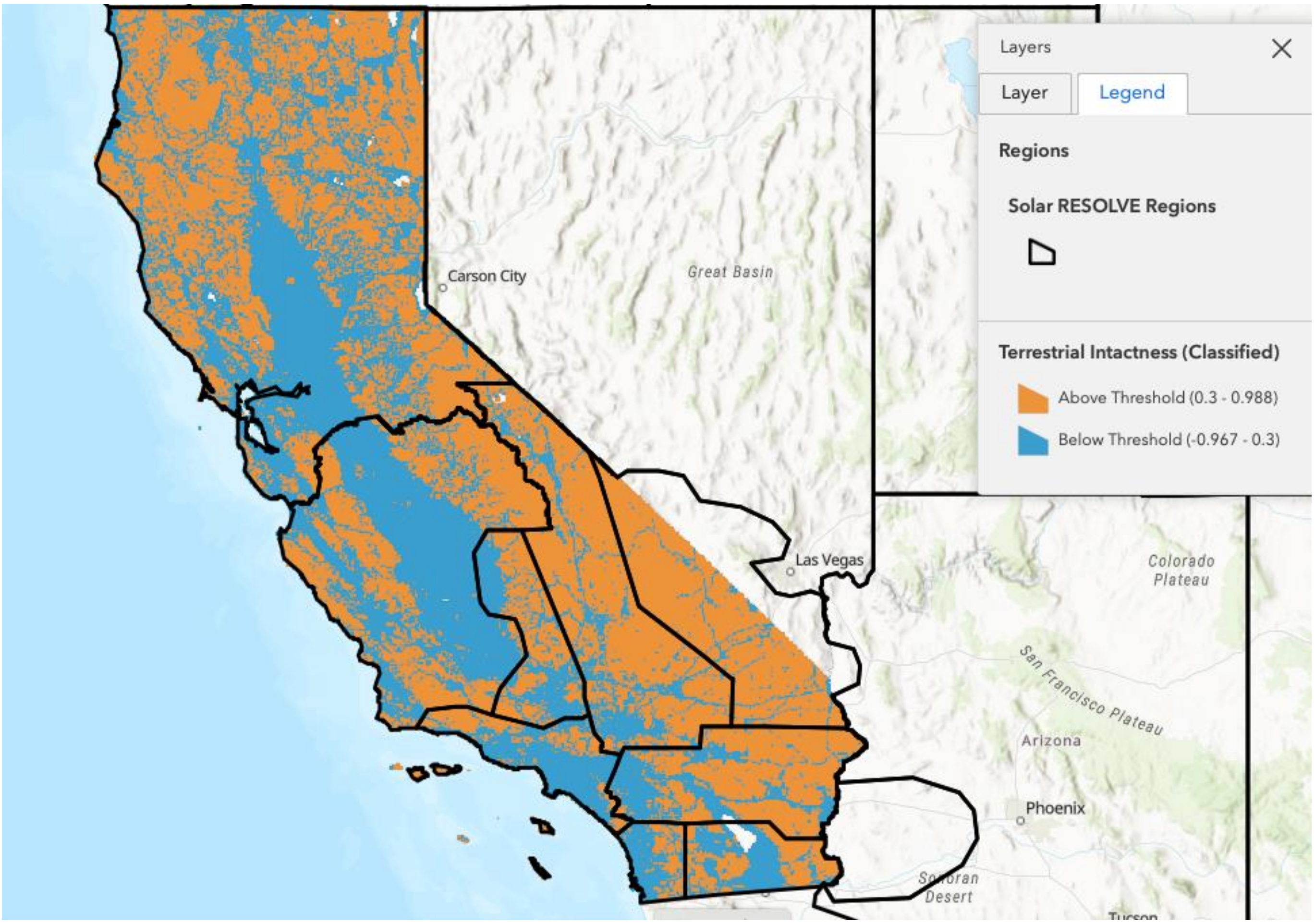
Landscape-scale disturbance falls across a continuum. A pristine desert ecosystem characterizes one end of the spectrum, and worst-case scenario characterized by loss of ecosystem function represents the other end of the spectrum (C. Barrows Ph.D., personal communication, September 14, 2023). A functioning 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.

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

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).

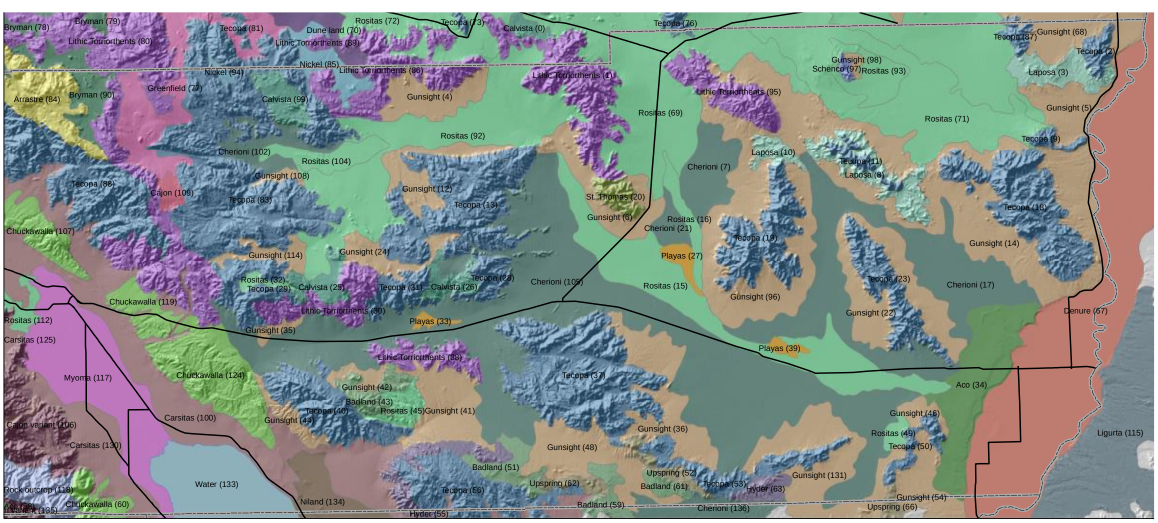
Groundwater in western deserts is notorious for being hard, that is, having high concentrations of $CaCO_3$. As it is pumped up for use, $CaCO_3$ dissociates, releasing CO_2 (Wood and Hyndman 2017). They estimated that groundwater depletion could account for a measurable fraction of annual CO_2 emission. 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

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

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 $Ca + CO_2 + H_2O <> CaCO_3$.

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

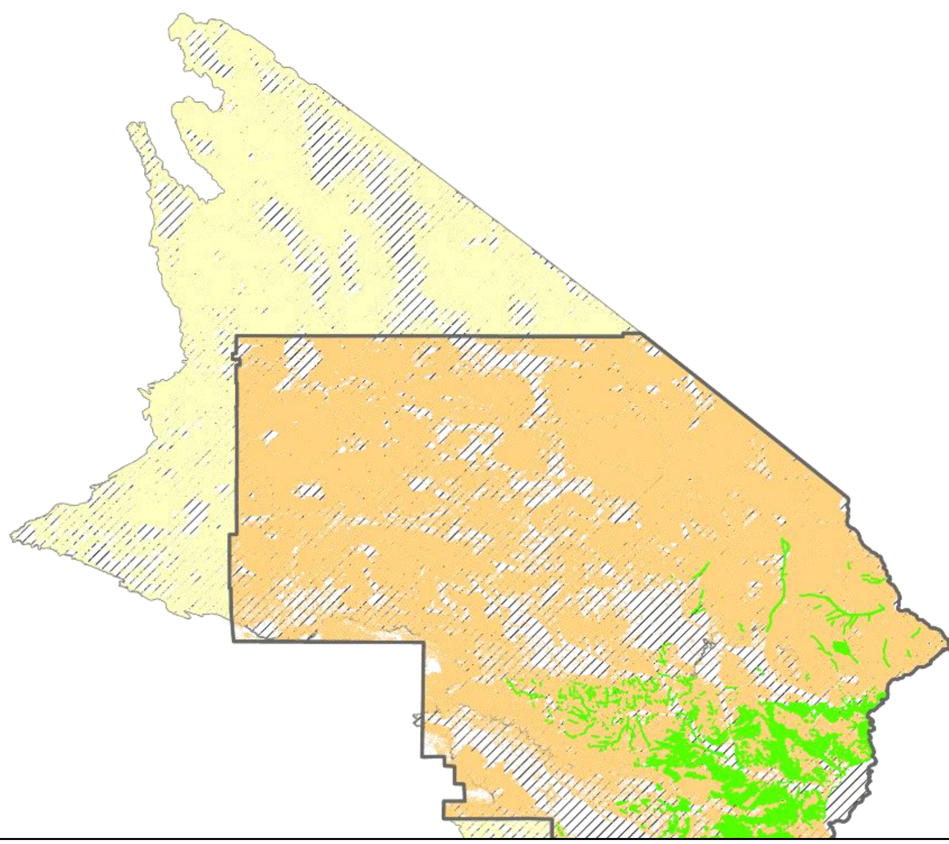
Microphyll woodlands/Creosote

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:

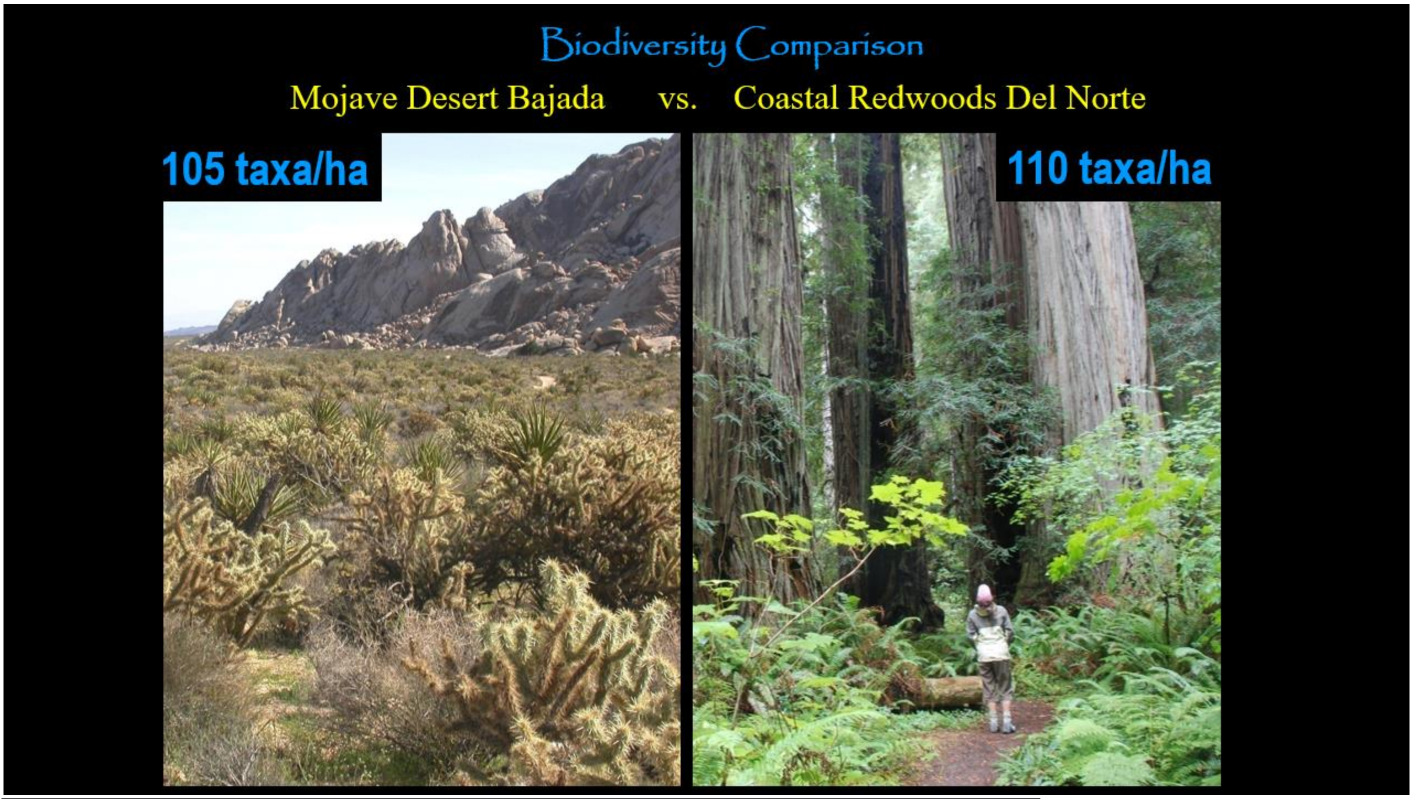
Native bee pollinators in the Joshua Tree National Park area are estimated to include more than 600 species representing 40 genera in 6 families.

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

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

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

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

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

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

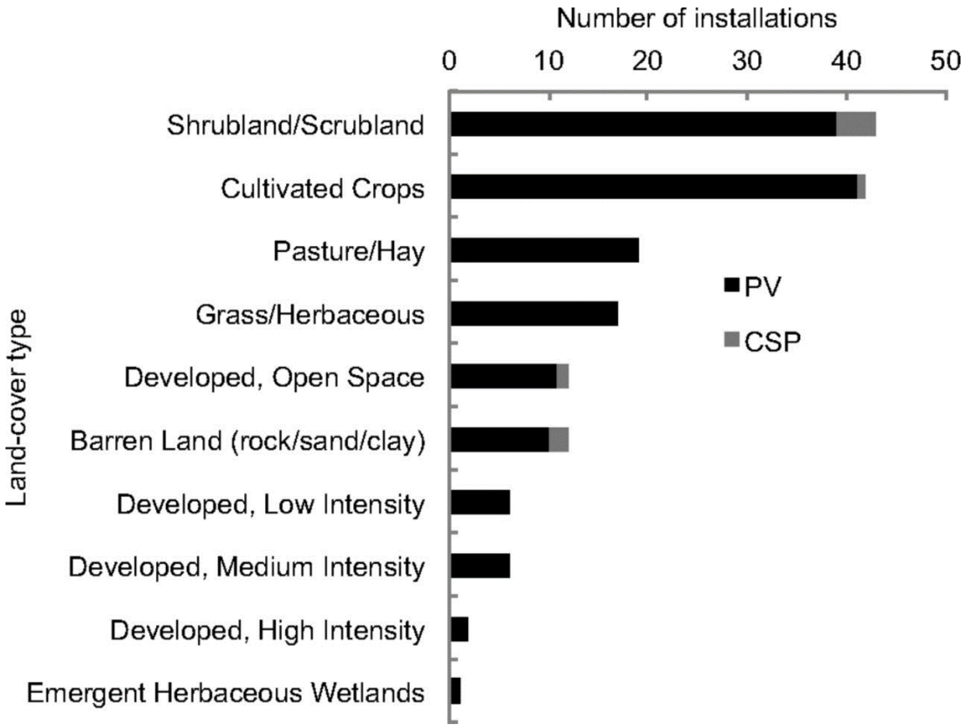
The state of California has long been recognized for its leadership in transitioning towards new, clean energy sources to reduce CO_2 atmospheric emissions. There are, however, two aspects to emissions reductions work.

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.



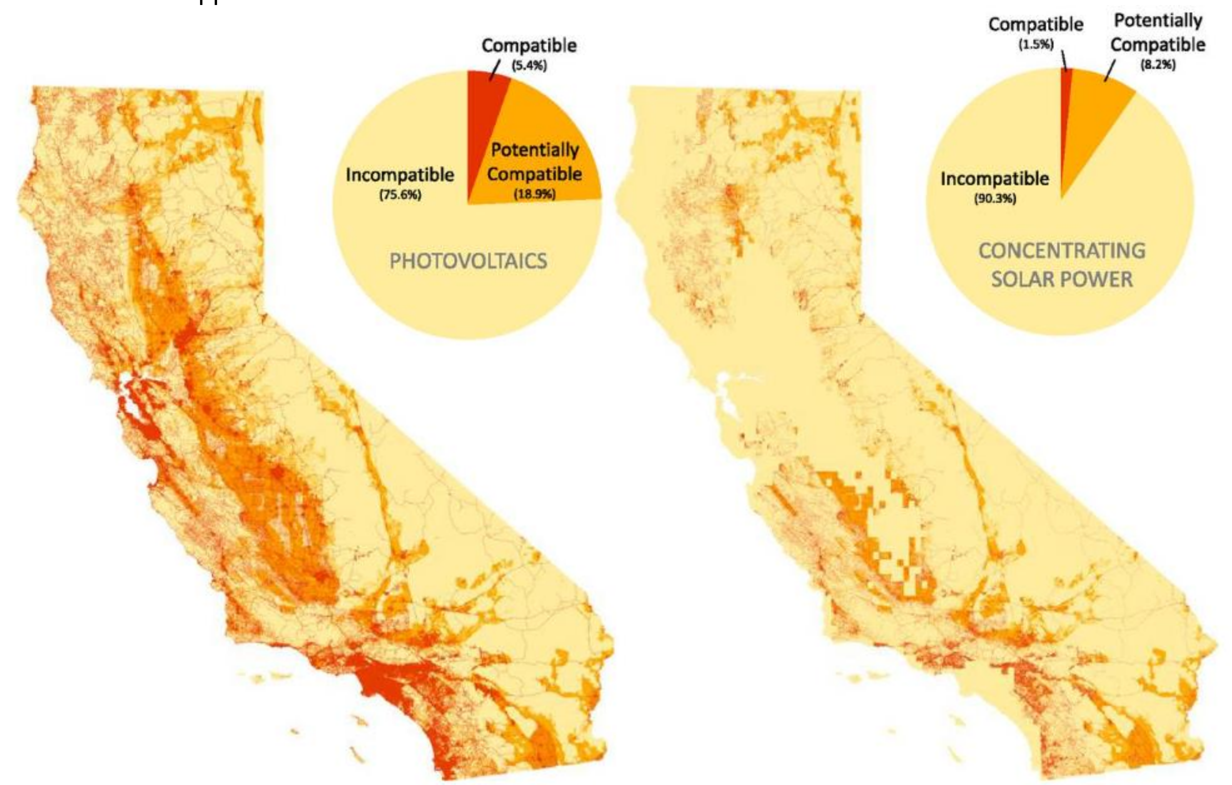
Hernandez et. al. 2015.

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.

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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.