



April 4, 2022

Matthew Botill, Branch Chief
California Air Resources Board
1001 I Street
Sacramento, California 95814

Re: Overlooking Inorganic Carbon Jeopardizes Modeling Accuracy

Dear Mr. Matthew Botill:

We thank the team at the California Air Resources Board (CARB) for presenting the 2022 Scoping Plan Update, Initial Modeling Results for Natural and Working Lands on Tuesday, March 15, 2022 and for providing space for public comments both during the workshop and in writing. Our signatories represent community members and non-profits working throughout the state on issues of desert conservation, access, and equity. This letter builds on the document provided to CARB on August 3, 2021.

We are pleased that CARB has designed a stand-alone scenario for desert carbon sequestration that does not include other landscapes. This is a step closer to providing the deserts with an appropriate designation. CARB's March 15 presentation, "Scenario 1 and Desert Carbon Stocks" slide 18, indicates that when left undisturbed, the desert ecosystem sequesters carbon at the highest level. We strongly support Scenario 1 as the preferred management scenario.

The Case for Better Analysis of Desert Organic and Inorganic Carbon

We remain concerned that the Natural and Working Lands initial modeling results do not accurately reflect the potential for carbon sequestration in terrestrial soils and inorganic carbon in the California desert. This will lead to incomplete modeling results and land management practices that allow for vegetation removal and soil disturbance in intact desert lands resulting in the loss of natural lands, carbon sequestration capabilities and the release of carbon into our atmosphere.

Both inorganic and organic carbon have similar effects on our atmosphere once they are exposed or weatherized (Swanson 2017; Allen et al. 2013). Therefore, it would be prudent to not overlook inorganic carbon – especially if it’s being dismissed simply because of a deficiency in understanding the desert ecosystem and for lack of resources to generate proper studies below ground.

It is our understanding that currently, CARB is only looking at the top 30 centimeters of topsoil to generate terrestrial carbon studies. Dismissing the deeper depths (between 30 to 100 cm) where desert carbon sequestration takes place is part of the problem. The Center for Conservation Biology notes that (see [Appendix A](#) for full document):

Globally, soils store more carbon (C) than the aboveground biosphere or the atmosphere (1,500GT versus 500GT and 720GT, respectively). Of that, 1,500GT of soil C, more than a third (500GT) of C is sequestered as inorganic calcium carbonate (CaCO₃; 500GT of C), more than is stored in all forests globally. Within that stored fraction, three pools that are ignored by CARB’s modeling are crucial for sequestering and managing C, including total soil carbon (see Carbon Cycle Institute 2022), desert soil organic C, (usually 20 to 100cm deep, the most commonly measured form of desert soil C), and inorganic carbonate C¹.

Omitting inorganic carbon from modeling leads to an underestimation of carbon stocks in the desert. We know that California deserts have been collecting inorganic carbon for millennia (Schlesinger 1985; Li et al. 2015) and that California’s hot deserts contain a large pool of inorganic carbon in the form of calcium carbonate (caliche), derived from biological processes.

Furthermore, according to a science brief from Defenders of Wildlife, Dr. Lindsay Rosa ([Appendix B](#)), California deserts hold 10% of the state's carbon sequestration capabilities.

We urge CNRA scientists to work with desert carbon sequestration experts, academics and scientists to help address this gaping hole left by the lack of desert carbon sequestration understanding.

Funding for Desert Carbon Sequestration Research

Even though there are enough scientific grounds for creating inputs for desert carbon sequestration modeling, there is still additional research yet to be initiated that could further illuminate our understanding of the complexities of carbon sequestration in below-ground soils. In collaboration with your offices, we would be happy to advocate for desert carbon sequestration research and/or investments in current or additional CNRA staff or consultants that could bring a holistic approach to understanding desert carbon sequestration.

Follow-up Questions for Clarification

We invite you to provide your thoughts or create space for a conversation with our group around the following:

1. Why are Deserts placed in a sub-category within “Sparsely Vegetated Lands”? Why not have “Deserts” be their own category – especially since there appear to be no other sub-categories within “Sparsely Vegetated Lands”?

¹ Notes on Carbon Dynamics in the California Deserts by Michael F. Allen, Ph.D., updated 2022

2. Did CARB decision makers take into account Dr. Allen's white paper entitled "Notes on Models of Carbon Dynamics for the California Deserts", provided to you in our letter dated August 3, 2021, and if so, were any of those recommendations for modeling pathways entertained? Are there any questions based on that reading?
3. In Slide #31 of your March 15, 2022 presentation, would deserts be considered under the "Non modeled landscapes" lands that provide additional opportunities for carbon sequestration? If so, can you specifically add deserts to the sample list?
4. Because the desert ecosystem sequesters carbon at the highest level when left completely undisturbed, Scenario 1, as your analysis indicates, is the preferred management scenario. This likely varies from other ecosystems presented. We weren't clear if the goal was to choose a single management scenario across all ecosystem types, or to shape management practices based on the highest carbon sequestration. Can you expand?

It is our hope to shed light on the incomplete data input in the current modeling process and to highlight the sequestration processes that work together to capture and store carbon deep in hot desert soils.

We appreciate your review of our material and welcome further conversations with you and your colleagues at CARB. The health of our planet and our communities deserve to have our carbon sinks in the desert working as they have for millennia. We thank you in advance for your consideration and all the work that this type of endeavor requires.

Best regards,

Signatories:

Andrea Williams, Director of Biodiversity Initiatives
California Native Plant Society

Brenda Gallegos, Conservation Program Associate
Hispanic Access Foundation

Chris Clarke, Ruth Hammett Associate Director, California Desert Program
National Parks Conservation Association

Daniel Barad, Senior Policy Advocate
Sierra Club California

Ellie M. Cohen, Chief Executive Officer
The Climate Center

Ileene Anderson, Senior Scientist/Public Lands Desert Director
Center for Biological Diversity

Jack Thompson, California Desert Regional Director
The Wildlands Conservancy

Jora Fogg, Policy Director
Friends of the Inyo

Kelly Herbinson and Cody Hanford, Joint Executive Directors
Mojave Desert Land Trust

Michael Allen, Ph.D., Distinguished Professor Emeritus
University of California Riverside

Dr. Rebecca R. Hernandez, Associate Professor of Ecology and Earth Systems Science
Global Ecology and Sustainability Lab | Wild Energy Initiative

Pamela Flick, California Program Director
Defenders of Wildlife

Robin Kobaly, Executive Director
The SummerTree Institute

Sendy Hernandez Orellana Barrows, Conservation Program Manager
Council of Mexican Federations in North America (COFEM)

Steve Bardwell, President
Morongo Basin Conservation Association

Susan A. Phillips, Director
Robert Redford Conservancy for Southern California Sustainability

cc: Dr. Adam Moreno, California Air Resources Board
Shelby Livingston, California Air Resources Board
Amanda Hansen, California Natural Resources Agency
Dr. Jennifer Norris, California Natural Resources Agency

APPENDIX A

Notes on Carbon Dynamics in the California Deserts

(content begins on next page)

Notes on Carbon Dynamics in the California Deserts

Prepared by Michael F. Allen, Ph.D., Distinguished Professor Emeritus,
Department of Microbiology and Plant Pathology, UC Riverside

Globally, soils store more carbon (C) than the aboveground biosphere or the atmosphere (1,500GT versus 500GT and 720GT, respectively). Of that 1,500GT of soil C, more than a third (500GT) of C is sequestered as inorganic calcium carbonate (CaCO_3 ; 500GT of C), more than is stored in all forests globally.

Within that stored fraction, three pools that are ignored by the State of California are crucial for sequestering and managing C, including:

1. Total soil carbon (see Carbon Cycle Institute 2022)
2. Deep desert soil organic C, (below usually 20 to 100cm deep, the most commonly measured form of desert soil C), and
3. Inorganic carbonate C.

The calcium carbonates that comprise this large store of C globally are intimately linked to the organic C cycle. Because inorganic C ($\text{C}_{\text{inorganic}}$) is intimately linked with biological organic C ($\text{C}_{\text{organic}}$) cycling, both during the sequestering and the weathering processes, it is inherently in disequilibrium with the surrounding ecosystem (Allen et al. 2013) (Martin et al. 2021). In our measurement of the ^{18}O composition of the surface soils across southern California deserts, upon exposure, there was a shift in the ratio indicating continuous turnover of exposed CaCO_3 .

As noted in the recent *EOS* overview of the *Carbonate Critical Zone Research Coordination Network* by Martin and colleagues (2021) on the carbonate zone,

"The rapid responses in the carbonate critical zone may provide a bellwether for wider climate change impacts on critical zone processes. Improving our understanding of the rates and timescales of processes, such as the effects of changing flood, drought, and fire frequencies, in the carbonate critical zone will provide vital information for comparison with the slower response of the silicate critical zone, where change may occur at timescales longer than common observational periods." and

"Carbonate minerals represent the largest global store of carbon, making research into carbon dynamics in the carbonate critical zone particularly important. Through numerous reactions and interactions, the inorganic carbon store is linked to organic carbon production, remineralization, and production of various natural acids. Carbonate mineral dissolution by carbonic acid consumes carbon dioxide, contributing to short-term drawing down of atmospheric carbon dioxide levels. However, carbonate mineral dissolution by other acids has the opposite effect of producing carbon dioxide coupling the carbonate critical zone and climate.

*Although equilibrium is **often assumed between soil carbon dioxide and groundwater, disequilibrium may result** (bolded for emphasis) 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."*

They continue with:

"A More Holistic View of the Critical Zone

Carbonate and silicate minerals are end-members of a spectrum of critical zone bedrock compositions, and fundamental differences in their physical and chemical properties create distinct characteristics in Earth's critical zone. Studies of these two end-members, as well as of regions of mixed mineralogical compositions, can provide a better understanding of the critical zone in its entirety.

To date, however, critical zone research has predominantly emphasized silicate landscapes, leaving us well short of such a holistic understanding. With increased focus on the neglected carbonate critical zone-particularly on the research directions and questions outlined here-we can fill important knowledge gaps about a part of Earth upon which we humans depend so closely."

Background—C dynamics in deserts.

Production of C_{organic} is generally considered low in hot desert ecosystems. However, a number of measurements of annual Net Ecosystem Exchange (NEE) (sometimes referred to as NEP if entire year is calculated) ranges up to $127\text{gC}/\text{m}^2/\text{y}$ (Jasoni et al. 2005), with a pool of 0.9 to $1.1\text{kgC}/\text{m}^2$ (Evans et al. 2014), rivaling some forests and grasslands. Net primary production (NPP) in the Mojave desert measured by harvest techniques, generally range from 10 to $30\text{gC}/\text{m}^2/\text{y}$, where belowground NPP is inferred using allometric techniques (Rundel and Gibson 1996). These values are made on several assumptions. Photosynthesis is limited by both upper and lower temperature and moisture values, whereas decomposition can remain high beyond those limits. Q_{10} values for RuBP Carboxylase is generally a bit over 2 for ten-degree increments between 10 and 40°C . Above 30°C , rates of photosynthesis decline. In deserts, however, soil respiration rates indicative of enzymatic activity can remain high up to 60 to 70°C (Cable et al. 2008). For this reason, C in desert ecosystems has been overlooked and even disregarded as an important element in global and regional models. But the dynamics of desert ecosystems are poorly understood, and remarkably complex. For example, creosote bush (*Larrea tridentata*) modifies its cold temperature activity through localized greenhouse gas production (Hayden 1998), and punctures cracks in the caliche layers in search of deep water that can extend photosynthetic activity beyond that predicted by precipitation inputs. Microphyll woodlands grow roots tens of meters deep to access groundwater, and funnel organic C through roots and microbial associations to those depths (Allen 2022).

There are numerous reports of high rates of net ecosystem exchange of C in deserts in both China (Xie et al. 2009) and the US (Wohlfahrt et al. 2008). Although these values have been criticized as being unreasonably high (Schlesinger et al. 2009) (Schlesinger and Amundson 2019), no one has provided an alternative explanation for the measured values. While scientists continue to study the patterns and mechanisms of C_{organic} , especially for C pushed deep belowground, we also know that California deserts have been accumulating $C_{\text{inorganic}}$ for millennia; both Schlesinger (1985) and Li et al. (2015) found a large deep sink of C formed under oases in the Tarim desert in China that has been accumulating over millennia. These large pools of stored C have the potential to be lost through anthropogenic disturbance and weathering.

Below I outline the mechanisms of C dynamics in desert ecosystems with a focus on the Colorado and Mojave ecosystems.

What is Caliche and Why is it Important?

Caliche is a layer of calcium carbonate (CaCO_3) formed beneath the soil surface and accumulating at the depth to which water percolates, depositing calcium (Ca). CO_2 from the atmosphere and from respiring roots and microorganisms, dissolves in water, forming bicarbonates ($-\text{HCO}_3^-$) and hydrogen ions (H^+). Combining with free Ca, the equilibrium reaction preferentially results in CaCO_3 . As soils dry, the concentration of CaCO_3 increases and CaCO_3 crystals precipitate; until the next precipitation event, when CaCO_3 redissolves, the reaction reoccurs and the dissolved CaCO_3 percolates in solution deeper to depth of leaching, re-precipitating. Upon disturbance and vegetation removal, CaCO_3 is exposed. Both laboratory (Swanson 2017) and field (Allen et al. 2013) data show that some of the $C_{\text{inorganic}}$ as CO_2 is released. Irradiation (Laanait et al. 2015) also can facilitate CaCO_3 weathering. When holes in caliche layers are observed, it is an indicator of the weathering. Ca can be wind-eroded (Frie et al. 2019) or moved vertically upon dissolving, or eroded downstream with precipitation events. The dissolving, precipitating, weathering, and erosion of Ca are continuous processes. Yet, despite the comparatively low productivity, the biota largely regulate nutrient cycling. In part, this regulation occurs through the actions of "islands of fertility" (Schlesinger and Berghardt 2013). But importantly, with disturbance, the "islands of fertility" break down biologically and chemically (Allen and MacMahon 1985). Disturbance and erosion shift localized equilibrium processing.

Caliche forms in bajadas below mountains comprised of high concentrations of Ca, in basalts (mineral CaO), silicates (CaSiO_3) and limestone CaCO_3 formed under the oceans and pushed up geologically, along with its derivatives, dolomite (with added Mg) and marble, limestone's metamorphic derivative. Weathering of well-known mountain ranges, including the Alps and the Himalayas, yields Ca. In semi-arid to arid regions with high Ca substrates, deep layering of CaCO_3 develops. Examples include most of Mediterranean Europe, and the deserts of the southwestern US and northwestern Mexico. Although $C_{\text{inorganic}}$, sequestered in arid to semiarid soils that

may be high, is not considered in global models; creating a large "missing sink of C" somewhere in terrestrial ecosystems.

Despite the large amount of CaCO_3 sequestered over millennia, three assumptions contribute to a view among decision-makers that this C can be ignored in the quest to understand C fluxes between the biosphere and the atmosphere. These are three dogmas that pose serious limitations to global carbon modeling and are contributing to the large gaps remaining in closing the global C models of atmosphere-biosphere-geosphere interactions. These are: (1) CaCO_3 is patchily distributed and not easily mapped, but easily ignored; (2) that because the dominant form is inorganic (CaCO_3), it is a geological and not a biological process, and therefore, no accounting need be undertaken using ecosystem models; and, (3) the assumption that because the rates of transformations and loss are on a geological time scale $C_{\text{inorganic}}$ dynamics are not relevant to global change models.

Further, three recent statements in the Mills et al. (2020) CEC report regarding the disturbance of desert lands has led to the assessment by some state offices, including the California Air Resources Board, that disturbance in the desert is acceptable for an assumed reduction of state-wide carbon budgets:

1) "The current expansion of large-scale solar in the western Mojave Desert is on abandoned agricultural land." *A cursory examination of Google images (below) clearly shows that the large solar arrays span desert bajadas across native vegetation and are not confined to former agricultural lands in both the Mojave and Colorado deserts.*

2) "The large differences in ^{18}O between the control and the [solar] panel locations suggest that calcium carbonate is quite dynamic on short time intervals. While there is evidence in intensively managed soils (irrigated) that carbonate dynamics can be observed on short time spans, ... evidence of the dynamics in more natural settings *is limited.*" (*italics mine*). *This is cited as a justification for a lack of action, when in fact, this should justify the need for more research.*

3) "*this process [carbonate dissolution and reprecipitation] has no effect on the overall soil carbon balance, since the net result of dissolution and reprecipitation (even if at a different depth) is zero.*" This may be contradicted by the Martin et al (2021) assessment of the scale and importance of carbonate-C dynamics.

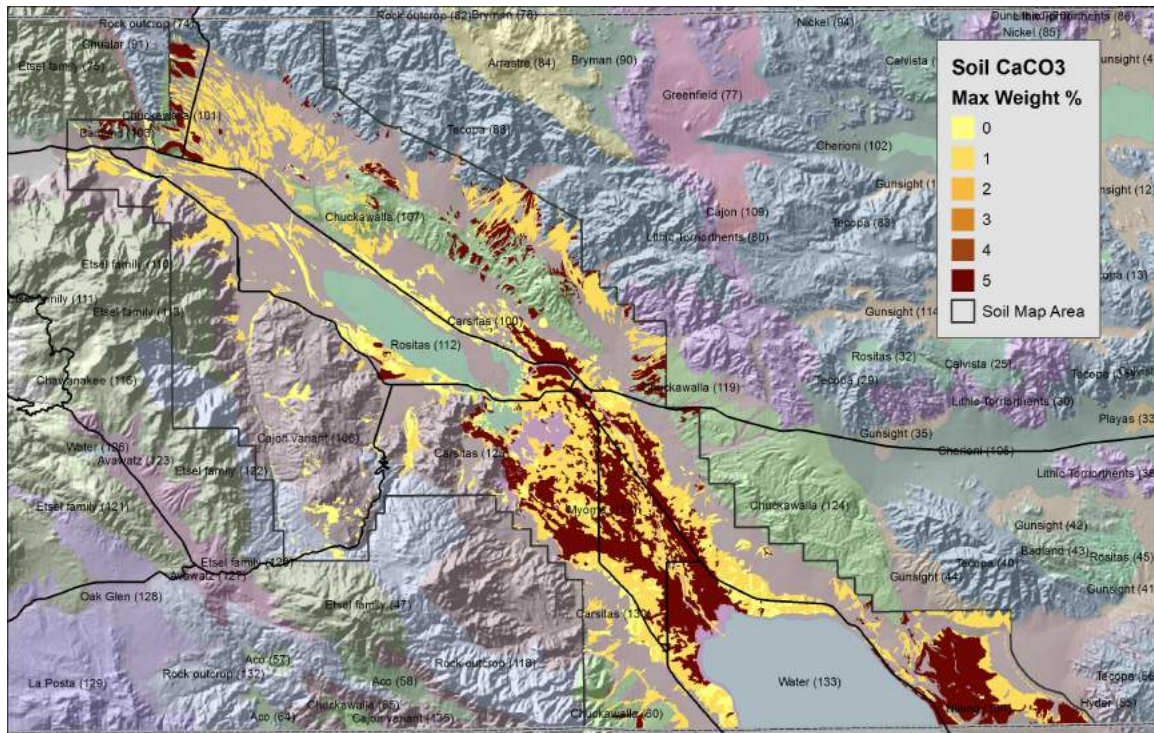
All three statements misrepresent what we know (and what we don't know) about carbonates and disturbance in California's deserts. Given that approximately 40% of the increase in atmospheric CO_2 driving global climate change is due to land use change (compared with 60% from fossil fuel burning), it is critical to understand the nature of the largest single terrestrial C pool, especially since much of it is in desert ecosystems.



Solar development in the Mojave Desert. Left was taken during construction, cutting through desert bajadas (photo from M. Allen); the two at right are subsequent overviews, where surface was exposed and graded, only to be invaded by the exotic grass *Schismus* spp (photo from Rebecca R. Hernandez with permission).

1) How much and where is Carbon in California deserts?

C_{inorganic}. Surface soil CaCO₃ is distributed widely, but in patches across the desert. In the surface layers, we can see for example, large swaths in the southern California (SoCal) deserts, where as much as 5% or more of the *surface* soil is CaCO₃ (Fig 1).



SSURGO Soil Data for Coachella Valley
(STATSGO shown in surrounding areas)

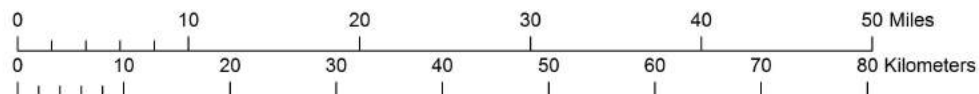


Figure 1. USDA NRS high resolution SSURGO map for surface soil CaCO_3 , adding the STATSGO data for areas surrounding the Coachella Valley, information from (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/office/ssr12/tr/?cid=nrcs142p2_010596). Map created by the Center for Conservation Biology, UCR.

(Schlesinger 1985) found that at depths of greater than a meter in the Chuckwalla Valley, as much as 12% of the soil was CaCO_3 , or between 4 and 8.4kg C/m², or as much C as is stored in mixed grass prairie as soil organic C.

Other $\text{C}_{\text{inorganic}}$ forms may also be critical in desert ecosystems. (Garvie 2006) reported an accumulation of 2.4g $\text{C}_{\text{inorganic}}$ /m²/y under saguaro cactus, as much as 40g $\text{C}_{\text{inorganic}}$ /m², through the production and accumulation of oxalic acid. The importance of oxalic acid rests not only as another form of C for sequestration, nor in its role in P (phosphorus) nutrition of plants (Jurinak et al. 1986), but also in an ability to lead to CaCO_3 accumulation (Rowley et al. 2017).

It is important to get a better handle on the C distributions and exchanges of both organic and biologically-derived inorganic forms. ***Clearly more extensive surveys and analyses of desert C are needed to know how much more is actually sequestered.***

2) What are the appropriate time scales to model C? Because the dominant form of C in the desert is inorganic (CaCO_3), should we ignore this sequestered carbon because its formation is presumed to be a long-term geological and not a short-term biological process? In essence, what is the time scale (see Martin et al. 2021)?

Bioweathering by fungi and lichens, and even by many plants, commonly occurs initially in the California desert mountains, resulting in a source of Ca downslope to the bajadas. The biogeochemical pathways provide for a continuous dance between Ca and atmospheric CO_2 across the landscape from the mountain tops to the desert floor, where C is biotically converted to a form, CaCO_3 , that can be sequestered. However, this form also can be rapidly weathered upon exposure.

The BioGeoChemical Pathways for Biologically-derived Inorganic C.

- 1) CO_2 (atmospheric) \rightarrow $\text{C}_6\text{H}_{12}\text{O}_6$ (photosynthesis): plants such as cacti, lichen algae, cyanobacteria,
- 2) $\text{C}_6\text{H}_{12}\text{O}_6 + \text{O}_2 \rightarrow \text{H}_2\text{C}_2\text{O}_4$ (bioweathering to oxalic acid): lichen fungi, plants, mycorrhizal fungi
- 3) $\text{Ca} + \text{H}_2\text{C}_2\text{O}_4 \rightarrow \text{CaC}_2\text{O}_4$ (calcium oxalate production): desert crusts, rhizosphere, mycorrhizosphere
- 4) $\text{CaC}_2\text{O}_4 \rightarrow \text{Ca} + \text{CO}_2$ (degradation and CO_2 release): bacteria, fungal exoenzymes

With rainfall, Ca binds with local CO_2 and H_2O forming CaCO_3 , plus hydrogen ions. Equilibrium models indicate that the reaction will move to CaCO_3 , but disequilibrium processes are common and should be accounted for (Martin et al. 2021).

5) $\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{HCO}_3^-$ (bicarbonate formation): root and microbial respired CO_2

6) $\text{Ca} + \text{HCO}_3^-$ (in solution) $\leftrightarrow \text{CaCO}_3 + \text{H}^+$

As the soils dry, the CaCO_3 precipitates, and upon layering, creates a caliche layer, often using fungal hyphae as a precipitation nucleus (Allen et al. 2014a).

7) If exposed, with rainfall, some fraction of the $\text{CaCO}_3 + \text{H}^+ + \text{O}_2 \leftrightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{Ca}$, where CO_2 diffuses into the soil atmosphere. The Ca diffuses deeper in the soil layer, where it re-precipitates with the higher soil CO_2 pressure from root and microbial respiration as $\text{CaCO}_3 + \text{H}^+$

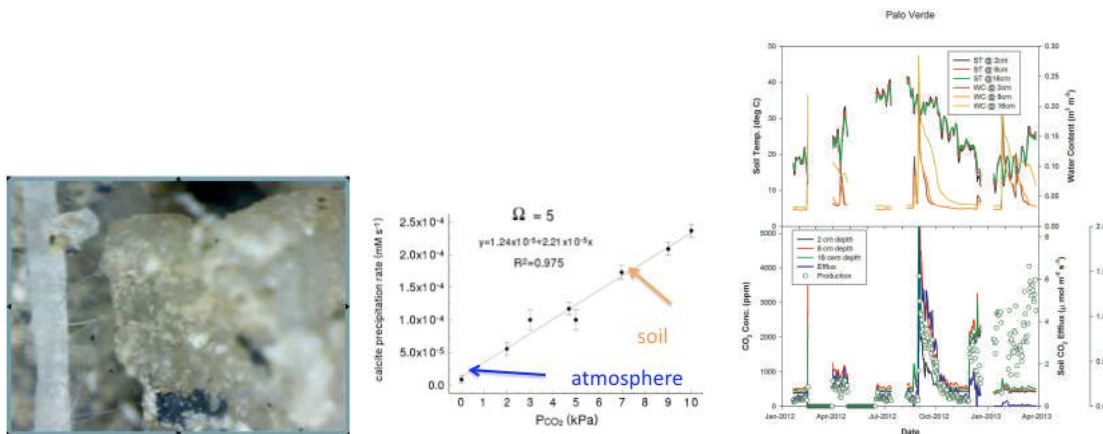


Figure 2. Left, automated minirhizotron image of the formation of CaCO_3 crystals along fungal hyphae and soil particle surfaces with soil drying (Allen et al. 2014a). Middle, calcite (the crystal form of CaCO_3) precipitation rate under low dissolved organic carbon conditions, showing atmospheric CO_2 levels and soil atmosphere CO_2 levels (LeBrón and Suárez 1998). Right, soil atmosphere conditions at Boyd Deep Canyon NRS showing the high soil atmosphere CO_2 following a precipitation event (Allen et al. 2013).

Description of Steps: It is important to remember that equilibrium does not equal stasis. Each time CaCO_3 goes into solution, some of the CaCO_3 dissolves into $\text{Ca} + \text{CO}_2 + \text{H}^+$, with a potential for CO_2 to be released back to the atmosphere. This is the disequilibrium mechanism whereby Ca moves from the mountains to the bajada, and then deeper into the bajada soils, just as it does in other ecosystems (Rowley et al. 2017).

1) CO_2 (atmospheric) $\rightarrow \text{C}_6\text{H}_{12}\text{O}_6$, or $\text{C}_{\text{organic}}$ (photosynthesis): plants, lichen algae, cyanobacteria

Photosynthesis and primary production is well understood, and I will not further elaborate. However, it is important to note that photosynthesis is carried on from the tops of desert mountains to the desert floors in plants and desert crusts. These

sources of organic C inputs should never be ignored, even if their rates are lower than in other ecosystems.

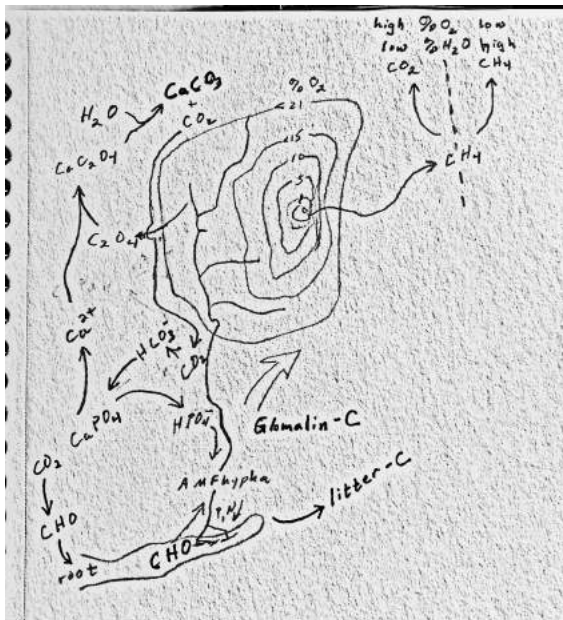
2) $C_6H_{12}O_6 + O_2 \rightarrow H_2C_2O_4$ (bioweathering): lichen fungi, plants, mycorrhizal fungi
Fungi and bacteria produce oxalic acid, among other acids including citric acid and carbonic acid. These acids, especially oxalic acid, in particular, allow the fungi of lichens and the mycorrhizal fungi of plants to acquire P from etched rock surfaces (Gadd et al. 2014).

3) $Ca + H_2C_2O_4 \rightarrow CaC_2O_4$ (calcium oxalate production): desert crusts, rhizosphere, mycorrhizosphere

Once arriving at the bajada, oxalic acid is also produced by a wide variety of organisms. Cacti produce high concentrations of oxalic acid (Franceschi and Nakata 2005). Many of the fungi in desert crust lichens, as well as other biotic crusts organisms produce acids. Ectomycorrhizal fungi, such as those associated with oaks and pines, produce these acids (e.g., Allen et al. 1996); additionally, arbuscular mycorrhizal fungi that colonize a majority of desert perennial plants, form Ca-oxalates when combined with CO_2 respired within the mycorrhizosphere, as a mechanism to obtain limiting P (Jurinak et al. 1986; Knight et al. 1989).

4) $CaC_2O_4 \rightarrow Ca + CO_2$ (C source, degradation): bacteria, fungal exoenzymes

Once Ca-oxalate is formed, like any organic material, both fungi and bacteria use it as a carbon source (Morris and Allen 1994) (Gadd et al. 2014).



5) $CO_2 + H_2O \rightarrow HCO_3^-$ (bicarbonate): root and microbial respired CO_2

Once rainwater or groundwater reaches the location where respiration occurs, whether from roots or microbes, bicarbonate is formed. This can be in the surface, or tens of meters deep. It is important to note that while atmospheric CO_2 is increasing (from 310ppm in 1950 to nearly 410ppm today), soil CO_2 can be many thousands of ppm, and we have measured over 2,500ppm in soils at the Boyd Deep Canyon Reserve (Figure 2).

Figure 3. Soil Carbon sequestration pathway including oxalotrophy, $C_{inorganic}$, and glomalin formation, $C_{organic}$, drawn from (Allen 1991) (Allen 2022) and (Rowley et al. 2017). This can occur up to tens of meters deep.

6) $\text{Ca} + \text{HCO}_3^-$ (in solution) $\leftrightarrow \text{CaCO}_3 + \text{H}^+$

A critical step in Carbon Sequestration?

Rowley and colleagues (2017) showed that the Ca-oxalate pathway concentrates Ca temporally and spatially, where C is sequestered through oxalotrophy through free Ca coupled with high concentrations of HCO_3^- , forming CaCO_3 (Figure 3).

Time Scales:

In our efforts to better understand the time scales of C dynamics, we undertook two types of studies. First, we analyzed the $\delta^{18}\text{O}$ signals of caliche across the Coachella Valley. These values showed that caliche was dynamic (Allen et al. 2013). This conclusion was supported by a subsequent study in the Mojave desert (Mills et al. 2020). The source of Ca was from wind erosion at a high rate in sites around the Salton Sea, between 330 and 600mg/m²/y (Frie et al. 2019).

At Deep Canyon and the Coachella Valley Agricultural Research Station, researchers re-ran the SLIC model (see model discussion below) using empirical CO₂ sensor data to determine the CaCO_3 in solution (Allen et al. 2013, (Swanson 2017)). Importantly, soil CO₂ can reach as high as 2,500ppm, as compared with atmospheric CO₂ of 395ppm (during those measurements), as soil respiration increased following precipitation events. CaCO_3 in solution tracked the CO₂ and H₂O. As soils dried out, some of the CaCO_3 in solution again precipitated forming new caliche deeper in the profile. However, eddy covariance measurements show a large CO₂ flux from both undisturbed soils and from severely disturbed sites with no measureable organic C (Allen et al. 2013, Swanson 2017).

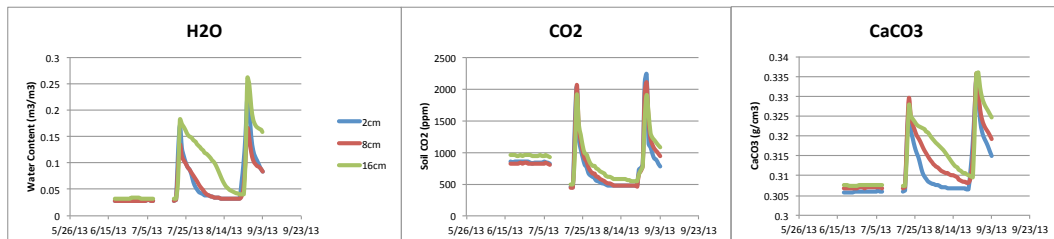


Figure 4. Daily time scales of soil water, CO₂ and modeled solution CaCO₃ (SLIC model) following a precipitation event at Boyd Deep Canyon in July through September of 2013 (Allen et al. 2013, Swanson 2017).

7) If exposed, with rainfall, $\text{CaCO}_3 + 2\text{H}^+ \leftrightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{Ca}$

$\delta^{18}\text{O}$ ratios show that in surface soils, CaCO_3 continually turns over (Allen et al. 2013, confirmed by Mills et al. 2020). There is considerable wind erosion of Ca across the deserts (Frie et al. 2019). This includes an estimated 330mg/m²/y in the relatively undisturbed desert shrubland/palm to 600mg/m²/y south of the Salton Sea. How much Ca comes from CaCO_3 and then is re-fixed we do not know - a disequilibrium that remains unknown and behooves further study.

8) $\text{Ca} + \text{HPO}_4^- \rightarrow \text{CaPO}_4$ (bound inorganic calcium phosphates) or if in the presence of sulfates, forming gypsum.

Although equilibrium kinetics denotes that most Ca tends to bind to $-\text{CO}_3$, in solution, it is a dynamic equilibrium. Some of the Ca also binds to phosphate forming calcium phosphates, or sulphate forming gypsum. This Ca could reform CaCO_3 , but could also erode in solution downstream, or blow in the wind (Frie et al. 2019).

(3) What we are missing is an overall synthesis of the rates of CO_2 exchange across the California deserts, both from landscape models, and from local validation measurements. These are crucial for a broad overview of C fluxes in the desert.

The Biogeochemical and Carbon Models. An assumption has been made in modeling C for California landscapes, that the rates of transformations in deserts are on a geological time scale and not relevant to global change models. As noted, I do not accept this assumption. Below are some of the models that should be tested:

DayCENT: (Parton et al. 1998). The Century model was designed to estimate long-term soil C accumulation. DayCENT is a version of Century using a daily time-step to better understand short-term C dynamics. It is the most sophisticated model available appropriate to generate long-term understanding of soil C.

(Rao et al. 2010) used DayCENT for studying the impacts of nitrogen (N) deposition on Net Primary Production (NPP) in deserts, mostly as related to fire. But there is one distinct limitation to the current generation of DayCENT models: the ability to access groundwater. During a year dominated by native forbs, simulated production was $20\text{-}40\text{g C/m}^2$, but measured production was $60\text{-}80\text{gC/m}^2$.

Using DayCENT, it was found that in Joshua Tree National Park the accumulated SOM-C ranged from 668 to 916g/m^2 , depending on N deposition. This compares with measurements ranging up to $2,000\text{g/m}^2$ (United States Department of Agriculture 2013).

Much of these production differences were probably due to accessing of deep-water sources. Furthermore, using DayCENT, we do not know inorganic C, the largest pool of C in California deserts.

But there are limitations that require a better incorporation of concepts described below and the data and model inputs specific to California's deserts. Both Rao and Mills have described limitations of DayCENT, and these modifications should be undertaken for CA deserts.

Regional expertise for DayCENT- Leela Rao CARB, G. Darrel Jenerette UCR

Limits to DayCENT 1: Deep dynamics.

The primary concern in this model was the inability to incorporate deep roots into organic C accumulation thereby missing a large pool. Many shrubs in the microphyll woodlands have deep roots and microbial associations (Virginia et al. 1986). Roots reaching deep and into groundwater allow the plant to continue growing and fixing carbon well into the dry periods (Ogle et al. 2004). For example, creosote bush sends horizontal roots through the shallow upland soils to find cracks in caliche. Then they dive deep, obtaining a large fraction of their water from within and below caliche layers (Ogle et al. 2004). In our estimates of deep-water use (Allen unpublished data), as much as 60 to 90% of the plant water in microphyll woodland plants came from the deep groundwater. Roots and their associated mycorrhizal fungi form a mycorrhizosphere down to groundwater (Allen 2022). Roots and fungi slough off complex carbohydrates and the mycorrhizal fungi produce glomalins, glycoproteins that form a large fraction of the stable organic matter. The mycorrhizosphere leaves this deeply buried C_{organic} . But of even greater importance, in the process of growing to water, the plant, fungal, and microbial components of the mycorrhizosphere respire CO_2 , which when dissolved in the groundwater, along with Ca, produces $CaCO_3$, again linking the organic and inorganic C cycles.

How important is deep water to biotic activity? In a California conifer-hardwood forest, we initially used DayCENT to characterize NPP (Allen et al. 2014). We also measured EvapoTranspiration and NEE using eddy-flux measurements and our sapflow measurements of water transport. DayCENT failed to identify the extended summer water flux because it did not have a mechanism to acquire deep water (Figure 5).

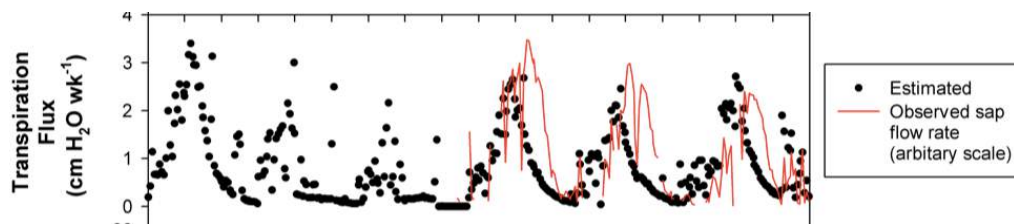


Figure 5. Kitajima and Allen-output from a model run from 2005-2010, from (Allen et al. 2014b), showing the comparison in Transpiration flux measurements with DayCENT modeling (dots) versus measured sapflow rates (red line). The lag in transpiration (which affects CO_2 fluxes) does not show in DayCENT as there is no provision for access to deep-water sources. As long as there is transpiration, there is fixation.

**Regional Expertise Eddy Covariance calibration measuring NEE: Ray Anderson
USDA Salinity Lab (UCR campus), G. Darrel Jenerette UCR**

HYDRUS: (Šimůnek et al. 2005). We shifted to HYDRUS 1D to study seasonal water flux and the role of deep water. Again, we compared modeled output to eddy covariance flux measurements and measured isotopic composition (δD and $\delta^{18}O$)

confirming the sources of the water (Kitajima et al. 2013). We modified the HYDRUS 1D to acquire the deep moisture. By making these changes in the model, we could account for the added growing season length and summer water use (Suarez and Šimůnek 1993). Given that the water isotopic composition of many desert species shows that a large fraction to the majority of the plant's water was from groundwater, making these adjustments was critical to overall C budgets, and will be critical for any estimates of C fluxes in desert soils.

Regional expertise for HYDRUS: Jirka Šimůnek - UCR Environmental Sciences (author of Hydrus), Tom Harmon UC Merced.

Limits to DayCENT 2: Inorganic C

The inorganic C ($C_{inorganic}$) in California deserts is very patchy, but can be quite high. Schlesinger (1985) undertook landmark studies in the alluvial plain outwash from the Eagle Mountains and the Coxcomb Mountains. He measured between 30 and 70 kg of $CaCO_3/m^2$, or between 4 to 8.4 kgC/ m^2 of $C_{inorganic}$. This would place the desert soil C content in the range of C in the middle of the C-rich Great Plains and temperate forest soils.

The problem is that caliche is distributed in patches across the deserts, and larger regional measurements do not exist. Thus, there is a need to better determine where and how much caliche is present across the SoCal deserts (see above discussion).

Inorganic C: Two models that should be used:

HYDRUS 1D

The first step in understanding inorganic C is to determine the equilibrium between pore water gas and water. Here, rather than assuming the input values, we used sensor readings of temperature, water and CO_2 (Allen et al. 2007). Henry's law states that $[CO_2(aq)] = KHPCO_2$, where the partial pressure of CO_2 (PCO_2) reading is the sensor output converted to atmospheres. The second step is to determine local soil pH. That can be measured directly or determined from the CO_2 dissolved in water ($CO_2(aq)$) where: $pH = 3.9 - 0.5 \log P_{CO_2}$.

Using pH and carbonate equilibrium, the other species can be determined, where $DIC_{total} = [H_2CO_3^*] + [HCO_3^-] + [CO_3^{2-}]$

Using these sensor data as input data to HYDRUS 1D, the HCO_3^- input and output from a known soil layer can readily be modeled (Thomas Harmon and Michael Allen, unpublished data).

Once the bicarbonate (HCO_3^-) and soil water is known, the soil $C_{inorganic}$ can be determined and converted to the form of caliche ($CaCO_3$) in a known soil layer using the SLIC model (Hirmas et al. 2010).

expertise: Thomas Harmon, UC Merced; Jirka Simunik, UC Riverside.

Soil Landscape Inorganic Carbon model (SLIC): (Hirmas et al. 2010). The SLIC model simulates soil $C_{\text{inorganic}}$ across the landscape. The strength is that the model simulates the exchanges between carbonate HCO_3^- and CaCO_3 , caliche. Caliche exists in a solid form when dry. Following water inputs, some of the CaCO_3 dissolves into Ca^{2+} , plus CO_2 plus protons. Depending upon the CO_2 concentration (using atmospheric CO_2), plus free Ca, CaCO_3 then reforms, the concentration of which depends on the equilibrium chemistry. The fact that dissolution occurs then CaCO_3 reforms means that as soil dries out, solid caliche is formed, deeper in the soil profile. As new Ca arrives from erosion, new CaCO_3 can form in the soil surface layers. Isotopic data using $\delta^{18}\text{O}$, show that there is a continual turnover of the surface layers of CaCO_3 when exposed (Allen et al. 2013, confirmed by Mills et al. 2020).

However, a critical missing element is that the SLIC model, as originally developed, is a chemical model only, building upon the atmosphere ($\sim 400\text{ppm}$), and does not integrate biological soil respiration, which isotopic ratios have suggested are the source for deep caliche (Schlesinger 1985). $\delta^{18}\text{O}$ ratios of surface caliche materials clearly demonstrate continuous turnover in the surface layers, with the potential for loss. Those values, even at 16cm depth, can exceed 2,500ppm (Figure 2, 4, 5).

Regional expertise: Daniel Hirmas, Environmental Sciences, UCR

Together these models coupled with empirical data, particularly for soil CO_2 and the current 3D spatial distributions of Ca, CO_2 , and CaCO_3 , should provide for a solid simulation of desert C and the impacts of anthropogenic and climate stressors on sequestration and fluxes.

References.

- Allen, M. F. 1991. The ecology of mycorrhizae. Cambridge University Press, Cambridge UK.
- Allen, M. F. 2022. Mycorrhizal Dynamics in Ecological Systems. Cambridge University Press, Cambridge.
- Allen, M. F., C. W. Barrows, M. D. Bell, G. D. Jenerette, R. F. Johnson, and E. B. Allen. 2014a. Threats to California's desert ecosystems. *Fremontia* **42**:3-8.
- Allen, M. F., C. Figueroa, B. S. Weinbaum, S. B. Barlow, and E. B. Allen. 1996. Differential production of oxalate by mycorrhizal fungi in arid ecosystems. *Biology and Fertility of Soils* **22**:287-292.
- Allen, M. F., G. D. Jenerette, and L. S. Santiago. 2013. Carbon balance in California Deserts: Impacts of widespread solar power generation., California Energy Commission Publication Number CEC-500-2013-063.
- Allen, M. F., K. Kitajima, and R. R. Hernandez. 2014b. Mycorrhizae and Global Change. Pages 37-59 in M. Tausz and N. Grulke, editors. *Trees in a Changing Environment: Ecophysiology, Adaptation, and Future Survival*.
- Allen, M. F., and J. A. MacMahon. 1985. Impact of disturbance on cold desert fungi-comparative microscale dispersion patterns. *Pedobiologia* **28**:215-224.

- Allen, M. F., R. Vargas, E. A. Graham, W. Swenson, M. Hamilton, M. Taggart, T. C. Harmon, A. Rat'ko, P. Rundel, B. Fulkerson, and D. Estrin. 2007. Soil sensor technology: Life within a pixel. *Bioscience* **57**:859-867.
- Cable, J. M., K. Ogle, D. G. Williams, J. F. Weltzin, and T. E. Huxman. 2008. Soil texture drives responses of soil respiration to precipitation pulses in the Sonoran Desert: Implications for climate change. *Ecosystems* **11**:961-979.
- CarbonCycleInstitute. 2022. CCI Comment on CARB NWL Modeling Scenarios SPU.
- Evans, R. D., A. Koyama, D. L. Sonderegger, T. N. Charlet, B. A. Newingham, L. F. Fenstermaker, B. Harlow, V. L. Jin, K. Ogle, S. D. Smith, and R. S. Nowak. 2014. Greater ecosystem carbon in the Mojave Desert after ten years exposure to elevated CO₂. *Nature Climate Change* **4**:394-397.
- Franceschi, V. R., and P. A. Nakata. 2005. Calcium oxalate in plants: Formation and function. *Annual Review of Plant Biology* **56**:41-71.
- Frie, A. L., A. C. Garrison, M. V. Schaefer, S. M. Bates, J. Botthoff, M. Maltz, S. C. Ying, T. Lyons, M. F. Allen, E. Aronson, and R. Bahreini. 2019. Dust Sources in the Salton Sea Basin: A Clear Case of an Anthropogenically Impacted Dust Budget. *Environmental Science & Technology* **53**:9378-9388.
- Gadd, G. M., J. Bahri-Esfahani, Q. Li, Y. J. Rhee, Z. Wei, M. Fomina, and X. Liang. 2014. Oxalate production by fungi: significance in geomycology, biodeterioration and bioremediation. *Fungal Biology Reviews* **28**:36-55.
- Garvie, L. A. J. 2006. Decay of cacti and carbon cycling. *Naturwissenschaften* **93**:114-118.
- Hayden, B. P. 1998. Ecosystem feedbacks on climate at the landscape scale. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* **353**:5-18.
- Hirmas, D. R., C. Amrhein, and R. C. Graham. 2010. Spatial and process-based modeling of soil inorganic carbon storage in an arid piedmont. *Geoderma* **154**:486-494.
- Jasoni, R. L., S. D. Smith, and J. A. I. Arnone. 2005. Net ecosystem CO₂ exchange in Mojave Desert shrublands during the eighth year of exposure to elevated CO₂. *Global Change Biology* **11**:749-756.
- Jurinak, J. J., L. M. Dudley, M. F. Allen, and W. G. Knight. 1986. The role of calcium-oxalate in the availability of phosphorus in soils of semiarid regions- A thermodynamic study. *Soil Science* **142**:255-261.
- Kitajima, K., M. F. Allen, and M. L. Goulden. 2013. Contribution of hydraulically lifted deep moisture to the water budget in a Southern California mixed forest. *Journal of Geophysical Research-Biogeosciences* **118**:1561-1572.
- Knight, W. G., M. F. Allen, J. J. Jurinak, and L. M. Dudley. 1989. Elevated carbon-dioxide and solution phosphorus in soil with vesicular-arbuscular mycorrhizal western wheatgrass. *Soil Science Society of America Journal* **53**:1075-1082.
- Laanait, N., C. E.B.R., Z. Zhang, N. C. Sturchio, S. S. Lee, and P. Fenter. 2015. X-ray-driven reaction front dynamics at calcite-water interfaces. *Science* **349**.
- LeBrón, I., and D. L. Suárez. 1998. Kinetics and mechanisms of precipitation of calcite as affected by PCO₂ and organic ligands at 25°C. *Geochemica et Cosmochimica Acta* **62**:405-416.

- Li, Y., Y. G. Wang, R. A. Houghton, and L. S. Tang. 2015. Hidden carbon sink beneath desert. *Geophysical Research Letters* **42**:5880-5887.
- Martin, J. B., P. C. De Grammont, M. D. Covington, and L. Toran. 2021. A new focus on the neglected carbonate critical zone. *Eos* **102**.
- Morris, S. J., and M. F. Allen. 1994. Oxalate-metabolizing microorganisms in sagebrush steppe soil. *Biology and Fertility of Soils* **18**:255-259.
- Ogle, K., R. L. Wolpert, and J. F. Reynolds. 2004. Reconstructing plant root area and water uptake profiles. *Ecology* **85**:1967-1978.
- Parton, W. J., M. Hartman, D. Ojima, and D. Schimel. 1998. DAYCENT and its land surface submodel: description and testing. *Global and Planetary Change* **19**:35-48.
- Rao, L. E., E. B. Allen, and T. Meixner. 2010. Risk-based determination of critical nitrogen deposition loads for fire spread in southern California deserts. *Ecological Applications* **20**:1320-1335.
- Rowley, M. C., H. Estrada-Medina, M. Tzec-Gamboa, A. Rozin, G. Cailleau, E. P. Verrecchia, and I. Green. 2017. Moving carbon between spheres, the potential oxalate-carbonate pathway of *Brosimum alicastrum* Sw.; Moraceae. *Plant and Soil* **412**:465-479.
- Rundel, P., and A. Gibson. 1996. *Ecological communities and processes in a Mojave Desert Ecosystem: Rock Valley, Nevada*. Cambridge University Press, Cambridge.
- Schlesinger, W. H. 1985. The formation of caliche in soils of the Mojave-desert, California. *Geochimica Et Cosmochimica Acta* **49**:57-66.
- Schlesinger, W. H., and R. Amundson. 2019. Managing for soil carbon sequestration: Let's get realistic. *Global Change Biology* **25**:386-389.
- Schlesinger, W. H., J. Belnap, and G. Marion. 2009. On carbon sequestration in desert ecosystems. *Global Change Biology* **15**:1488-1490.
- Schlesinger, W. H., and E. S. Berghardt. 2013. *Biogeochemistry. An analysis of global change*. third edition. Academic Press.
- Šimůnek, J., M. T. van Genuchten, and M. Sejna. 2005. *The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media.*, University of California, Riverside.
- Suarez, D. L., and J. Šimůnek. 1993. Modeling of carbon dioxide transport and production in soil: 2. Parameter selection, sensitivity analysis, and comparison of model predictions to field data. *Water Resources Research* **29**:499-513.
- Swanson, A. C. 2017. *Disturbance, restoration, and soil carbon dynamics in desert and tropical ecosystems*. University of California-Riverside.
- United States Department of Agriculture, N. R. C. S., and United States Department of the Interior, National Park Service. 2013. Soil survey of Joshua Tree National Park, California., http://soils.usda.gov/survey/printed_surveys/.
- Virginia, R. A., M. B. Jenkins, and W. M. Jarrell. 1986. Depth of root symbiont occurrence in soil. *Biology and Fertility of Soils* **2**:127-130.



- Wohlfahrt, G., L. F. Fenstermaker, and J. A. Arnone. 2008. Large annual net ecosystem CO₂ uptake of a Mojave Desert ecosystem. *Global Change Biology* **14**:1475-1487.
- Xie, J. X., Y. Li, C. X. Zhai, C. H. Li, and Z. D. Lan. 2009. CO₂ absorption by alkaline soils and its implication to the global carbon cycle. *Environmental Geology* **56**:953-961.

APPENDIX B

CLIMATE MITIGATION IN CALIFORNIA: THE IMPORTANCE OF CONSERVING CARBON IN DESERTS

(content begins on next page)

Climate Mitigation in California: The importance of conserving carbon in deserts



MBCA

morongo basin conservation association

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.

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 CO₂ 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).

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 CO₂ Enrichment Facility (NDFE). This study compared plots of desert with current CO₂ levels to plots with projected 2050 CO₂ levels. To do this, they piped extra CO₂ over the plots. At the completion of the study, the researchers compared the carbon between the plots with current CO₂ levels and those with projected CO₂ 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 CO₂ levels rise, deserts will have increased capacity to sequester in response to projected elevated atmospheric CO₂. Deserts store 9.7% of California carbon and based on the NDFE 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.

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 CO₂ 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.

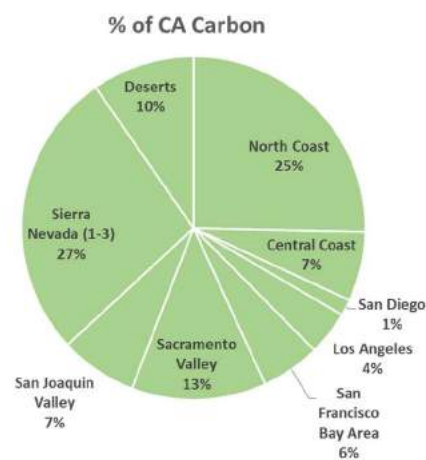
Read more about the desert carbon storage process here: <http://www.desertrep.org/?p=2270>

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?

Lindsay Rosa, Defenders of Wildlife,
lrosa@defenders.org

Susy Boyd, Mojave Desert Land Trust, susy@mdltr.org

Moises Cisneros, Sierra Club,
moises.cisneros@sierraclub.org

Pat Flanagan, Morongo Basin Conservation Association,
patflanagan29@gmail.com