August 3, 2021

Dr. Adam Moreno
Lead Natural Working Lands Climate Scientist
California Air Resources Board
1001 I Street
Sacramento, CA 95814

Re: Implementation of Below Ground Carbon Sequestration Modeling

Dear Dr. Moreno:

We thank you and your team at the California Air Resources Board (CARB) for taking time to meet with representatives of several environmental protection groups and concerned individuals on Thursday, July 22, 2021 to provide feedback on aspects related to quantifying a statewide carbon target for use in the upcoming Scoping Plan Update (California's roadmap for combating climate change).

During this meeting we were made aware that currently, CARB's potential modeling system for quantifying carbon in California lacks the appropriate systems to record the amount of carbon sequestration taking place below-ground. It's our understanding that CARB's existing models have been developed to fit the Intergovernmental Panel on Climate Change (IPCC) protocols -- which are deficient in desert carbon sequestration studies and modeling systems.
Based on scientific evidence, it is our position that:

- Production of organic carbon is low in hot desert ecosystems. Therefore, carbon in desert ecosystems has been overlooked or even criticized as a crucial element in global and regional models. ***But there are very high pulses of carbon inputs that scientists do not understand.***

- Up to 10% of carbon sequestration in California stems from below-ground activity in its deserts (see Appendix B attached).

- California's hot deserts contain a large pool of inorganic carbon, calcium carbonate, derived from biological processes. While this might not be a large new input, ***it could be a large loss of carbon following anthropogenic disturbance*** with carbon released back into the atmosphere.

- Carbon is patchy across California's deserts, and can be distributed between 1 and 60 meters deep, below depths commonly surveyed.

- Inorganic carbon is fixed but dependent upon bioweathering of calcium. While the chemical steps are well known, the temporal and spatial interaction patterns are complex.

Therefore, we urge you and your colleagues to consider Appendix A, a white paper authored by Dr. Michael Allen, Distinguished Professor Emeritus, Department of Microbiology and Plant Pathology, University of California, Riverside as a means to properly model carbon sequestration in the California desert; and Appendix B, a fact sheet by Defenders of Wildlife scientist, Dr. Lindsay Rosa.

Highlights from Dr. Allen's white paper (with citations) that can serve as a roadmap include:

Models of carbon accumulation ~

- **DayCENT**: Parton et al. 1998. Global and Planetary Change: 19:35

- **Hydrus**: Šimůnek, & Suarez. 1993. Water Resources Research, 29: 487

- Šimůnek et al. 2005. University of California, Riverside, Research Reports, 240.

However, *empirical data of groundwater access is critical* to accurately model carbon accumulation: Kitajima et al. 2013. Journal of Geophysical Research- Biogeosciences 118: 1561, data underlying Allen et al. 2014. In M. Tausz, N.E. Grulke (eds). Trees in a changing environment.

Model of calcium carbonate sequestration ~

- **SLIC**: Hirmas et al. Geoderma 154: 486. *But actual rhizosphere CO_2 concentration empirical data* are needed as inputs: Allen et al. 2013. CEC-500-2013-063.

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 "lungs" in the desert protected and conserved. We thank you in advance for your consideration and all the work that this type of endeavor requires.

Best regards,

Signatories:

Sam Young
Important Plant Areas Program Manager
California Native Plant Society

Dr. Rebecca R. Hernandez, Associate Professor
Wild Energy Initiative - Muir Institute of the Environment | Energy and Efficiency Institute
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APPENDIX A

NOTES ON MODELS OF CARBON DYNAMICS
FOR THE CALIFORNIA DESERTS

(content begins on next page)

Notes on Models of Carbon Dynamics for the California Deserts

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

Production of organic Carbon ($C_{organic}$) is generally low in hot desert ecosystems. Net primary production in the Mojave desert generally ranges from 10 to 30gC/m^2/y (Rundel and Gibson 1996), with a pool of 0.9 to 1.1kgC/m^2 (Evans et al. 2014). Photosynthesis is limited by temperature and moisture, and decomposition can remain high. Q_{10} values for RuBP Carboxylase is generally credited as a bit over 2 for ten degree increments between 10 and 40°C. Above 30°C, rates of photosynthesis decline rapidly. In deserts, however, soil respiration rates indicative of enzymatic activity can remain high up to 60 to 70°C (Cable et al. 2011). For this reason, C in desert ecosystems has been overlooked or even criticized as a crucial element in global and regional models.

Importantly, there are reports of very high rates of net ecosystem exchange of C (e.g., Xie et al. 2009, Wohlfahrt et al. 2008). These have been criticized as being unreasonable (Schlesinger and Amundson 2019), but no one has provided an alternative explanation for the measured values. While scientists continue to study the patterns and mechanisms of $C_{organic}$ in deserts, we know that California deserts have been accumulating inorganic C ($C_{inorganic}$) for millennia (Schlesinger 1986). While some measurements of the rates of input are controversial, including localized, temporal values equal to those of forest ecosystems (e.g., Schlesinger et al. 2009, Schlesinger and Amundson 2019), *a large pool of stored C has the potential to be lost through anthropogenic disturbance and exposure*. The mechanisms of C dynamics in desert ecosystems are outlined here with a focus on southern California.

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.

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 CO$_2$. Nature Climate Change **4**:394-397.

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.

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.

What is Caliche?

Caliche is a layer of calcium carbonate ($CaCO_3$) formed between the soil surface, and accumulating at the depth to which water will percolate carrying calcium (Ca) and to which roots will respire CO_2. CO_2 from respiring roots and microorganisms, plus atmospheric CO_2, dissolves in rainwater forming bicarbonate HCO_3^- and hydrogen ions (H^+). Using the free Ca, the equilibrium reaction results in $CaCO_3$, and the $CaCO_3$ crystals precipitate, until the next storm, when the reaction reoccurs and percolates the dissolved $CaCO_3$ in solution down to that storm's depth.

Caliche forms in bajadas below mountains comprised of high concentrations of Ca, particularly basalts (mineral CaO) and 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. When in semi-arid to arid regions, deep layering of $CaCO_3$ forms, such as in most of Mediterranean Europe, and the deserts of the southwestern US and northwestern Mexico. As much C in the form of CO_3 is sequestered in arid to semiarid soils as in plant organic C mass globally, and there remains a large "missing sink of C" somewhere in terrestrial ecosystems.

Despite the large amount of $CaCO_3$ sequestered over the past several thousand years, 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 assumptions that pose serious limitations to global carbon modeling and are at least contributors to the large gaps remaining in closing the global C models. These are: (1) $CaCO_3$ is patchily distributed globally and not easily mapped, (2) that the processes are geological and, because the dominant form is inorganic ($CaCO_3$), it is a geological and not biological process. Therefore, no accounting need be undertaken using ecosystem models. And (3), there is an assumption that the rates of transformations and loss are on a geological time scale and not relevant to global change models.

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.

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

Surface soil $CaCO_3$ is distributed widely, but in patches throughout 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 $CaCO_3$ (Fig 1).
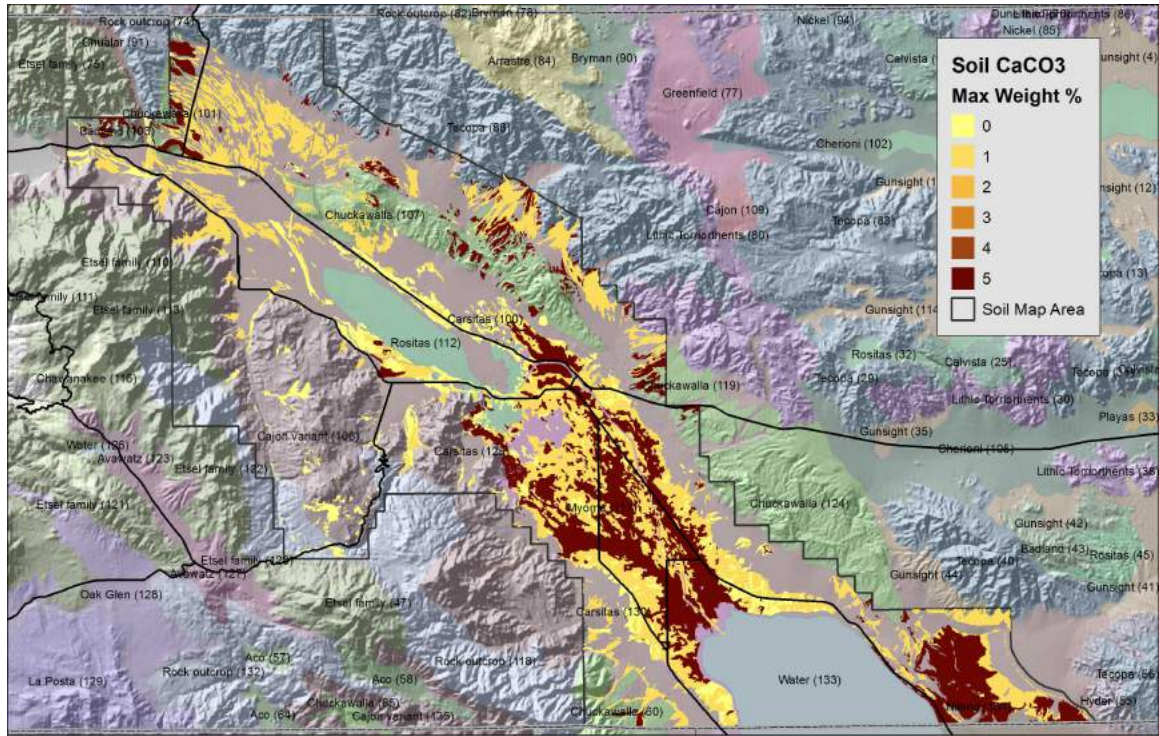

SSURGO Soil Data for Coachella Valley
(STATSGO shown in surrounding areas)

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 in the Chuckwalla Valley of greater than a meter, as much as 12% was $CaCO_3$, or between 30 and 70kg/m^2 of $CaCO_3$; or between 4 and 8.4kg $C_{inorganic}$/m^2, or as much C as is stored in mixed grass prairie as soil organic C.

Schlesinger, W.H. 1985. The formation of caliche in soils of the Mojave Desert, California. *Geochimica et Cosmochimica Acta* 49: 57-66.

Other C forms may also be critical in desert ecosystems. Garvie (2006) reported an accumulation of 2.4g $C_{inorganic}$/m^2/y under saguaro cactus accumulating as much as 40g $C_{inorganic}$/m^2, through the production and release of oxalic acid. The importance

of oxalic acid rests not only in and of itself, nor its role in P (phosphorus) nutrition of plants (Jurinak et al. 1986), but in an ability to lead to $CaCO_3$, or caliche accumulation (discussed below).

Garvie, L.A.J. 2006. Decay of cacti and carbon cycling. *Naturwissenschaften* **93,** 114–118. https://doi.org/10.1007/s00114-005-0069-7

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 of desert C are needed to know how much is actually sequestered.***

2) Do the processes occur only in geologic time scales and, because the dominant form is inorganic ($CaCO_3$), can we ignore this sequestered carbon because it is a geological and not a biological process? In essence, what is the time scale?

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) -> $C_6H_{12}O_6$ (photosynthesis): plants, lichen algae, cyanobacteria

2) $C_6H_{12}O_6 + O_2$ -> $H_2C_2O_4$ (bioweathering): lichen fungi, plants, mycorrhizal fungi

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

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

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

6) $Ca + HCO_3^-$ (in solution) <-> $\mathbf{CaCO_3}$ + H^+

As the soils dry, the $CaCO_3$ precipitates, and upon layering, creates a caliche layer.

7) If exposed, with rainfall, $CaCO_3 + H^+ + O_2$ <-> $CO_2 + H_2O + Ca$

8) $Ca + HPO_4^-$ -> $CaPO_4$, $CaSO_4$ (gypsum)

cycle back to step 1 and step 4.

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 $Ca + CO_2 + H^+$, with a potential for CO_2 to be released back to the atmosphere. This is a

mechanism whereby Ca moves from the mountains into the bajada, and then deeper into the bajada.

1) CO_2 (atmospheric) -> $C_6H_{12}O_6$, or $C_{organic}$ (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.

2) $C_6H_{12}O_6 + O_2$ -> $H_2C_2O_4$ (bioweathering): lichen fungi, plants, mycorrhizal fungi

Fungi and bacteria produce oxalic acid, among others including citric acid, carbonic acid, and nitric 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 (e.g., Gadd et al. 2014).

Gadd, G.M. et al. 2014. Oxalate production by fungi: significance in geomycology, biodeterioration and bioremediation. Fungal Biology Reviews 28: 36-55. https://doi.org/10.1016/j.fbr.2014.05.001.

3) $Ca + H_2C_2O_4$ -> 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 (Franceschi and Nakata 2005). Many of the fungi in desert crust lichens, but also other biotic crusts produce them. Ectomycorrhizal fungi, such as associated with oaks and pines, produce these acids (e.g., Allen et al. 1996) and even the arbuscular mycorrhizal fungi, formed with the majority of desert perennial plants, form Ca-oxalates as a mechanism, when combined with increasing CO_2 respired within the mycorrhizosphere, to obtain limiting P (Jurinak et al. 1986, Knight et al. 1989).

Allen, M.F. C. Figueroa, B.S. Weinbaum, S.B. Barlow, and E.B. Allen. 1996. Differential production of oxalates by mycorrhizal fungi in arid ecosystems. Biology and Fertility of Soils 22: 287-292.

Franceschi, V.R. and P.A. Nakata. 2005. Calcium oxalate in plants: formation and function. Annual Review of Plant Biology 56: 41-71.

Jurinak, J.J., L.M. Dudley, M.F. Allen & 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.

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.

4) $CaC_2O_4 \rightarrow Ca + CO_2$ (C source, degradation): bacteria, fungal exoenzymes. Once Ca-oxalate is formed, like any organic material, there are both fungi and bacteria awaiting to use it as a carbon source (Morris and Allen 1994, Gadd et al. 2014).

Morris, S.J. and M.F. Allen. 1994. Oxalate metabilizing microorganisms in sagebrush steppe soils. Biology and Fertility of Soils 18: 255-259.

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 (see model discussion below). It is important to note that while atmospheric CO_2 is increasing (from 310ppm in 1950 to 410 today), soil CO_2 can be many thousands of ppm, and we have measured over 2,500ppm at the Boyd Deep Canyon Reserve (see below).
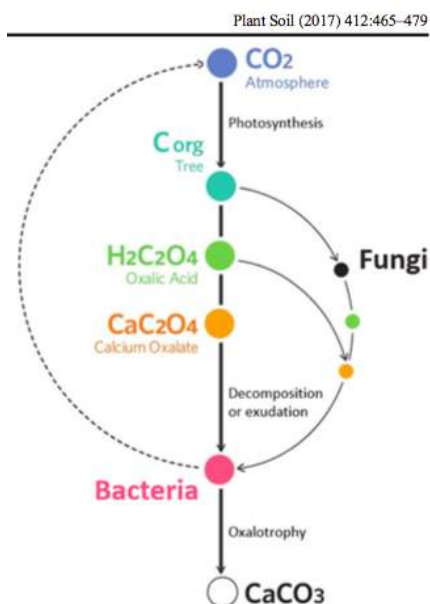

Fig. 1 A simplified model of the Oxalate-Carbonate Pathway (OCP), a process that transfers carbon dioxide from atmosphere to secondary calcium carbonate. As described by Cailleau et al. (2014), the process commences when a calcium oxalate producing species (Tree) organically sequesters carbon during photosynthesis (Corg), converting it into oxalic acid and then calcium oxalate. Once released from organic material during decomposition or as exudes, calcium oxalate is subsequently catabolised by oxalotrophic bacteria (Bact.), converting one mol as carbonate and releasing another as respired carbon dioxide. Fungi also assist in the process by either breaking down oxalic rich matter and depositing calcium oxalate for catabolism by bacteria, or by fungal oxalotrophy

6) $Ca + HCO_3^-$ (in solution) $\leftrightarrow \mathbf{\textit{CaCO}_3} + H^+$

The critical step in Carbon Sequestration!

In a comprehensive synthesis, Mike Rowley, in Lausanne, Switzerland, and his colleagues showed that the Ca-oxalate pathway concentrates Ca temporally and spatially, where C is sequestered through oxalotrophy through free Ca coupled with the high concentrations of HCO_3^-, forming $CaCO_3$ (Figure 2).

Figure 2. A model showing biotically-controlled CO_2 sequestration focused on the Yucatán Peninsula, from Rowley et al. 2017.

Rowley, M.C., H. Estrada-Medina, M. Tzec-Gamboa et al. 2017. Moving carbon between spheres, the potential oxalate-carbonate pathway of Brosimum alicastrum Sw.; Moraceae. *Plant and Soil 412*: 465-479.

Time Scales:
In our efforts to better understand the time scales of C dynamics, we undertook two types of studies. First, we analyzed the $\delta^{18}O$ signals (Delta-Oxygen-18 is an indication of groundwater/mineral interactions) of caliche across the Coachella Valley. These values showed that caliche was dynamic (Allen et al. 2013). This

conclusion was collaborated by a subsequent study in the Mojave desert (Mills et al. 2020).

At Deep Canyon, my research group further re-ran the SLIC model (see model discussion below) using our empirical CO_2 sensor data to determine the $CaCO_3$ in solution (Allen et al. 2013, Swanson 2017, Swanson et al. in preparation). Importantly, soil CO_2 can reach as high as 2,500ppm, as compared with atmospheric CO_2 of 395ppm (during the measurements), as soil respiration increased following precipitation events. $CaCO_3$ in solution tracked the CO_2 and H_2O. 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 CO_2 flux from both undisturbed soils and from sites with no measureable organic C (Allen et al. 2013, Swanson 2017).
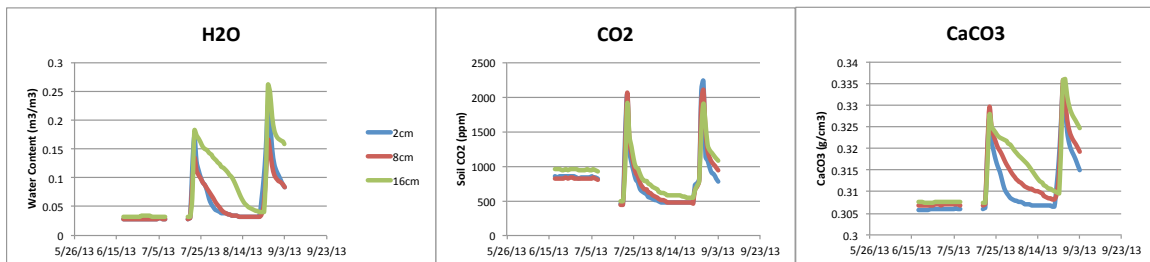

Figure 3. Daily time scales of soil water, CO_2 and modeled solution $CaCO_3$ (SLIC model) following a precipitation event at Boyd Deep Canyon in July through September of 2013 (Allen et al. 2013, Swanson 2017).

Allen, M. F., G. D. Jenerette, L. S. Santiago. 2013. Carbon Balance in California Deserts: Impacts of Widespread Solar Power Generation. California Energy Commission. Publication number: CEC-500-2013-063.

Swanson, AC. 2017. Disturbance, Restoration, and Soil Carbon Dynamics in Desert and Tropical Ecosystems. PhD. Dissertation. University of California-Riverside.

7) If exposed, with rainfall, $CaCO_3 + H+ + O_2 <-> CO_2 + H_2O + Ca$

$\delta^{18}O$ ratios show that in surface soils, $CaCO_3$ continually turns over (Allen et al. 2013, confirmed by Mills et al. 2020). We do not know where, or how much Ca is redistributed with erosion, but there is considerable wind erosion of Ca, especially as calcium sulphate (Frie et al. 2019).

Allen, M. F., G. D. Jenerette, L. S. Santiago. 2013. Carbon Balance in California Deserts: Impacts of Widespread Solar Power Generation. California Energy Commission. Publication number: CEC-500-2013-063.

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 (16), 9378-9388 DOI: 10.1021/acs.est.9b02137

Mills, Jennifer, Laura Lammers, and Ronald Amundson. 2020. Carbon Balance with Renewable Energy: Effects of Solar Installations on Desert Soil Carbon Cycle. California Energy Commission. Publication Number: CEC-500-2020-075

8) $Ca + HPO_4^-$ -> $CaPO_4$ (bound inorganic P, $CaSO_4$ (gypsum)

Even though in equilibrium, Ca tends to attach to $-CO_3$ but some can bind to phosphate or sulphate (forming gypsum), move in solution downstream, or even blow via wind erosion (Frie et al. 2019).

Frie, A, A Garrison, M Schaefer, S Bates, J Botthoff, M Maltz, S Ying, T Lyons, MF Allen, EL Aronson, R Bahreini. 2019. "Dust Sources in the Salton Sea Basin: A Clear Case of an Anthropogenically Impacted Dust Budget." Environmental Science & Technology. 53(16):9378-9388. doi: 10.1021/acs.est.9b02137.

(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 Models: One modeling concept uses the assumption that the rates of transformations are on a geological time scale and not relevant to change models. These are the models that should be used and tested.

DayCENT: 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.

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. But there are limitations that require a better incorporation of concepts described below and the data and model inputs specific to California's deserts.

Rao et al. 2010 used DayCENT for studying the impacts of Nitrogen deposition on Net Primary Productivity (NPP -or how much CO2 vegetation takes in during photosynthesis minus how much CO2 plants release during respiration) 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 20-40g C/m^2, but measured production was 60-80gC/m^2.

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.

Using DayCENT, Joshua Tree National Park, the accumulated SOM-C (soil organic matter-carbon) ranged from 668 to 916g/m2, depending on N deposition. This compares with measurements ranging up to 2,000g/m^2 (USDA 2013).

United States Department of Agriculture, Natural Resources Conservation Service, and United States Department of the Interior, National Park Service. 2013. Soil survey of Joshua Tree National Park, California. (Accessible online at: http://soils.usda.gov/ survey/printed_surveys/)

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.

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

Limits to DayCENT 1: Deep water.
Our primary concern was an inability in the model to incorporate deep roots into organic C accumulation due to the model not integrating deep root dynamics. Many shrubs in the microphyll woodlands have deep roots and microbial associations (e.g., Virginia et al. 1986). Roots reaching deep and especially to groundwater level, 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 groundwater. Moreover, roots and the mycorrhizosphere (the region around a mycorrhizal fungus colonizing plant roots) contribute to increasing atmospheric CO_2, increasing the partial pressure pushing bicarbonate concentrations (see SLIC modeling below). These plant mycorrhizospheres are producing CO_2 for the creation of HCO_3^-, binding with Ca to form $CaCO_3$ deep in the profile at unknown rates.

Ogle, K., R.L. Wolpert, and J.F. Reynolds. 2004. Reconstructing plant root area and water uptake profiles. Ecology 85: 1967-1978.

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.

In a California conifer-hardwood forest, we initially used DayCENT to characterize NPP (Allen et al. 2014). We also measured ET (EvapoTranspiration, or transpiration plus evaporation) and NEE using eddy-flux measurements (Michael Goulden data, UC Irvine) 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 4).
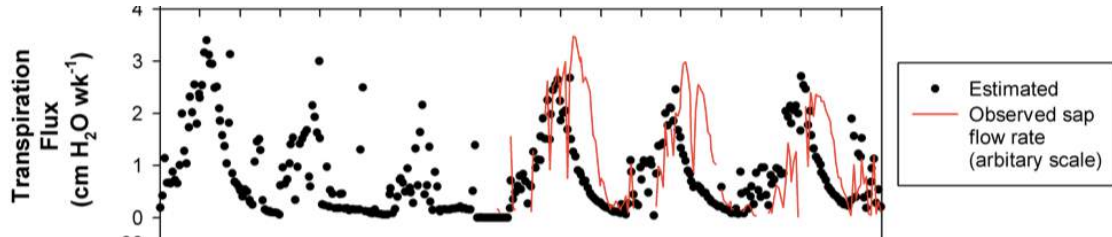

Figure 4. Kitajima and Allen-output from a model run from 2005-2010, from Allen et al. 2014, showing the comparison in Transpiration flux measurements with DayCENT modeling (dots) versus measured sapflow rates (red line). The lag in transpiration (which affects CO_2 fluxes) does not show in DayCENT as there is no provision for access to deep-water sources. As long as there is transpiration, there is fixation.

Allen, M.F., K. Kitajima, R.R. Hernandez. 2014. Mycorrhizae and global change. Pp. 37-59: in M. Tausz, N.E. Grulke (eds). Trees in a changing environment. Springer-Plant Sciences, Dordrecht, The Netherlands.

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

HYDRUS: Simunek, 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, Research Reports, 240.

For this reason, 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 = delta-deuterium, or hydrogen-2, and $\delta^{18}O$, or delta-oxygen-18) to confirm 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. 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 invaluable for any estimates of C fluxes in desert soils.

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

Suarez, D. L., and J. Šimůnek (1993), Modeling of carbon dioxide transport and production in soil: 2. Parameter selection, sensitivity analysis, and com- parison of model predictions to field data, Water Resources Research 29: 499–513, doi:10.1029/92WR02226.

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_i) 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 inorganic C or C_i. This would place the soil C in the range of C in the middle of the Great Plains, and even the lower end of the C-rich temperate forest soils.

Schlesinger, W. H. 1985. The formation of caliche in soils of the Mojave-Desert, California. Geochimica Et Cosmochimica Acta **49**:57-66.

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. For this determination, 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 PCO_2 reading (partial pressure of carbon dioxide, which reflects dissolved C02) is the sensor output converted to atmospheres. The second step is to determine local soil pH (how acidic or basic the soil is) that can be measured directly or determined from $CO_2(aq)$, aqueous carbon dioxide, or the gas dissolved in water, where: pH = 3.9 - $0.5\log P_{CO2}$.

Using pH and carbonate equilibrium, we can determine the other species,

DIC_{total} - [H_2CO_3*] + [HCO_3^-] + [CO_3^{2-}]

We can use these sensor data as an input to HYDRUS 1D to simulate the HCO_3 input and output from a known soil layer (Thomas Harmon and Michael Allen, unpublished data).

Allen, M.F., R. Vargas, E. 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.

Once the HCO_3^- (bicarbonate) 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, 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. doi: https://doi.org/10.1016/j.geoderma.2009.05.005

The SLIC model simulates soil $C_{inorganic}$ 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 $\delta^{18}O$, 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 soil atmosphere (~400ppm), and does not integrate biological soil respiration, which isotopic ratios have suggested are the source for deep caliche (Schlesinger 1985). $\delta^{18}O$ 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. We do not know the CO_2 concentrations deep at the groundwater level.

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. doi: https://doi.org/10.1016/j.geoderma.2009.05.005

Allen, M. F., G. D. Jenerette, L. S. Santiago. 2013. Carbon Balance in California Deserts: Impacts of Widespread Solar Power Generation. California Energy Commission. Publication number: CEC-500-2013-063.

Mills, Jennifer, Laura Lammers, and Ronald Amundson. 2020. Carbon Balance with Renewable Energy: Effects of Solar Installations on Desert Soil Carbon Cycle. California Energy Commission. Publication Number: CEC-500-2020-075

Regional expertise: Daniel Hirmas, Environmental Sciences, UCR
For organic C cycling, an acceptable approach would be to run DayCENT, but integrating the length of C acquisition with access to deep water, extending the time for photosynthesis into each drought period. This requires collection of empirical

data of the timing of active photosynthesis coupled with isotopic data on water sources, as per Ogle et al. 2014.

The best models for inorganic carbon would probably be the newest version of Hydrus 1D combined with SLIC, but again integrating empirical data of mycorhizosphere CO2 at the depths where water is acquired and CaCO3 deposited. 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.

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

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

California Carbon Sinks

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

Quick take

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

Read more about the desert carbon storage process here: http://www.desertreport.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.
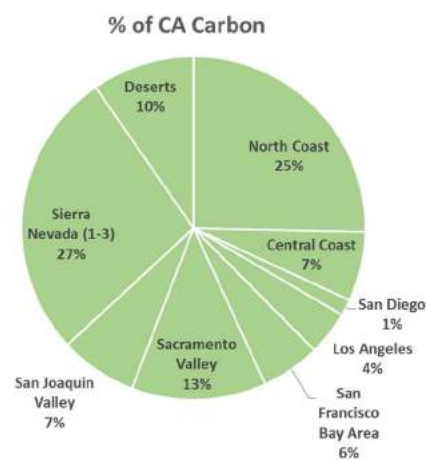
Map highlighting carbon-rich areas (top 20%) within each ecoregion and current coincidence with higher human disturbance. Sierra Nevada – East was combined with the Inland Desert ecoregion to represent California's deserts as a singular unit.

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?
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