CALIFORNIA ENERGY COMMISSION

Energy Research and Development Division

FINAL PROJECT REPORT

Carbon Balance with Renewable Energy: Effects of Solar Installations on Desert Soil Carbon Cycle

Gavin Newsom, Governor

December 2020 | CEC-500-2020-075

PREPARED BY:

Primary Authors:
Jennifer Mills, Laura Lammers, and Ronald Amundson

University of California
Dept. of ESPM
120 Mulford Hall
Berkeley, CA
94720
510-643-7890
https://ourenvironment.berkeley.edu

Contract Number: EPC-15-039

PREPARED FOR:
California Energy Commission

Alex Horangic
Project Manager

Jonah Steinbuck, Ph.D.
Office Manager
ENERGY GENERATION RESEARCH OFFICE

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

ACKNOWLEDGEMENTS

The authors thank the National Park Service (Mojave National Preserve) for granting the research permit and supporting this project's ongoing observations in the Park. The authors thank Ryan Thomas and the staff at the SunPower Rosamond solar facility for allowing to access their facility for sampling and instrumentation. The National Resource Conservation Service Soils Laboratory, in Lincoln, Nebraska, provided splits of archived soil samples originally collected in the Mojave Desert in 1973. Finally, the authors thank the staff and support of the California Energy Commission.

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Carbon Balance with Renewable Energy: Effects of Solar Installations on Desert Soil Carbon Cycle is the final report for the project (Contract Number EPC-15-039) conducted by the University of California, Berkeley. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

This research examined the response of California desert soil carbon to 21st-century climate change, and the effect of large-scale solar installations on desert soil carbon balances. Three sites in the Mojave National Preserve were instrumented and monitored intensely for two years. A heat, water, and geochemical model was developed to mimic current conditions, and extrapolate conditions into the future as California's climate changes. The Mojave Desert is one of the most rapidly warming areas in the United States, and empirical evidence of potential declines in soil carbon storage due to warming have been discovered. The current expansion of large-scale solar in the western Mojave Desert is on abandoned agricultural land. A year of intensive micrometeorological measurements at a utility-scale solar installation shows that panels produce complex changes in the heat and water balance of the site. Since vegetation is kept to a minimum under most solar installations, there is expected to be a slow loss of remaining soil organic carbon due to a lack of inputs. Due to this slow loss of remaining soil organic carbon, large-scale solar installations, especially those on already impacted agricultural lands, are not expected to contribute in any significant way to the soil carbon loss. Inorganic carbon stocks, based on geochemical modeling, are predicted to remain and increase, though at a slightly slower rate than the control site.

Keywords: feedbacks, large-scale solar, deserts, soil carbon

Please use the following citation for this report:

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.

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EXECUTIVE SUMMARY

Introduction

The climate of the United States is changing due to carbon dioxide (CO_2) and other greenhouse gas emissions, and one of the fastest warming areas in the country is the Mojave Desert of California and Nevada. In the past 50 years, this region has warmed between 2°Fahrenheit (F) (1°Celsius) and in some areas, up to 5°F (3°C), already exceeding the global temperature rise limit of 4°F (2°C) that the international community set in the Paris Climate Accord.

The desert is changing with the increased temperatures, and understanding the type of changes, and their rate, will help government, land managers, and citizens plan for adaptation. In turn, understanding rates and potential magnitudes of change can be an incentive to change the state's energy trajectory and shift toward a more carbon-free electrical generation sector.

There is uncertainty about whether the release of CO_2 from soils under solar panels exceeds the offsets provided by renewable energy production. This project examines the effect of large-scale solar installations on desert soil carbon balances and addresses how desert soil carbon balances respond to changing temperatures. The research involved installing research infrastructure and sensors for continuous monitoring of environmental variables (micrometeorology, soil temperature, water content, and carbon dioxide) at multiple locations in the Mojave Desert, and the adaptation of a common ecosystem process model to predict greenhouse gas fluxes for the Mojave region. It also involved developing a sophisticated, coupled, heat-water-chemistry model to capture present soil processes and conduct numerical experiments on how climate change and solar panels will affect soil carbon balances. The results provide a first approximation of the effects of renewable energy siting decision-making on the desert environment of California.

Project Purpose

California's ability to supply renewable energy to the electricity sector by large-scale solar installations in deserts is growing rapidly, and at the same time the climate in these regions is rapidly changing. These dual processes and changes bring with them uncertainty.

Articles about solar installations have suggested that the panels will change the soil hydrological (water) conditions, dissolved inorganic calcite (a calcium carbonate mineral), and potentially release CO_2 at rates that exceed the carbon offsets that solar electricity produces (Allen and McHughen, 2011).

Since it has only been recently recognized how quickly the desert's climate is changing, there has not been any research to understand the desert soil carbon response, or to project continued responses into the coming decades.

California decision-makers and ratepayers should be aware of the effects of renewable energy systems, and the fate of California in the absence of attempts to reduce greenhouse gas emissions from all energy sectors. Deserts are ideal locations for solar energy installations, yet this ecosystem is visually iconic, with an array of plants and animals of great biotic and cultural importance. Measuring the way panels modify temperature, humidity, and rainfall distribution provides important data that can inform concerns about ecological impacts. This project, while not examining every type of installation that has been developed, offers rigorous data for large-scale solar projects being developed on the abandoned agricultural lands of the western Mojave Desert.

Project Approach

To characterize the response of desert soil carbon cycling to changes - both acute land-use change due to utility-scale solar installation and longer-term 21st-century climate change, the following data were required:

- An understanding of the present rates of carbon cycling at natural, undisturbed sites in the Mojave.
- An understanding of how utility-scale solar installations influence soil conditions and thus soil carbon cycling in desert systems.

To obtain this data the Berkeley research team required the collaboration of three stakeholders. The National Park Service permitted the team to install weather stations and soil sensors, and sample soils. The SunPower Corporation helped provide access to a solar installation in the western Mojave Desert near Rosamond, California and the Natural Resource Conservation Service of the United States Department of Agriculture graciously provided archived soil samples, collected in 1973.

A series of study sites were sampled and instrumented along an elevation gradient in the Mojave National Preserve that encompassed three major vegetation-ecosystem types and at a utility-scale solar installation. The team excavated 20 soil trenches, described and sampled the layers, and installed temperature, water, and carbon dioxide sensors in the trenches. Simultaneously, weather stations were installed, wired, and launched. Following field work, the researchers chemically and physically characterized the soils in the laboratory. Data from sensors were manually downloaded on a roughly three-month schedule, and sensors were maintained and repaired as needed. Soils originally sampled in 1973 were resampled, and their carbon, nitrogen, and isotope composition were measured to determine their response to warming temperatures over the past 45 years.

Project Results

The research produced expected findings, and in addition, some surprises. Research findings include:

- The installation of solar panels marks a significant change in the landscape. Yet, the effects on temperature, moisture, and humidity caused by panel placement and movement, while interesting from a scientific perspective, have only a small influence on soil processes.
- Expected and unexpected differences were observed between study sites at different elevations and corresponding vegetation zones. A novel finding was the rapid ecosystem "pulses" in CO_2 production that occur in response to small meteorological thresholds. These data and observations along the elevation gradient (more than two years of total observations) now provide a scientific database for the Mojave or the

nearby Great Basin Deserts and serves as a guide to modeling the response to ongoing warming.

- A surprising discovery was the apparent loss of organic carbon in soils over the past 45 years as temperatures have increased. Due to corresponding changes in chemical and isotopic characteristics of soil organic matter, this loss seems to be due to increased biological rates of carbon respiration to CO_2. This suggests that the earth's soils are responding to warming by releasing CO_2, further exacerbating atmospheric CO_2 buildups. This is called a positive feedback loop, one in which once a process starts, a somewhat self-sustaining and reinforcing mechanism maintains the process.
- In the western Mojave Desert, the largest and most rapid expansions are occurring in areas of the desert that are now abandoned agricultural lands. On these lands, the original flora and fauna were removed in the 20th century, the ground water depleted, and cropping systems were abandoned. The vegetation on these abandoned lands is largely an early successional stage of floral recovery and is distinct from the native vegetation on surrounding undisturbed desert.
- The very modest amounts of soil organic carbon that existed in the soils prior to solar panel installation are largely on a slow decline due to the removal or prevention of growth of vegetation under panels. The amount and rate loss of CO_2, estimated for a worst-case scenario, is much less than the carbon offsets provided by electrical generation.
- Inorganic carbon (as the mineral calcite) is subject to even slower, and more subdued, changes over time. Even the worst (and improbable) scenario—total loss of organic and inorganic carbon from most sites—is but a minor addition to the atmosphere compared to the positive feedback loop of which the desert is apparently a part.

Knowledge Transfer

This project is largely science-based and driven by data accumulation and its analysis via geochemical and ecosystem models. All project monitoring data has been uploaded to the HydroShare data repository for environmental data, which can be accessed here: https://www.hydroshare.org. Insights resulting from this work have resulted in the development of several papers that will be submitted for publication to peer-reviewed journals. Results from the project have been presented at multiple international geoscience conferences, including the American Geophysical Union and Goldschmidt conferences.

End-users of this work may include researchers, policymakers, and resource management decision-makers. It is likely that the work will stimulate further research projects on the desert's response to changing conditions. The research on the effect that solar panel installations have on micrometeorological conditions will be informative for regulatory considerations and the design of multi-use solar facilities.

Benefits to California

California has invested policy and funding to use solar energy to curb GHG emissions such as CO_2. There is uncertainty about whether the installations in turn cause an increase in soil CO_2 emissions, and how the changing global climate will measurably impact soil carbon balances. A large portion of California's population lies within a rapidly warming region, and the changes will continue to affect people directly through increasing heat extreme frequencies, and indirectly through changes in the natural world around them. This project focuses on examining the soils of the Mojave Desert region—a small but important part of these earth system changes.

The installation of solar energy farms in deserts will likely continue into the near future. The research in this report provides realistic estimates of the ways and rates at which it may impact the soils on which they are situated. As the solar industry matures, it may use this research to consider opportunities to explore if, and how, desert solar installations might be multi-benefit areas, where native vegetation and fauna may coexist with sophisticated hardware that requires continuous monitoring, maintenance, and repair. This research examines the likely long-term adjustment of these areas once solar panels have been installed.

The project also identifies the rapidly changing temperatures of the Mojave Desert, and the sensitivity of soil carbon cycling to these climatic changes. The work reveals that the region is likely already in a process of responding to these climate changes by releasing more carbon. Providing sound science on how the present desert responds to climatic differences, and how it should respond to changes in these baselines, is important for policy and decisions makers to know when developing policies and regulations in the energy sector.

CHAPTER 1: Introduction

This project explored the effect of 21st-century climate change on the carbon (C) balance of California desert soils, and the effect of large-scale desert solar installations on the soil carbon balance. This interest in the effects of climate/land use is extremely relevant in that the temperatures of southern California are among the most rapidly increasing of the lower 48 states, and the Mojave Desert is in the midst of a solar boom that now contributes about 30 percent of the state's annual electrical power output (California ISO, December 2019 Monthly Renewables Performance Report).

The deserts of California are vulnerable to direct and indirect human activity and are an abundant source of wind and solar energy that assists the state in decarbonizing its energy sector. This research examines the results of these activities on the microclimate of soils and ecosystems, and the subsequent effect on soil carbon (organic and inorganic).

Dryland soils are not particularly carbon-rich, but because they cover approximately 40 percent of the global terrestrial land surface (Schimel 2010) they are potentially an underappreciated contributor to the Earth's carbon and climate system. For example, recent global biome model studies have pointed out that interannual variability in atmospheric carbon dioxide (CO_2) concentration is correlated to biosphere–atmosphere CO_2 exchange in arid and semiarid regions (Ahlström et al. 2015). Much of this year-to-year variability is driven by temperature and water availability effects on productivity and respiration in drylands (Jung et al. 2017).

The Mojave Desert, located in the far southwestern region of North America, is the smallest and driest of the North American deserts (Thomey et al. 2014) and is experiencing rapid and widespread environmental change. Significant warming has occurred over the past 100 years in the southwestern United States, most markedly in the Mojave region (Anderegg and Diffenbaugh 2015). The aridification of western North America is expected to proceed and accelerate in the next century, perhaps most severely in the southwestern United States (Seager et al. 2013; Cook, Ault, and Smerdon 2015). Additionally, open shrubland vegetation in the Mojave Desert region is being converted to solar energy facilities and other developed landcover types (Soulard and Sleeter 2012; Hernandez et al. 2015) with significant perturbations to soils, vegetation, and biogeochemical cycling occurring in the process.

This report provides a summary and analysis of the results to date of the authors' investigation of desert functioning in response to modern climate and the unique microclimate and geochemical effects that solar panels provide to desert soil environments.

CHAPTER 2: Project Approach

Quantifying the Effects of Perturbations on the Mojave Desert Carbon Balance

In this chapter, the authors describe the design and implementation of the various subcomponents of the research. The overarching goal of this project was to characterize the response of coupled organic and inorganic desert carbon cycling to perturbations—acute land-use change due to utility-scale solar installation and longer-term 21st-century climate change. To do this, the following data were required:

- An understanding of the present rates of carbon cycling at natural, undisturbed sites in the Mojave.
- An understanding of how utility-scale solar installations influence soil conditions and thus soil carbon cycling in desert systems.

Characterizing Carbon Cycling in Mojave Ecosystems and Its Climate Sensitivity

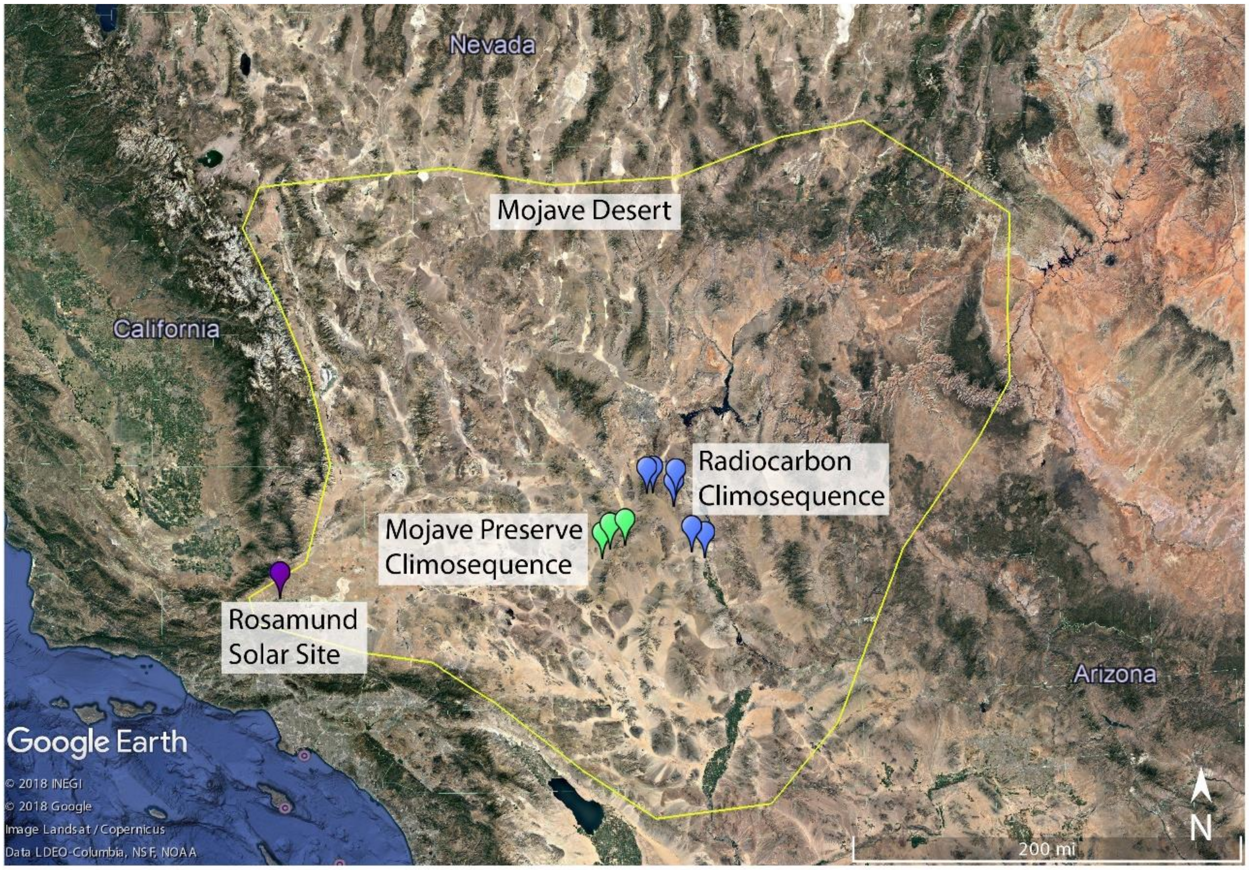
To address the first point, a series of sites were sampled and instrumented along an elevation gradient in the Mojave National Preserve that encompassed three major vegetation/ecosystem types: low elevation creosote shrubland, mid-elevation Joshua tree-dominated shrubland, and a high elevation mixed pinyon-juniper woodland. This is referred to as the "Mojave National Preserve (MNP) climosequence" for the remainder of this report, and served as a template for using recent and present-day soil environmental conditions and soil responses as the baseline for modeling effects of future climate change. In addition, a climate gradient (originally sampled in 1973) was resampled to determine how, and the rate at which, soil organic carbon processes have changed during 45 years of steady and increasing climatic warming.

Soil Climate Transect in Mojave National Preserve

The study of sites along climate gradients, called "climosequences" (Jenny, 1941), is a common technique in empirical studies to determine how the earth operates in differing climatic settings. Climosequence data can be used to project how, and the rate at which, systems will change as climate changes.

The authors of this project have previously set up and monitored climosequences in the Great Basin (and peripheral Mojave) deserts of Nevada (R.G. Amundson, Chadwick, and Sowers 1989; Oerter et al. 2018). However, these transects were either on parent material not typical of the California Mojave Desert (R.G. Amundson, Chadwick, and Sowers 1989) or were too far north in the Great Basin deserts (Oerter et al. 2018). After two reconnaissance trips through the Mojave region, it became clear that the most representative and extensive region of desert, typical to California, was within the boundaries of the Mojave National Preserve of the National Park Service. To constrain the study to common landforms (relatively geologically young alluvium dominated by material from granitic rock), three sites were located along the Kelso-Cima and Cedar Canyon Roads (Figure 1). Along this transect of sites, the flora (driven by increasing rain and decreasing temperatures) shifts from low elevation creosote brush, to a Joshua tree assemblage, and finally to a juniper and sagebrush assemblage (Figure 2). There is little biotic overlap among the three sites, reflecting the strong impacts of climate on floral success. The vegetation cover and composition were quantified with four 50-meter random line-intercept transects (a standard plant survey technique).

Figure 1: Location of Mojave Study Sites



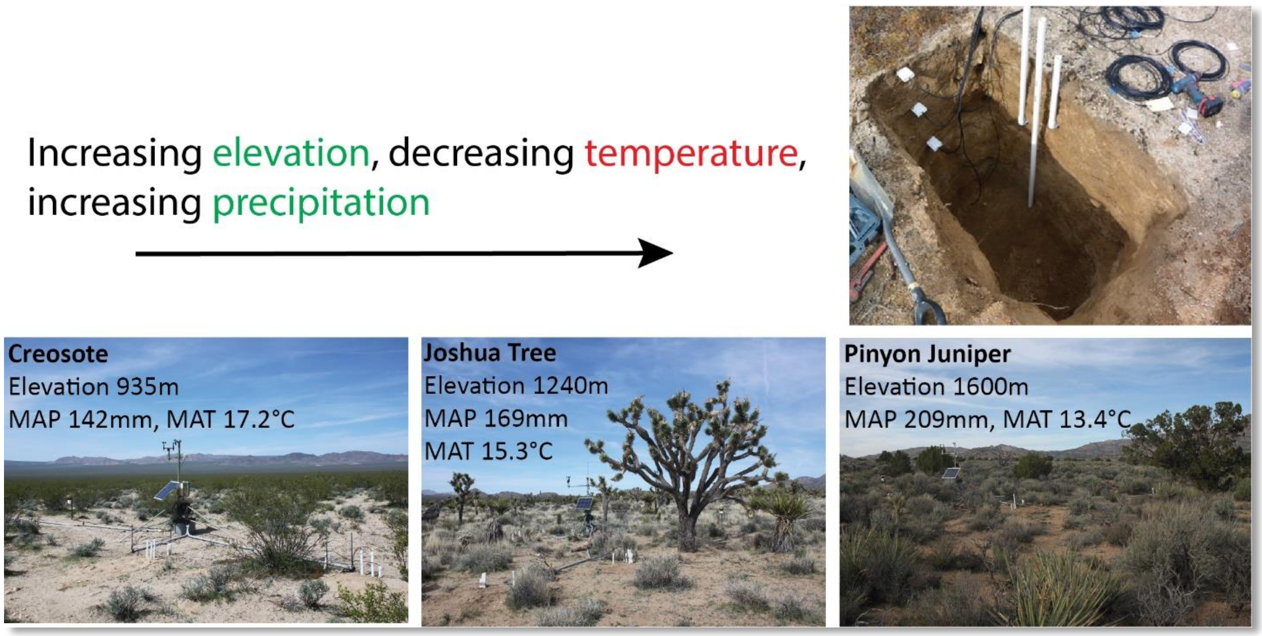
Map showing all study sites referenced in this report.

Source: Google Earth (www.earth.google.com). Image: Landsat/Copernicus. Map data from LDEO-Columbia, NSF, NOAA

At each site, three soil pits were excavated (including bare soil and under-canopy profiles) and instrumentation installed to continuously monitor meteorological and soil conditions (Figure 2). A meteorological station monitored air temperature, relative humidity, downwelling photosynthetically active radiation, wind speed and direction, precipitation and atmospheric pressure. Soil pits were excavated to a depth of greater than 1.3 meters and then each exposed soil horizon was described and sampled. Sensors were installed in the exposed pit faces to measure volumetric water content, temperature, and water potential at depths of 5, 25, 50, and 125 centimeters. Bulk density cores were collected at the same depths as the installed sensors. To install soil CO_2 sensors, the project team excavated a horizontal, cylindrical cavity 20 cm into the exposed soil pit face to accommodate a length of one-inch PVC tubing, added a 90-degree PVC elbow at the outer edge of the cavity, and extended PVC tubing to the soil surface. The soil pits were then backfilled, and solid-state soil CO_2 sensors were lowered to the PVC elbow. The PVC tubing was capped and sealed with silicone sealant above the soil surface. Data from all sensors were logged at 10-minute intervals with a Campbell Scientific datalogger.

Soil pits were excavated, and in-situ monitoring began in January 2017; the sites are still being maintained and continue to produce data. Data is retrieved manually from the dataloggers every two to three months. This collection also allows the team to repair and maintain the instruments and collect additional samples or information as required.

Figure 2: Mojave Preserve Climosequence Study Sites



Mojave Preserve Climosequence Study Sites. Top: soil pit showing in-situ monitoring instrumentation. Bottom: Climosequence sites along an elevation gradient spanning the three major Mojave ecological zones.

Source: University of California, Berkeley

Soil samples from each horizon were transported back to Berkeley, dried, and processed for further analysis. At each site, depth profiles of bulk density, particle size distribution, bulk mineralogy, organic carbon and nitrogen content and isotopic composition (weight percent organic C and Nitrogen [N], $\delta^{13}C_{organic}$, $\delta^{15}N_{organic}$), carbonate content and isotopic composition (weight percent calcium carbonate [$CaCO_3$], $\delta^{13}C_{carbonate}$, $\delta^{18}O_{carbonate}$), and the chemical composition of saturated paste extracts were measured.

Climate Transect of Archived Soil Samples

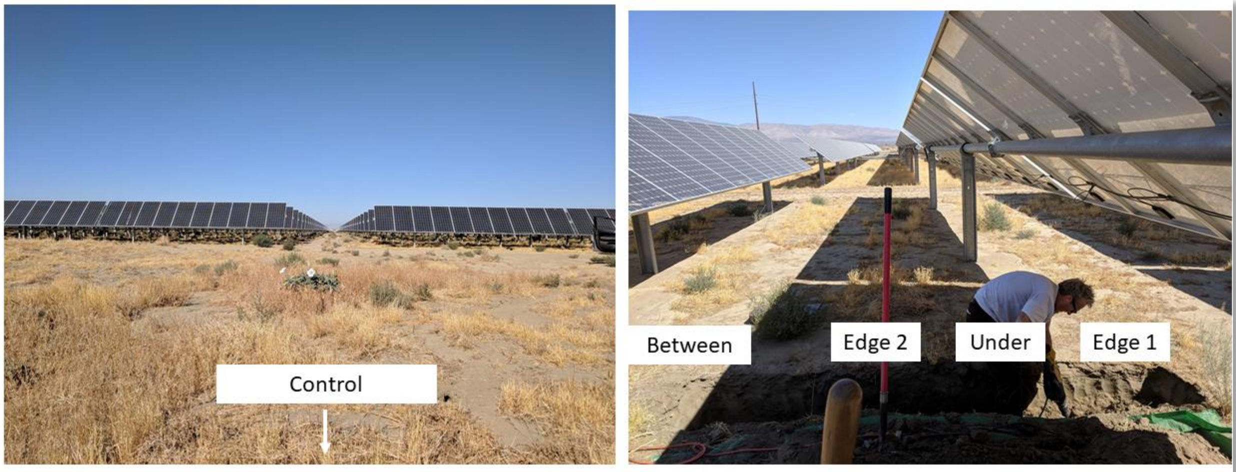
In addition to the Mojave Preserve climosequence, soils were sampled from an elevation sequence of six sites originally sampled by the USDA in 1973 ("Radiocarbon Climosequence"—Figure 1). The goal of this sampling was to measure the radiocarbon (^{14}C) content of soil organic carbon at the sites in 1973 and 2018 to constrain the rate at which organic carbon is being cycled in these systems, and how that rate varies as a function of climate. Archived splits of the original samples were obtained from the USDA national laboratory in Lincoln, Nebraska, and the 2018 resampling was done by the project team in January 2018. Soil organic C and N content, and the isotopic composition ($\delta^{13}C$, $\delta^{15}N$) as well as the radiocarbon content (^{14}C) were measured for both sampling dates.

Characterizing Local Microclimate, Soil Conditions, and Carbon Balance at Utility-Scale Solar Installation

To determine how utility-scale solar installations influence soil conditions and thus soil carbon cycling in desert systems, in-situ monitoring at a SunPower utility-scale solar plant in Rosamond, California was implemented in a manner similar to that done at the Mojave Preserve Climosequence. Access to a utility-scale solar installation proved to be a long and challenging process. SunPower Inc., who was the industry partner, did not maintain ownership of installations once they were developed, and the ownership of all facilities refused to allow site monitoring due to what appeared to be legal or press concerns, even with SunPower's assistance. Finally, in the spring of 2018, a site built by SunPower that contracted energy sales to Stanford University was identified. Months of negotiations began between the ownership and the University of California (UC), over the nature of the work and liability issues. UC attorneys were concerned with the level of UC liability commitments, and thus the agreement had to wait to go to a meeting of the UC Board of Regents, who had to approve the final agreement. Once this occurred, a meeting with on-site project managers was set up, and a research design was approved.

In September 2018, three team members excavated a trench perpendicular to a row of panels (allowing soil samples and in-situ monitoring to examine (a) between panels, (b) at panel edges, and (c) directly under the center of panels [Figure 3]). Soil horizons were identified, described, and sampled before in-situ monitoring equipment equivalent to that used at the Mojave Preserve climosequence sites was installed. A control soil pit, about 200 meters away, was trenched, sampled, and instrumented; a weather station was also installed at the control site to monitor meteorological conditions. The control site and panels are located on abandoned agricultural land—representative of the degraded land where most utility-scale solar installations in this region of the Mojave are now being built. A sparse plant cover, consisting primarily of annual grasses and forbs, exists on the control site, and vegetation is maintained at low levels under the panels. Continuous monitoring of meteorological and soil conditions at the control and under panel sites allowed researchers to (a) quantify how utility-scale solar installations influence parameters relevant to soil carbon cycling (for example, evaporative demand, heat fluxes, and soil water dynamics) and (b) develop model parameterizations representative of solar installations to use in soil biogeochemical models. This in-situ monitoring was supplemented with ex-situ analysis of organic carbon and carbonate content (weight percent organic C and $CaCO_3$), as well as their isotopic composition ($\delta^{13}C_{organic}$, $\delta^{13}C_{carbonate}$, $\delta^{18}O_{carbonate}$) to determine if measurable changes to the soil organic and inorganic carbon pools occur as a result of solar panel installation and operation on a timescale of years (the site was installed in 2015).

Figure 3: Monitoring Setup at Rosamond Solar Site



Soil pit excavation and in-situ monitoring installation at the Rosamond solar site, showing locations of monitored soil profiles.

Source: University of California, Berkeley

Predicting Response of Soil Carbon Stocks to 21st Century Climate and Acute Land Use Change: Biogeochemical Modeling

The extensive observations have been coupled with two biogeochemical models—DayCent, to model organic carbon dynamics, and HYDRUS to model soil physics and inorganic carbon dynamics—to predict how soil organic and inorganic carbon will respond to perturbations on a decadal timescale.

DayCent is a widely used ecosystem model that simulates greenhouse gas flux dynamics (CO_2, methane [CH_4], and nitrous oxide [N_2O]) on a daily timescale. It has been under development since the 1980s and represents soil organic carbon cycling, hydrological processes, plant productivity, and other ecosystem process in great detail (Parton et al. 1998). Much of the model is based on empirical relationships developed in shortgrass prairie ecosystems of North America, but the model has been adapted to run in numerous other environments. Here Daycent was parameterized using data from three climosequence studies in the Mojave Desert region—the MNP climosequence from the current investigation, in addition to two climosequences in Nevada (Fish Lake Valley and Kyle Canyon) on the Mojave/Great Basin periphery (R.G. Amundson, Chadwick, and Sowers 1989; Oerter et al. 2018). The research team used the model to simulate soil organic carbon stocks and soil respiration fluxes at all of these sites and validated the simulations against observations. Downscaled regional climate projections were then assembled for all three climosequence studies and forecasts of soil carbon stocks and soil respiration to 2100 were created.

The HYDRUS 1D soil physics model, coupled to the UNSATCHEM major ion chemistry module, was used to model the response of the soil inorganic carbon pool to utility-scale solar installation. A large number of reactive transport codes have been developed in recent years, capable of simulating unsaturated flow, heat transport, and reactive chemistry in the vadose zone. For the modeling effort in this investigation, key capabilities included the use of:

- Atmospheric boundary conditions (time-dependent upper boundary for heat, water, and chemical fluxes).
- Feedbacks between water content and plant evapotranspiration.
- Reactive chemistry, including kinetic control of mineral precipitation/dissolution reactions.

Given these requirements, the HYDRUS suite of codes (Šimunek et al. 2006; Šimůnek, van Genuchten, and Šejna 2008) was chosen based on its strength in modeling heat and water dynamics in highly unsaturated (low-water) systems. HYDRUS was developed specifically for soil systems, and thus explicitly accounts for atmospheric boundary conditions (precipitation and potential evapotranspiration) and root water uptake. The built-in UNSATCHEM module (Simunek, Suarez, and Sejna 1996), in turn, tracks major ion chemistry, including CO_2 production from root and microbial respiration and carbonate system reactions (including kinetic rate laws for calcite precipitation). In the future, this modeling effort will be extended to include reactive transport models of the Mojave Climosequence sites developed in HP1 (Jacques and Simunek 2005), which integrates the HYDRUS codes for simulating water and heat transfer with the PhreeqC geochemical code (Parkhurst and Apello 2013). This will help develop more nuanced chemical representations, including user-specific kinetic rate laws, mineral precipitation-porosity feedbacks, and soil organic matter degradation/CO_2 production dynamics explicitly developed from the more than two years of in-situ observations at these sites.

CHAPTER 3: Project Results

3.1 Understanding Baseline Soil Carbon Cycling in Natural (Undisturbed) Ecosystems of the Mojave: Results from the Mojave Preserve Climosequence

The storage of organic carbon (and somewhat related, inorganic carbon) is determined by the balance between carbon inputs to soil, generally as dead plant biomass, and losses of organic carbon from soils, largely as respired CO_2. This balance is diagrammed in Figure 4.

Figure 4: A Diagram of the Soil Organic Carbon Cycle

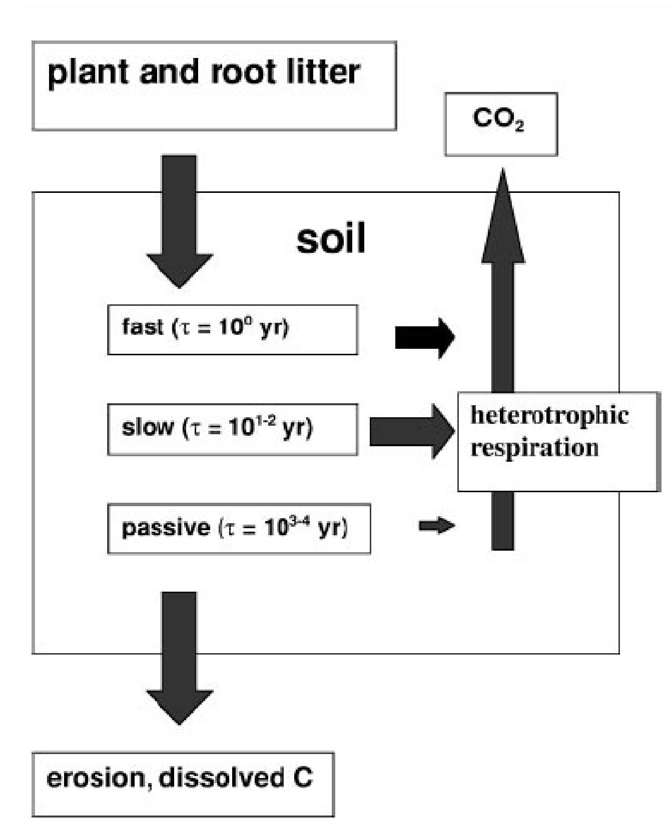


Diagram showing major components of the soil organic carbon cycle.

Source: Amundson (2001)

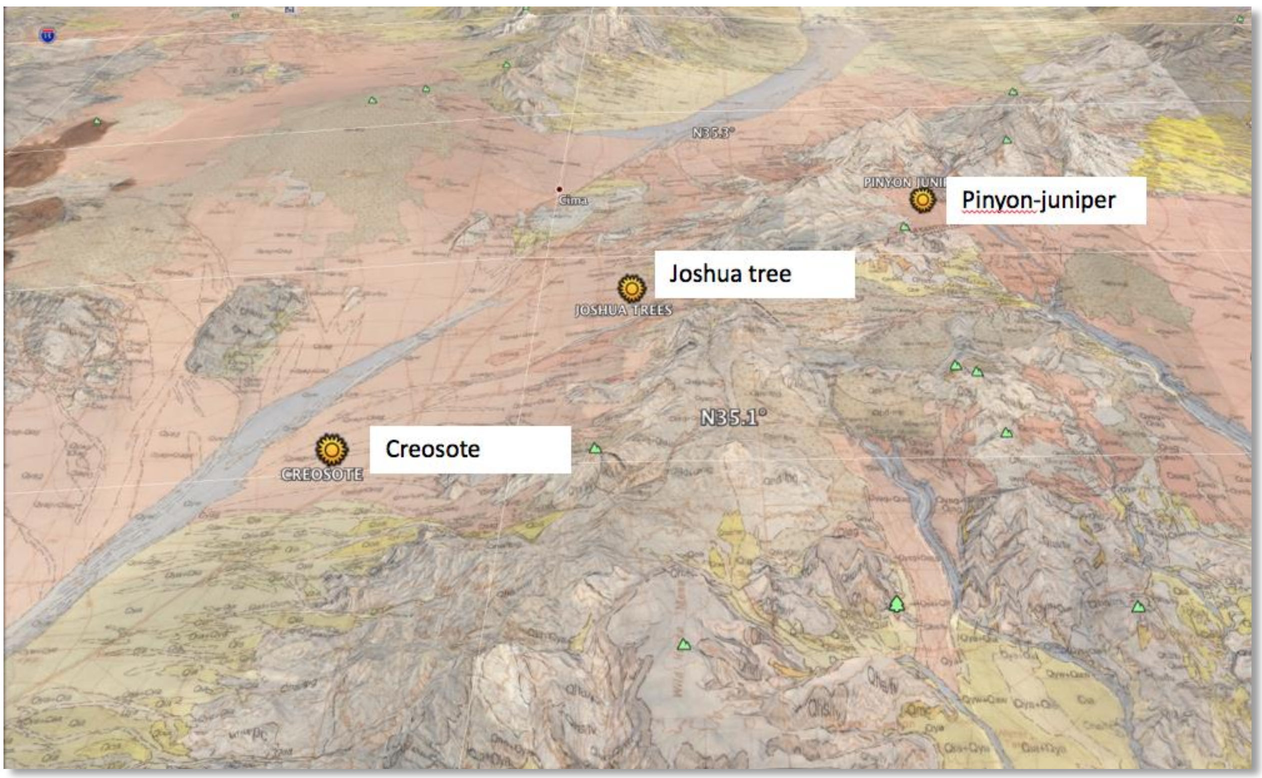
Climate is a first-order control on these processes. In deserts like the Mojave, plant productivity, which comprises the largest input to the soil organic carbon pool through leaf, root, and other organic matter inputs, is primarily limited by water availability. Ecosystem carbon losses from plant respiration and microbial decomposition of soil organic matter to CO_2 also require available water and tend to increase with temperature. Thus, along a desert climosequence in which precipitation (and plant production) increases and temperature decreases with elevation, it is expected that the amount of carbon in the soil will increase with elevation. An important metric of soil carbon cycling, which allows comparison of soils in different climate zones, is the rate at which the carbon stored in the soil organic matter pool is cycled, sometimes called the "turnover rate" or "residence time":

Turnover rate (years) = total soil carbon (kilograms [kg] C per square meter of landsurface to the depth of sampling)/soil CO_2 emission rate (kg C $m^{-2}y^{-1}$).

The temperature sensitivity of this rate then can be used to predict how soil carbon storage will change as temperatures in a location change.

To focus the study on the climate effects, sites were selected where other state factors, such as geological parent material, age, and potential biota, were held as similar as possible under field conditions. Late-Pleistocene alluvial fan deposits were chosen and are comprised largely of sandy granitic materials (Figure 5).

Figure 5: Location of MNP Climosequence Overlain on Geological Map



Mojave National Preserve climosequence locations overlain on a geological map, demonstrating that all are located on granitic alluvium (shown in pink).

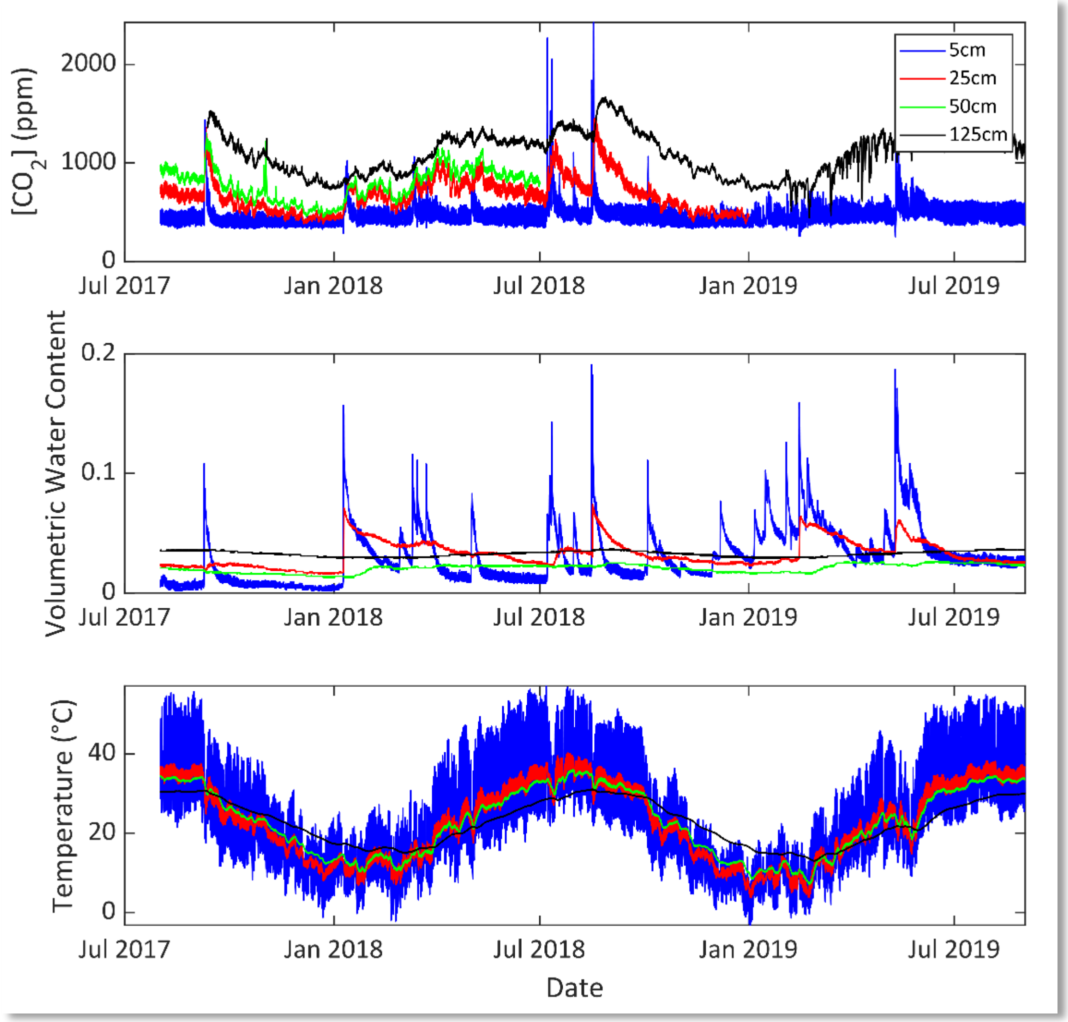
Source: Miller (2012)

There are now over two years of continuous measurements of meteorological and soil process data for inter-canopy and vegetated soil profiles at each of the MNP Climosequence sites. Data from the inter-canopy soil profiles at the two extremes—the lowest elevation, most arid Creosote site, and the highest elevation, least arid Pinyon-Juniper site—are shown in Figure 6 and Figure 7, respectively. Soil pits were excavated and in-situ monitoring commenced in January 2017, but the first six months of data were discarded as the soil returned to quasi steady-state after the excavation disturbance and recompacted, and initial issues with data collection were resolved.

What follows are some key general observations of CO_2 production and flux from the climosequence:

- There is higher CO_2 production with depth and with elevation, especially at the more densely vegetated, higher elevation sites.
- CO_2 production also more closely follows the seasonal temperature cycle at the higher elevation sites.
- There are higher CO_2 fluxes in under-canopy versus inter-canopy profiles.

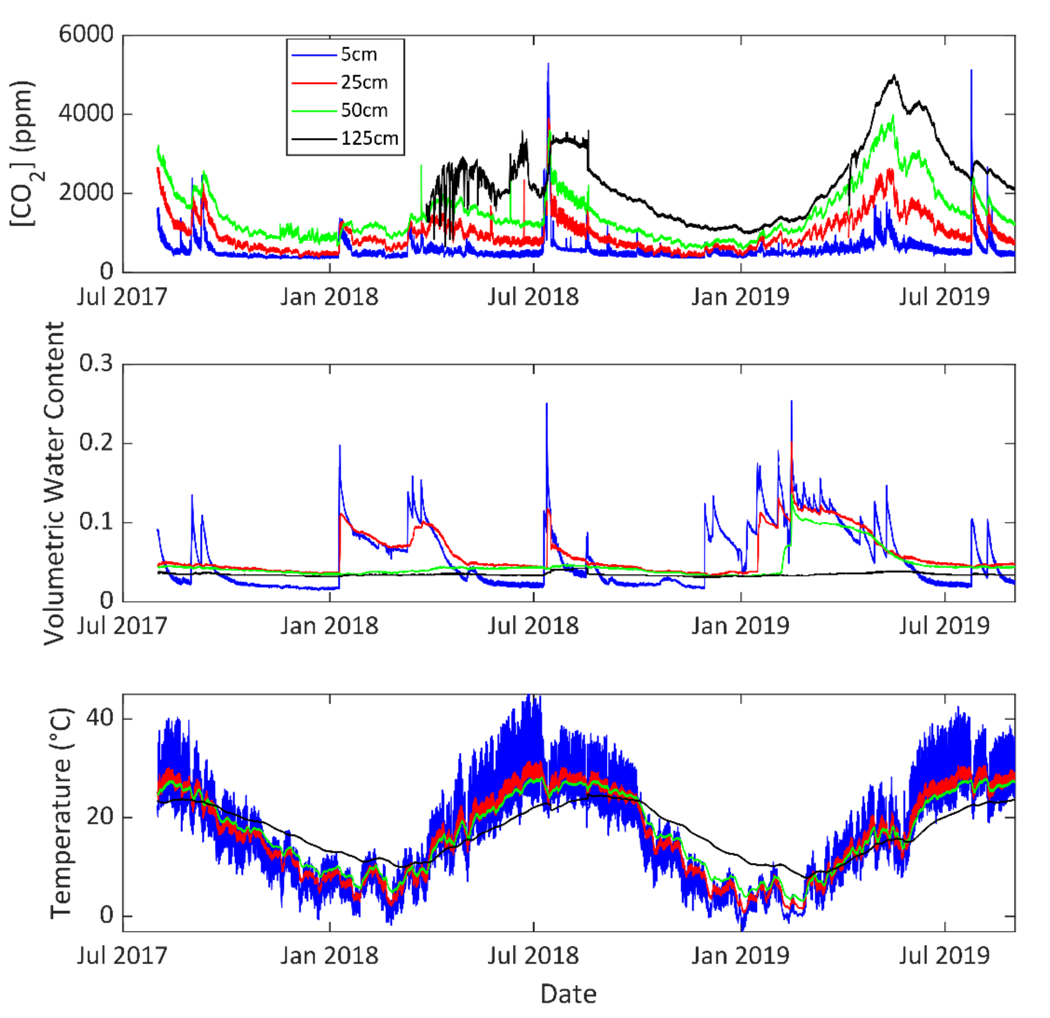
Figure 6: Two Years of In-Situ Monitoring Data from the Creosote Site



Two years of in-situ monitoring data from the bare-soil profile at the most arid site in the MNP Climosequence (Creosote), showing how soil CO_2 concentrations respond to seasonal changes in temperature and water availability. Data (top to bottom): soil CO_2 concentration, volumetric water content, and temperature. Colors denote depth in soil profile: 5 centimeters (cm) (blue), 25 cm (red), 50 cm (green), and 125 cm (black).

Source: University of California, Berkeley

Figure 7: Two Years of In-Situ Monitoring Data From the Pinyon-Juniper Site



Two years of in-situ monitoring data from the bare-soil profile at the highest elevation site in the MNP Climosequence (Pinyon Juniper), showing how soil CO_2 concentrations respond to seasonal changes in temperature and water availability. Data (top to bottom): soil CO_2 concentration, volumetric water content, and temperature. Colors denote depth in soil profile: 5 cm (blue), 25 cm (red), 50 cm (green), and 125 cm (black). Note the difference in y-axis values compared to Figure 6.

Source: University of California, Berkeley

Table 1 shows the trends in plant species composition, and the area of bare ground and biotic crusts versus elevation. In general, total plant cover increases with elevation; there is largely a unique flora at each elevation zone, and biotic crusts play an important role at the lowest and highest elevation zones.

Table 1: Percent Ground Cover at the Three Climosequence Sites

Ground Cover	Creosote	Joshua Tree	Pinyon Juniper
Bare	68.344	56.91	44.77
Burro Brush	8.652	1	
Creosote	15.328		
Crust	3.068		0.38
Dead Bush	2.432	5.42	
Low Grass	3.524	0.34	
Hopsage	0.244		1.39
Amnosia	0.784		
Dead grass		1.38	
Ephedra		11.82	5.71
Forb		0.05	0.42
Gramma		7.3	6.036
Mendota		0.39	
Muley grass		1.15	3.08
Needle grass		15.35	0.69
Pencil cholla		2.01	
Rubber brush		0.17	
Golden bush			2.04
Silver cholla		0.05	
Desert sage			5.67
Snakeweed			3.29
Banana yucca			1.09
Big sage			8.79
Juniper			4.8
Four wing salt bush			1.17

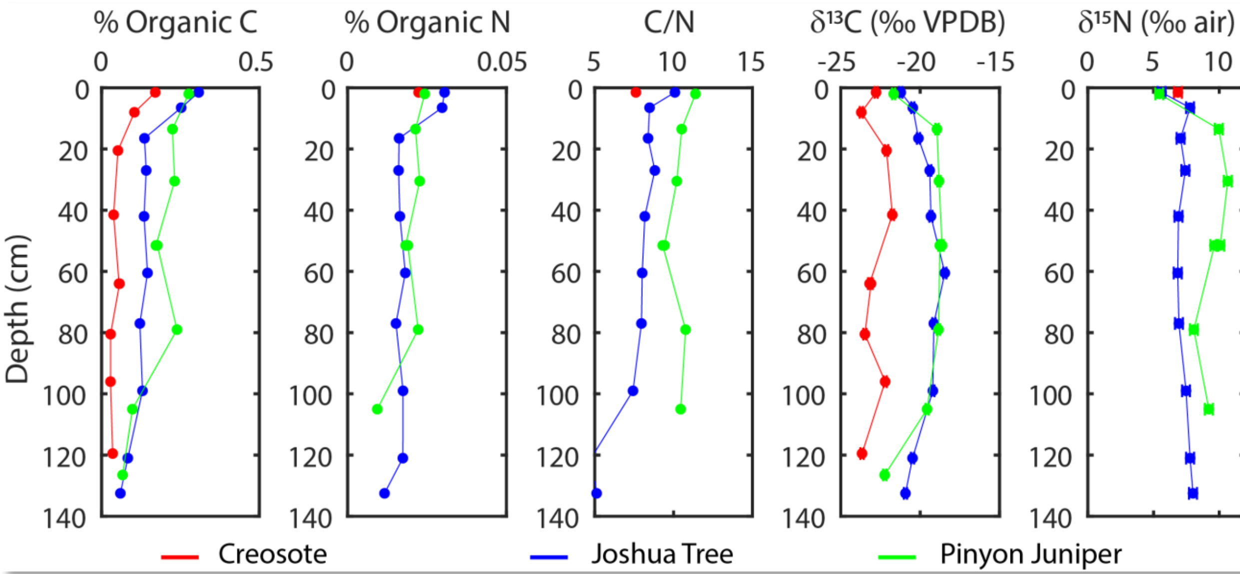
Source: University of California, Berkeley

Figure 8 shows depth trends in soil organic carbon and nitrogen with elevation. In general, the trends match well known patterns with decreasing temperature and increasing moisture:

- Soil carbon increased with elevation, as did nitrogen. The most arid elevation had too little nitrogen for measurement.
- The ratio of C/N increased with elevation, reflecting decreasing rates of carbon cycling and the presence of less intensively cycled organic matter.
- The stable isotope composition (ratio of 13C/12C) of carbon in the organic matter increased with elevation, reflecting modest inputs of C4 grasses that have a higher 13C content.

- Somewhat unexpectedly, the 15N (ratio to 14N) was higher at the highest elevation. The general pattern for the Mojave Desert (Oerter et al. 2018) and elsewhere (R. Amundson et al. 2003) is that $\delta^{15}N$ increases with increasing temperatures.

Figure 8: Soil Organic Carbon and Nitrogen Data From the Mojave Preserve Climosequence

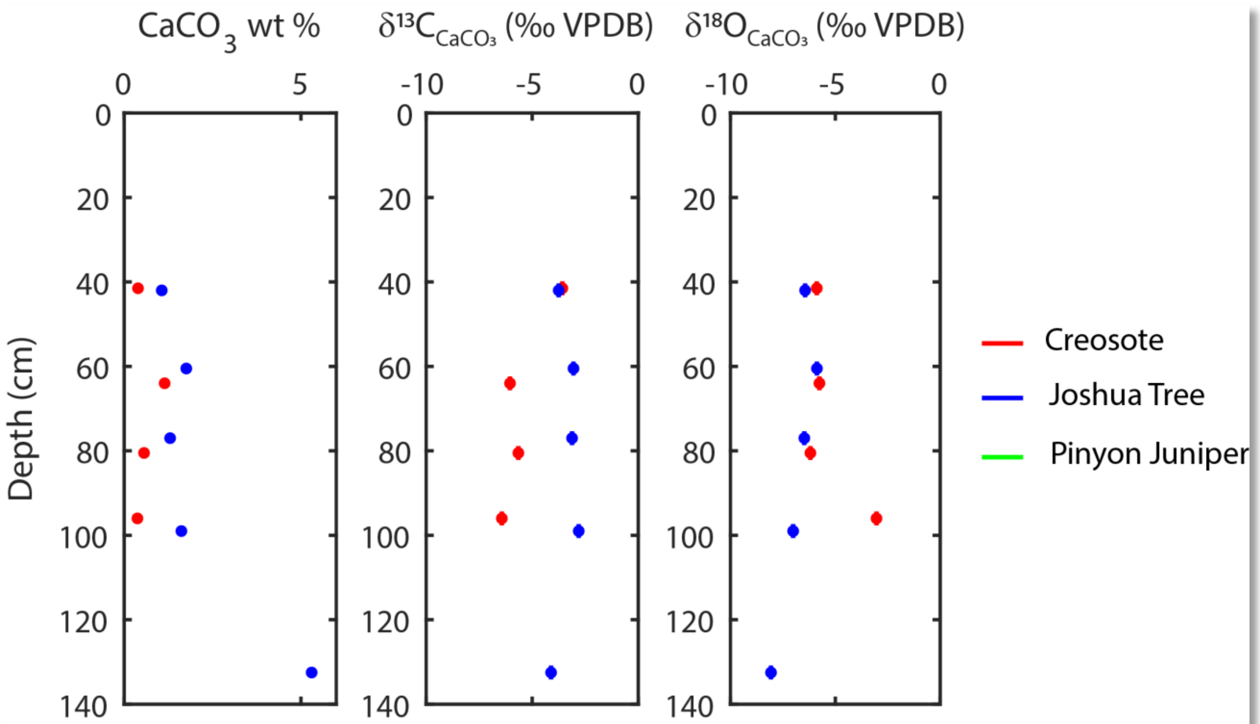


Soil organic carbon and nitrogen data from inter-canopy soil pits at each of the MNP Climosequence sites.

Source: University of California, Berkeley

Calcium carbonate ($CaCO_3$), the inorganic form of carbon in arid soils, is largely accumulated by the slow acquisition of calcium from atmospheric deposition and its downward migration into soils by dissolution and reprecipitation (Figure 9). The sources of the atmospheric deposition are the vast playas, stream channels, and outcrops in arid regions that supply dust and salts that are redistributed around the landscape. Thus, the amount of carbonate in soil is a function of the soil's age (carbonate is low in young soils) and elevation. As rainfall exceeds a critical threshold, the semi-soluble carbonate minerals are largely removed from the soil profile.

Figure 9: Soil Carbonate Content and Isotopes From the Mojave Preserve Climosequence



Soil carbonate data from inter-canopy soil pits at each of the MNP Climosequence sites. No measurable carbonate was found in the highest elevation, Pinyon Juniper profile.

Source: University of California, Berkeley

Elucidating and Parameterizing the Drivers of CO_2 Production

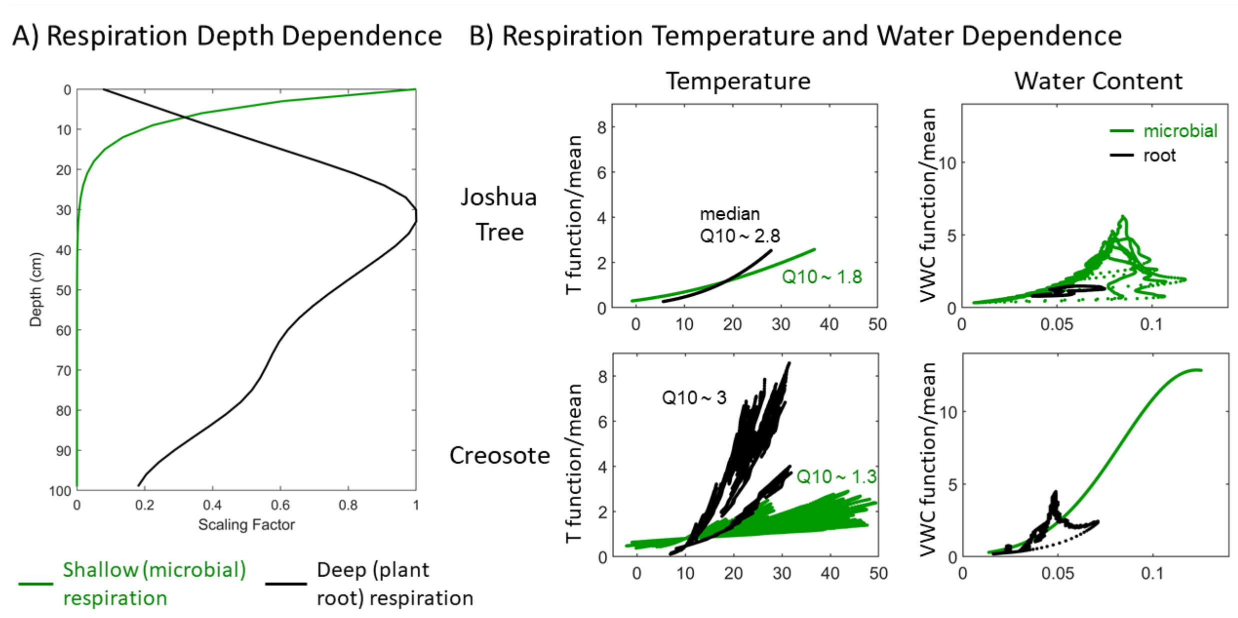
Developing a predictive understanding of carbon cycling and resultant CO_2 fluxes in arid regions like the Mojave Desert is particularly challenging because the carbon cycle is highly variable—spatially and temporally—and tightly linked to environmental forcings. Small shifts in the soil water and energy balance can lead to large changes in carbon dynamics. Thus, the first step in developing predictive carbon cycle models for Mojave soils is to develop a quantitative understanding of how soil respiration and CO_2 production vary as a function of soil conditions (temperature and water availability) in these water-limited environments.

The rich dataset of in-situ CO_2 measurements from the MNP Climosequence was analyzed using a production-diffusion framework, and continuous CO_2 production fluxes were calculated at various depths in the soil directly from the in-situ CO_2 data. The dependence of CO_2 fluxes on measured soil water and temperature data was then determined. Soil CO_2 fluxes were calculated using the flux gradient method (Vargas and Allen 2008); CO_2 production in each soil layer was calculated as the difference in diffusive flux across the top and bottom of the layer. This method relies on using an instantaneous steady-state assumption, where the production flux must equal the difference between the diffusive flux into and out of the horizon. The soil CO_2 production data were then fit to a model that uses quasi-mechanistic representations of the respiration flux—a model that assumes respiration can be described as a baseline respiration, scaled by functions of depth, temperature, and water content. The respiration functions were then fed into a forward, time-dependent production-diffusion model of soil CO_2

concentrations to further optimize some of the fitted parameters in the absence of a steady-state assumption.

It was observed that near-surface soils are highly sensitive to water availability and are more sensitive to water than soil deeper in the soil profile (especially at the higher elevation sites). Thus, soil CO_2 production cannot be modeled with a single temperature and water content dependence—instead, the respiration that dominates the surface must be separated from that of the deeper profile. This was done by assuming that total CO_2 production is comprised of a shallow respiration component that declines exponentially with depth and a deeper respiration component that follows the root distribution profile (Figure 10). This is functionally similar to assigning total CO_2 production to a heterotrophic (microbial) and an autotrophic (plant root) respiration term, although there was no attempt to experimentally differentiate microbial versus root respiration. It was found that the shallow respiration term is best fit by functions sensitive to instantaneous conditions, while the deeper respiration term is best represented with a function that is sensitive to average water content over the past month. This is consistent with the partitioning of respiration into microbial and root terms—microbial activity, and thus heterotrophic respiration, is thought to be concentrated in the top centimeters of the profile in desert soils (Fierer et al. 2003; Cable et al. 2009) and should be sensitive to instantaneous conditions, while root respiration by drought-adapted desert plants is more sensitive to antecedent conditions.

Figure 10: Modeled Depth, Temperature, and Water Content Dependence of Soil Respiration



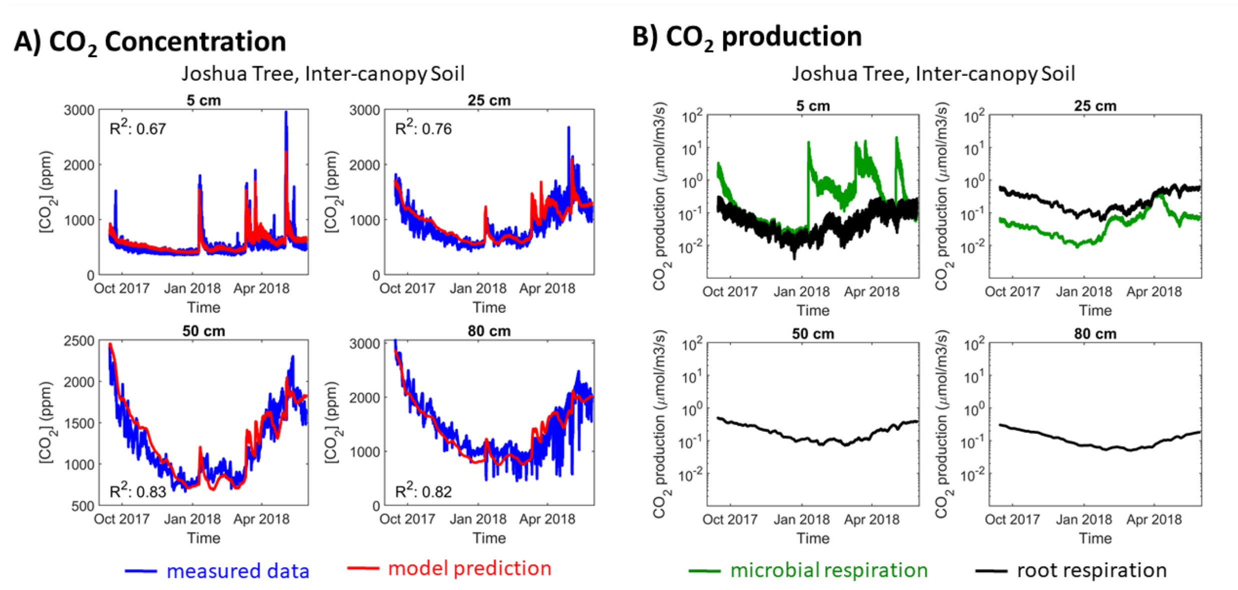
(A) Depth dependence of modeled CO_2 production functions, showing the exponentially declining microbial respiration and deeper, plant-root respiration that follows the root distribution profile. (B) Temperature and volumetric water content scaling factors for the microbial (green) and plant root (black) respiration, normalized by their means.

Source: University of California, Berkeley

The water content and temperature sensitivity of modeled respiration for the Creosote and Joshua Tree sites are shown in Figure 10B. At both sites, shallow microbial respiration is considerably less temperature-sensitive than the deeper root respiration—the Q10 (respiration response to a 18°F (10°C) increase in temperature) of shallow respiration is between 1.3 and 1.8, while that of root respiration is closer to 3. Notably, the shallow respiration temperature sensitivity is similar to the Q10 of 1.6 estimated for Mojave soils from chamber flux measurements (Cable et al. 2011). Most importantly, the surface-dominated microbial respiration is more responsive to water content (Figure 10B), and the arid Creosote has a greater water sensitivity relative to the higher, less arid sites.

Figure 11 shows the results of a time-dependent model of CO_2 production and diffusion embedded with these temperature and water-content dependent respiration functions for the inter-canopy soil at the Joshua Tree site. The model replicates observed patterns in CO_2 concentration over time and with depth (Figure 11A) and demonstrates how CO_2 production responds to seasonal environmental drivers (Figure 11B). The highly water sensitive microbial respiration in shallow soils (5 centimeter [cm] depth) increases by two orders of magnitude with the onset of winter monsoon rains in January 2018, while the root respiration largely responsible for production throughout the rest of the profile is more consistent throughout the year, generally following the seasonal temperature signal.

Figure 11: Results of CO_2 Production-Diffusion Model Driven by Temperature and Water-Sensitive Respiration



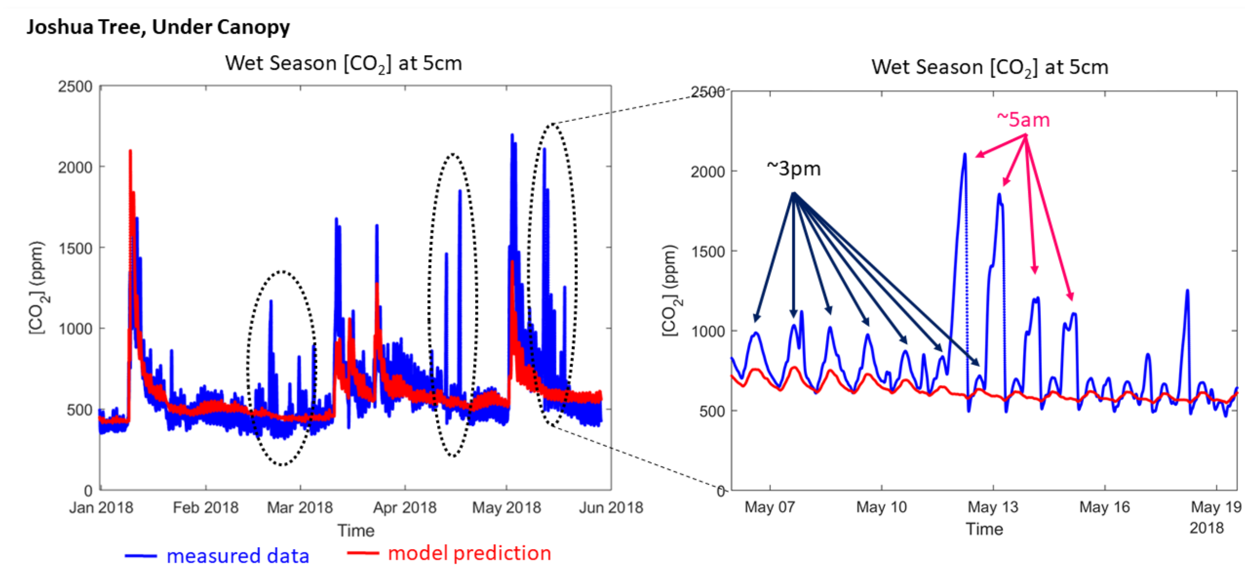
(A) Measured (blue) versus modeled (red) CO_2 concentrations and (B) associated CO_2 production functions for the inter-canopy soil profile at Joshua Tree (note the log scale of the y axis).

Source: University of California, Berkeley

Finally, the measurements revealed two patterns in CO_2 production that are not readily explained by the modeled temperature and water sensitive respiration functions: nighttime pulses of CO_2 at the mid- to high-elevation sites, and regular CO_2 consumption at the most arid site. At the Joshua Tree and Pinyon Juniper sites (less arid, more densely vegetated sites), repeated pulses of CO_2 in the shallowest soils (5 cm depth) at *night* (Figure 12) were observed. This was initially puzzling because no changes in volumetric water content were observed at this depth, and temperatures were at a daily minimum. However, while no changes in soil water content were observed, these episodes of nighttime CO_2 production correlated with changes in air temperature and relative humidity—specifically, they tended to occur when the air temperature approached the dew point temperature. Thus, it was hypothesized that these nighttime pulses in CO_2 are caused by dew production and the delivery of water to the immediate soil surfaces (including the litter layer). This is consistent with the finding of highly water-sensitive near-surface soils and suggests that understanding the delivery of non-precipitation sources of water is required to fully understand soil carbon cycling in these systems.

Placed in a broader context, the observation that CO_2 production rates can largely be explained using a two-source model is consistent with the emerging recognition that deserts have a continuous background set of carbon cycling processes that can be predicted on ambient temperatures and moisture (for example, Oerter et al. 2018), but that these ecosystems also have surficial biotic crusts and related communities that respond rapidly to the availability of water, the most limiting resource in these regions. The data and the model presented here form the first detailed analysis of complex behavior of Mojave Desert soil carbon cycles in response to these very different controls.

Figure 12: Nighttime Pulses of CO_2 Observed in Shallow Soils at High Elevation Sites

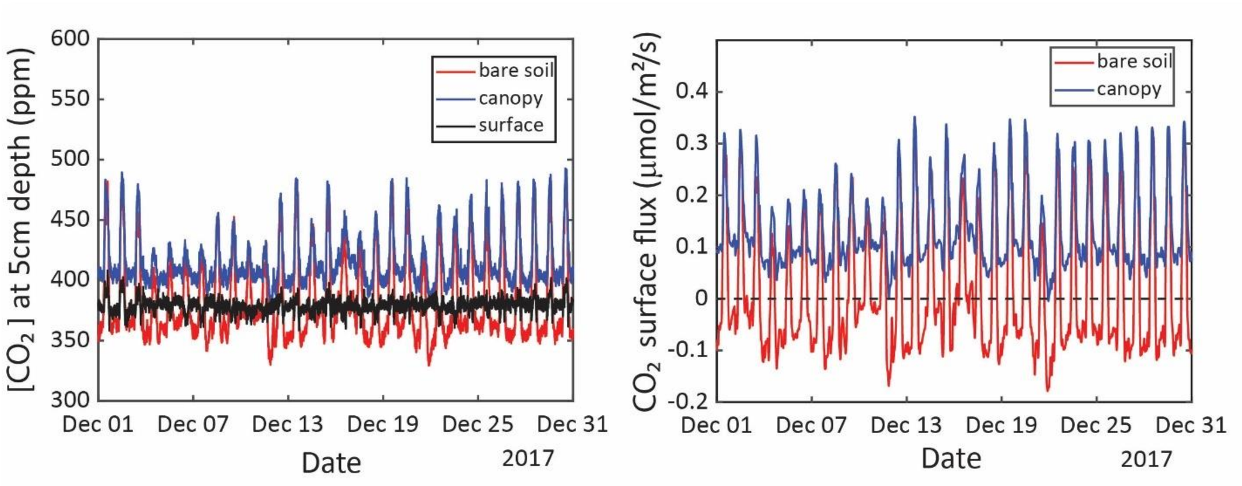


Observed nighttime pulses of CO_2 in the shallow soil at high elevation sites. The authors hypothesize this is due to dew formation and the delivery of water to the surface soils/litter layer.

Source: University of California, Berkeley

At the Creosote site, particularly in inter-canopy soils, a number of intervals when the soils become CO_2 sinks cannot be explained by biological processes alone. Negative CO_2 surface fluxes on the order of -0.1μmol/m^2/s regularly occur at night during the dry season in inter-canopy soils (Figure 13). These negative surfaces fluxes are driven by almost continuous nighttime CO_2 consumption into the soil surface (0–15cm depth), a flux which is strongly dependent on the amplitude of the diurnal temperature oscillation (daily maximum – minimum temperature). Acute CO_2 consumption events (up to -0.2μmol/m^2/s surface flux) also occur following precipitation in these inter-canopy, low elevation, soils. The mechanisms driving these CO_2 sinks are being investigated. For example, the consumption following rain events is consistent with CO_2 consumption due to $CaCO_3$ dissolution, potentially augmented by biocrust photosynthesis. However, back-of-the-envelope calculations suggest that thermal effects on the dissolved inorganic carbon system (carbonate mineral solubility and CO_2 gas partitioning into the aqueous phase) alone cannot account for the magnitude of CO_2 consumed at night throughout the year. In contrast, CO_2 adsorption on soil minerals, which is strongly temperature-dependent, is a possible mechanism for this nightly consumption. The role of CO_2 adsorption is being explored, as well as its role in observed consumption in other arid systems (Hamerlynck et al. 2013; Parsons et al. 2004; Ma et al. 2013).

Figure 13: Nighttime Consumption of CO_2 Regularly Observed During the Dry Season at Lowest Elevation Site



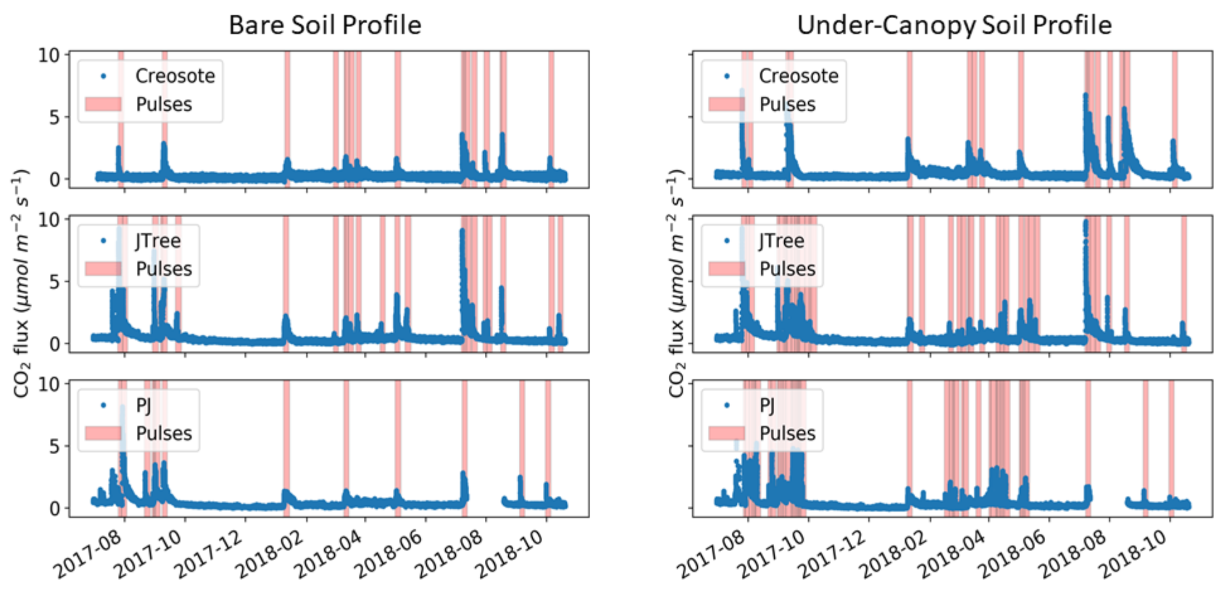
Near-surface CO_2 dynamics during drought at the lowest elevation, Creosote site. CO_2 concentration at 5 cm depth (left) and surface CO_2 flux (right) for the inter-canopy (red) and under-canopy (blue).

Source: University of California, Berkeley

Quantifying the Contribution of Ephemeral, Moisture-Driven Soil Respiration Pulses to Overall CO_2 Fluxes

As discussed above, this research opens insights into the very dynamic and surficial processes that cycle carbon in response to ephemeral changes in water availability. High-resolution, in-situ measurements from the MNP climosequence are being used to test elements of the "pulse-reserve" paradigm in arid land ecology (Reynolds et al. 2004), in which rainfall triggers pulses of growth, storage, and reproduction in plants and pulses of soil water availability and respiration in soils. An algorithm was designed to identify pulses in near-surface soil water content (5 cm depth) and surface CO_2 flux at each of the MNP sites based on the rate of change of the timeseries data. The "pulse" was determined to end when the variable (water content or CO_2 flux) returned to the 30-day rolling mean. Figure 14 shows the outcome of the CO_2 pulse identification algorithm, with surface flux pulses highlighted by red bands. In particular, note the significantly higher CO_2 fluxes observed in the under-canopy profiles relative to the inter-canopy profiles, especially at the most arid, Creosote site. This strong spatial variability is characteristic of the "islands of fertility" that develop in arid shrubland environments, where soil carbon and nutrients become concentrated in the soils surrounding shrubs and depleted in the interspace.

Figure 14: Identifying CO_2 "Pulses" in the MNP Climosequence Data

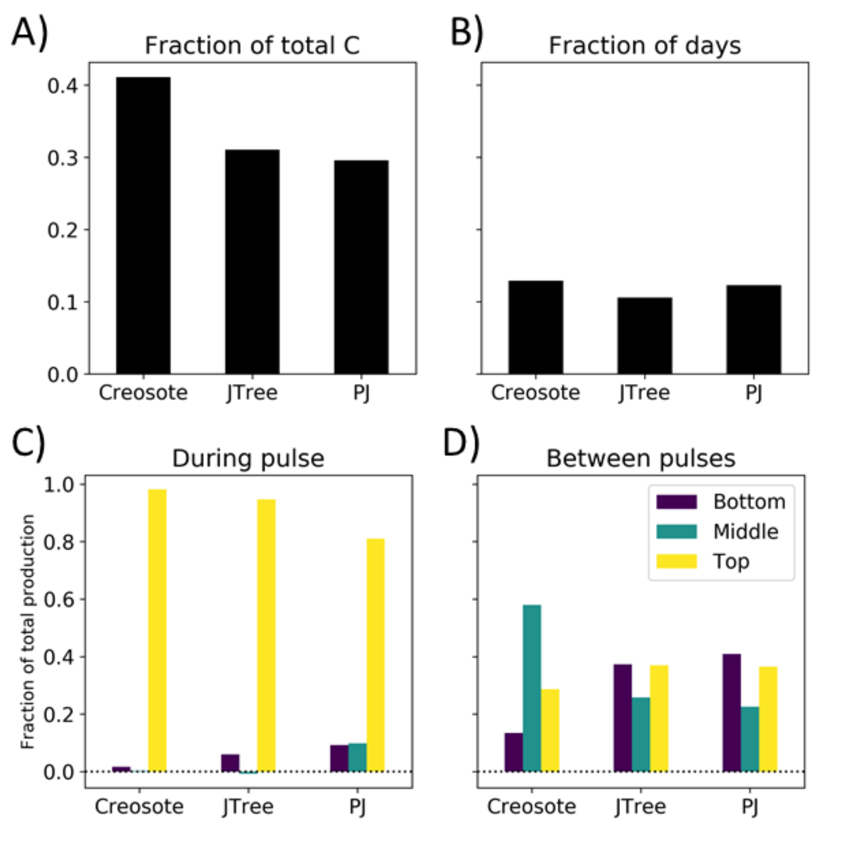


Outcome of the CO_2 pulse identification algorithm for the inter-canopy (left) and under-canopy (right) soil profiles from the MNP climosequence sites. Pulses in surface CO_2 flux are highlighted by red bands.

Source: University of California, Berkeley

The contribution of pulses to the total observed CO_2 flux has been calculated for each profile. From July 2017 to November 2018, CO_2 pulses contributed a larger fraction of cumulative CO_2 efflux at the low elevation, arid Creosote site than at the higher elevation Joshua Tree and Pinyon Juniper sites (Figure 15A). However, pulses accounted for a similar percentage of time at all sites, suggesting greater importance of pulses to total ecosystem carbon balance at arid sites (Figure 15B). During surface flux pulses, CO_2 released from soils was largely produced in the top 12.5 cm of the soil profile (71 percent to 99 percent—Figure 15C), whereas between pulses, the majority of CO_2 efflux was produced in middle to lower depths (50 percent to 70 percent—Figure 15D). This is consistent with the previous findings that highly water-dependent microbial respiration dominates surface soil CO_2 respiration during monsoon periods (Figure 11B), while deeper root respiration more closely follows the seasonal temperature cycle. In addition, pulse events, though infrequent, were larger (in terms of CO_2 produced) and briefer during warm months, as compared to CO_2 pulses during cooler months. Pulse size was significantly related to precipitation event size but was not positively correlated with time since the last pulse. These results suggest that changes in the frequency and timing of precipitation events in the Mojave will be accompanied by consequent shifts in total annual soil CO_2 efflux and in the soil carbon pools contributing to this flux.

Figure 15: Contribution of CO_2 Pulses to Overall CO_2 Efflux



Results from pulse dynamics analysis. (A) Fraction of total cumulative CO_2 efflux produced during CO_2 pulse events at each MNP Climosequence site. (B) Fraction of days identified as belonging to a CO_2 pulse at each site. (C) and (D): Fraction of total CO_2 production occurring in three depth intervals—top (2.5–15 cm), middle (15–37.5 cm), and bottom (below 37.5 cm)—(C) during pulse events and (D) between pulses.

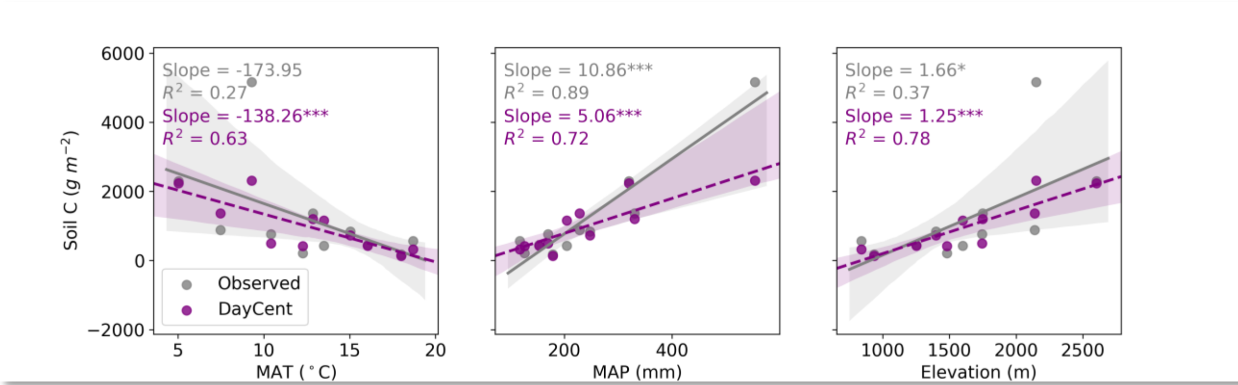
Source: University of California, Berkeley

Modeling Soil Organic Carbon Dynamics: Results From the Daycent Ecosystem Model

Earth system models, those used to explain and predict the global carbon and climate cycles in the near future, typically include carbon cycle modules that simulate the contribution of vegetation and soil processes to the complex earth system. One of the challenges is to test and improve the ability of these modules to accurately describe the diversity of Earth's soil environment, and in particular, deserts, which have been largely understudied. Thus, the authors parameterized and ran the DayCent model, an ecosystem model that simulates soil C and N cycling and resultant greenhouse gas fluxes, using data from the MNP climosequence sites as well as eight sites from previous climosequence studies in the Mojave (R.G. Amundson, Chadwick, and Sowers 1989; Oerter et al. 2018). This was undertaken as a proof-of-concept investigation into whether DayCent could be used to model soil carbon dynamics in arid ecosystems (far removed from the temperate prairie systems originally used to develop the model) and to provide an estimate of how soil organic carbon stocks will respond to 21st-century climate change. DayCent recreated climate-driven patterns in soil carbon storage observed at the climosequence sites; SOC declined with increasing temperature and increased with increasing precipitation (Figure 16).

Model predictions of soil CO_2 flux were compared to field observations, continuously measured (in 2017–2019 at the MNP climosequence) and intermittently sampled (2013–2014), of soil respiration calculated from soil gas profiles. DayCent consistently overestimated soil respiration and surface CO_2 fluxes (at some sites by up to 600 percent compared to profile measurements), indicating that further calibration of DayCent or changes to model mechanisms will be needed to produce regional estimates of greenhouse gas fluxes in arid regions like the Mojave.

Figure 16: Observed and Modeled SOC Stocks Using the DayCent Model



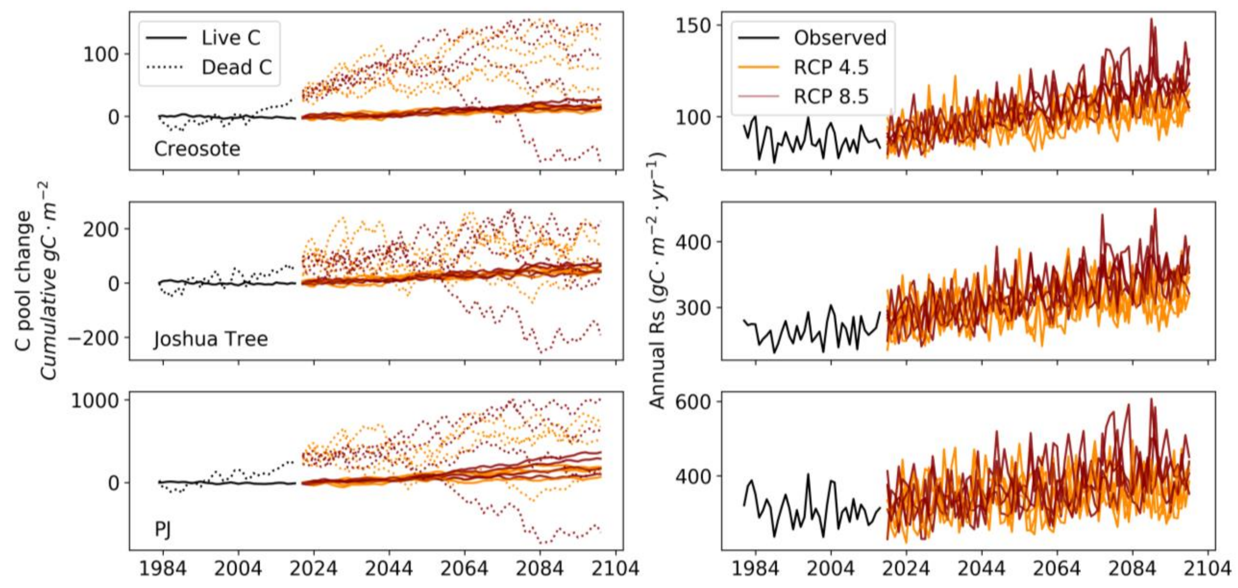
Observed and modeled soil organic carbon (top 20 cm) as a function of mean annual temperature (left), mean annual precipitation (middle), and elevation (right). Linear models were fit to observed and modeled data points, with statistics shown in the matching text. Shading represents the 95 percent confidence interval for the fitted model

Source: University of California, Berkeley

DayCent was then used to predict how soil carbon stocks and CO_2 fluxes will evolve in response to 21st-century climate change. At each site, the DayCent model was run with downscaled climate projections from four different Global Climate Models and two emission scenarios (RCPs, or representative concentration pathways from Intergovernmental Panel on Climate Change), which were chosen based on recommendations from the CalAdapt initiative. RCP 4.5 represents an optimistic scenario in which climate-forcing emissions peak near the year 2040 and then decline, while RCP 8.5 represents a pessimistic scenario in which emissions continue to rise through 2050 and then plateau near the year 2100. The results of these simulations suggest a range of possible outcomes over the coming century as the climate of the southwestern United States becomes more arid (Figure 17). From 2018 to around the middle of the century, DayCent projected increases in total carbon storage (above-ground + soil C) of around 50 g/m^2. The mechanisms that underly this predicted carbon increase likely are driven by the assumption that there will be more nutrients available for plant production, and thus plant inputs are assumed to offset increased rates of microbial decomposition. After this point, projected soil carbon stocks appeared to level off or decline under most models of projected climate. Notably, under the Average model and RCP 8.5 scenario, total C stocks declined significantly below the 1981–2018 average value based on measured climate. Under most climate models and emissions scenarios, DayCent projected soil respiration/CO_2 flux increases through the end of the century (Figure 17).

As discussed below, other empirical observations point to likely soil carbon losses as Mojave Desert temperatures increase. The mismatch between DayCent predictions, and those of empirical observations, is one of the major challenges facing Earth System soil carbon modelers, and this project will be useful as an evaluation of these discrepancies.

Figure 17: Projected Changes in Soil Organic Carbon Stocks and Soil Respiration



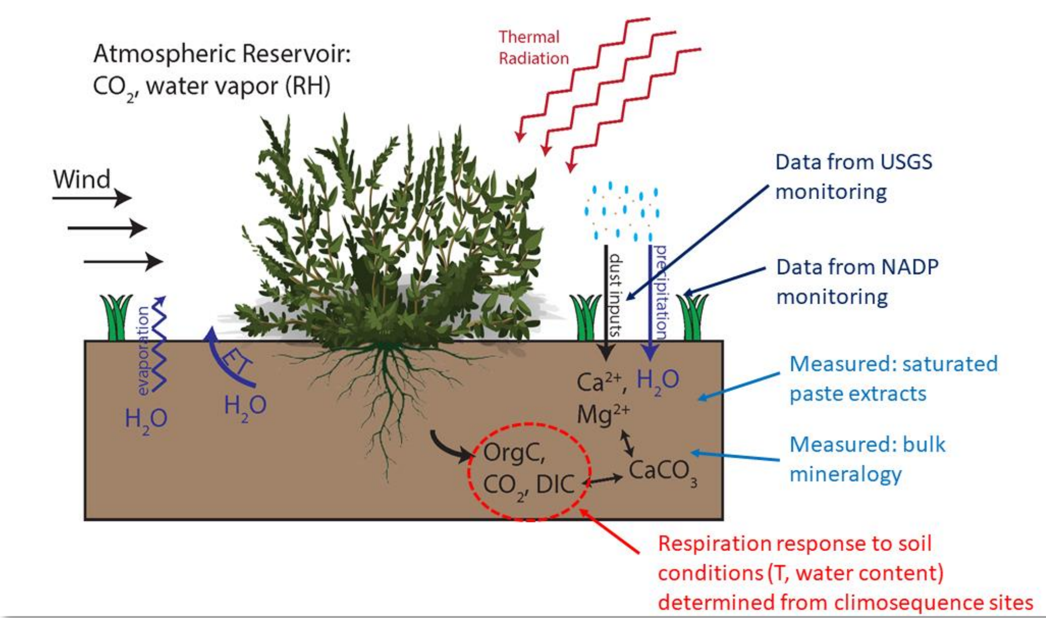
Mojave Preserve climosequence aboveground and belowground organic carbon (left panels), and soil respiration (right panels) forecast with the DayCent model between 1981 and 2100.

Source: University of California, Berkeley

Development of a Soil Hydrogeochemical Model to Describe Soil Inorganic Carbon Dynamics over Decadal Timescales

As a major component of this CEC project, observations from the MNP climosequence sites were used to develop and parameterize a reactive transport modeling framework to describe inorganic carbon dynamics in Mojave soils. Carbonate minerals in soils form largely from calcium delivered to the soils as calcium-bearing dust that settles on the land surface and is dissolved and transported into the soil by precipitation. The calcium, combined with carbonate anions derived either from previous calcium carbonate dissolution or from biologically-produced CO_2, leads to carbonate formation when the soil subsequently dries out (Breecker, Sharp, and McFadden 2009). The amount and distribution of soil inorganic carbon is thus controlled by factors that influence the calcium input rate (dust composition and deposition rate), water input and distribution (precipitation rates, soil hydrology, and potential evapotranspiration), soil temperature (which influences reaction kinetics and mineral/gas solubility) and soil CO_2 concentrations (from plant root respiration and microbial degradation of soil organic matter) (Monger and Gallegos 2000; Schlesinger 1985—Figure 18).

Figure 18: Modeling Soil Carbon Processes in Arid Soils



Processes influencing calcium carbonate precipitation/dissolution in arid soils and sources of data used to parameterize them in the reactive transport model developed here.

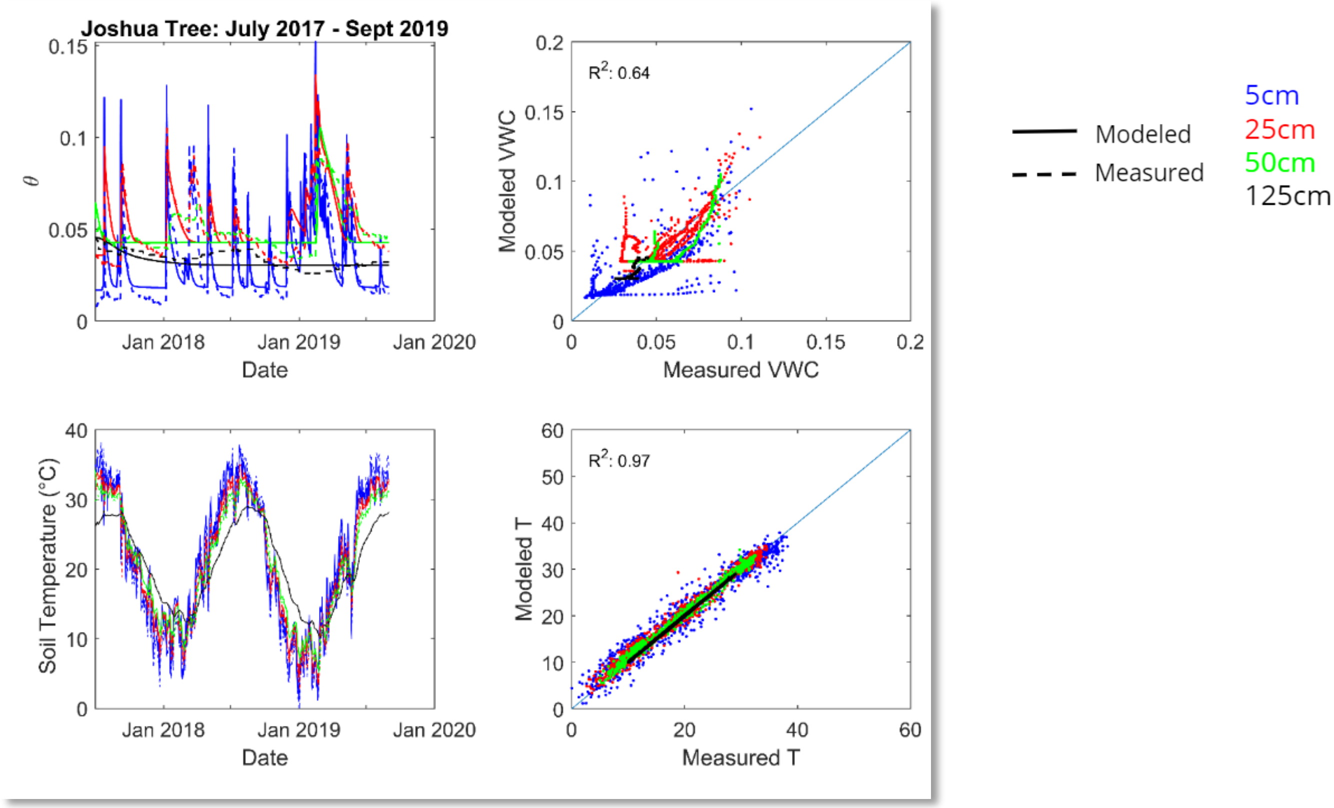
Source: University of California, Berkeley

Modeling inorganic carbon dynamics over short (annual–decadal) timescales requires an accurate description of three critical mode components: water, heat, and chemistry. Key data sources for these components are as follows:

- Water dynamics. Unsaturated flow at the climosequence sites was parameterized through a combination of measured particle size data (used to calculate van Genuchten unsaturated flow parameters using pedotransfer functions) and model optimization to observed volumetric water contents. Measured meteorological data were used to calculate potential evapotranspiration using the Penman-Monteith combination equation and much simpler Hargreaves equation. It was discovered that the Hargreaves equation produced estimates of evapotranspiration highly similar to those calculated from the Penman-Montieth method at all MNP climosequence sites; thus the Hargreaves estimate was deemed acceptable for estimating potential evapotranspiration for longer-timescale simulations where detailed meteorological data are not available. A combination of measured and literature root profiles and root water uptake data were used to parameterize water removal via plant uptake.
- Heat dynamics. The in-situ monitoring data was used to develop functions to describe the temperature at the soil surface (top of the soil profile) and at 125 cm depth (bottom of the soil profile) as a function of readily available air temperature and solar radiation data following Kemp et al. (1992). This provided a much more realistic representation of the large amplitude diurnal temperature oscillations experienced by near-surface soils than assuming the soil surface temperature was equivalent to the air temperature.

Figure 19 shows results from modeling heat and water dynamics at the mid-elevation, Joshua Tree site. The model parameterization described above captures the salient details in heat and water transport in these highly water-sensitive ecosystems.

Figure 19: Modeling Heat and Water Dynamics at the MNP Climosequence



Comparison of modeled (solid lines) and measured (dashed lines) soil water and heat dynamics at the Joshua Tree (mid-elevation) site over two full years of in-situ monitoring.

Source: University of California, Berkeley

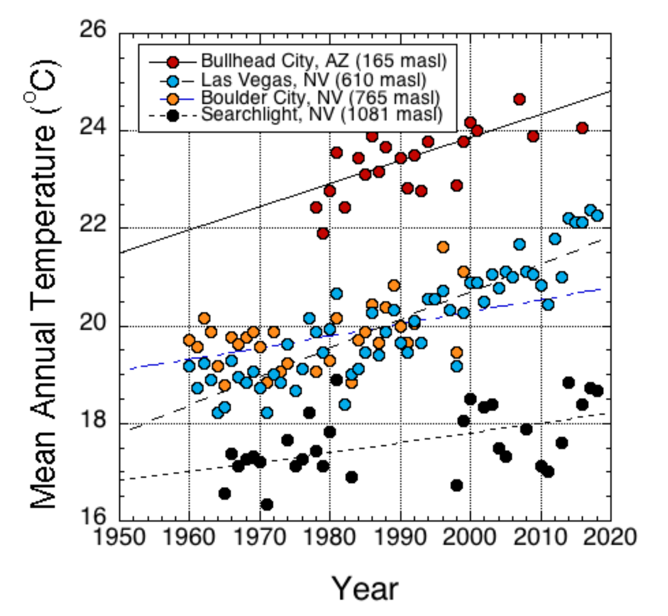
- Chemistry. Measured soil organic carbon and carbonate contents were used to constrain current soil C stocks at each site. Saturated paste extracts were used to parameterize the major ion content of the initial soil water. Data on precipitation chemistry was obtained from the National Atmospheric Deposition Program and additional divalent cation + alkalinity inputs from dust deposition were estimated from long-term dust monitoring data from Reheis et al. (2009). Dry deposition cannot be modeled using HYDRUS; thus, the Ca^{2+}, SO_4^{2-}, and alkalinity derived from estimated annual $CaCO_3$ and $CaSO_4$ dust fluxes was evenly distributed in the precipitation chemistry throughout the year. Functions describing CO_2 production via microbial and root respiration as a function of soil conditions (temperature and water availability) were developed for each of the MNP climosequence sites as outlined previously in this section. These custom-developed functions will be incorporated into forthcoming models developed using HP1 (HYDRUS coupled to PHREEQC); current models using the UNSATCHEM module use the findings outlined above to inform parameterization of the built-in CO_2 production functions (for example, microbial respiration in these arid soils is much more water-sensitive and less temperature-sensitive than the default settings developed for grassland ecosystems).

Work to explore how inorganic carbon speciation changes over short timescales at these natural sites is still ongoing, but this modeling framework is used to explore the potential response of the soil inorganic carbon pool to utility-scale solar installation in Section 3.3.

3.2 Understanding the Climate Sensitivity of Organic Carbon Cycling in the Mojave: Results from the Mojave Radiocarbon Climosequence

A second climosequence was designed consisting of six soils previously sampled in 1973 along an elevation gradient following the California–Nevada border (Figure 1) to measure the radiocarbon (^{14}C) content of soil organic carbon at the sites in 1973 and 2018 to constrain the rate at which organic carbon is being cycled in these systems, and how that rate varies as a function of climate. Measurements of organic C, organic N, C/N ratio, stable C and N isotopes, and radiocarbon (^{14}C) for the 1973 soils (obtained from the National Resources Conservation Service [NRCS] archive) and 2018 soils (sampled by the project team in January, 2018) are shown below (Figure 21). Unexpectedly, nearly all surface (and near-surface) samples in 2018 have less C and lower C/N ratios than those in 1973, violating the assumption commonly made for such short-term comparisons that the soils were at steady state. Upon tabulating climate data for the 4 cities within or near the transect, it was discovered that the mean annual temperatures have increased between ~2.7°F (1.5˚C) to 5°F (3˚C) (Figure 20)—an increase that meets or exceeds the maximum anticipated increase under the Paris Accords. Thus, the present Mojave Desert is a natural experiment for how the remainder of the Earth may react in the first half of this century.

Figure 20: Mean Annual Temperature Change From 1950 to 2019 in the Mojave Region

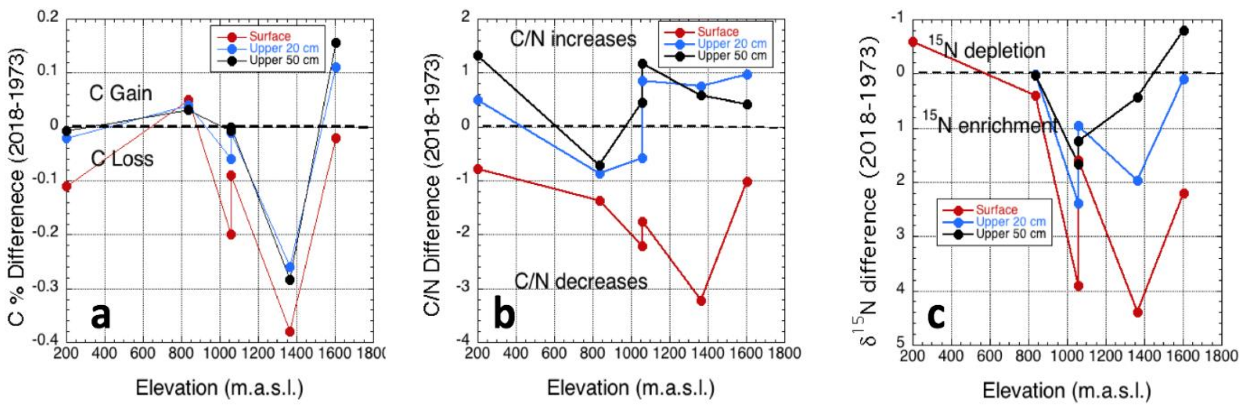


Trends in mean annual air temperature since 1960 for four cities within or near the study area. All data are from the National Oceanic and Atmospheric Administration web portal and can be accessed here: https://www.ncdc.noaa.gov/cdo-web/.

Source: University of California, Berkeley

Although there are some exceptions, the 2018 soils (particularly in the uppermost portions of the profiles) have (1) less C, (2) lower C/N ratios, and (3) higher $\delta^{15}N$ values than those in 1973 (Figure 21). All these changes are consistent with soils in warmer climates: (1) increasing temperature increases decomposition rates by microbes (and reduced water availability decreases plant inputs), (2) increasing temperatures cycle organic matter to greater extents, reducing C/N ratios, and (3) there is a strong global trend that soil N increases its ^{15}N content with increasing temperatures due to the loss of ^{15}N-depleted N forms with increasing temperature (R. Amundson et al. 2003; Houlton and Bai 2009). Moreover, it was found that surface soils exhibit larger changes than deeper soils.

Figure 21: Organic C and N Content and Isotopic Composition of Radiocarbon Climosequence Sites

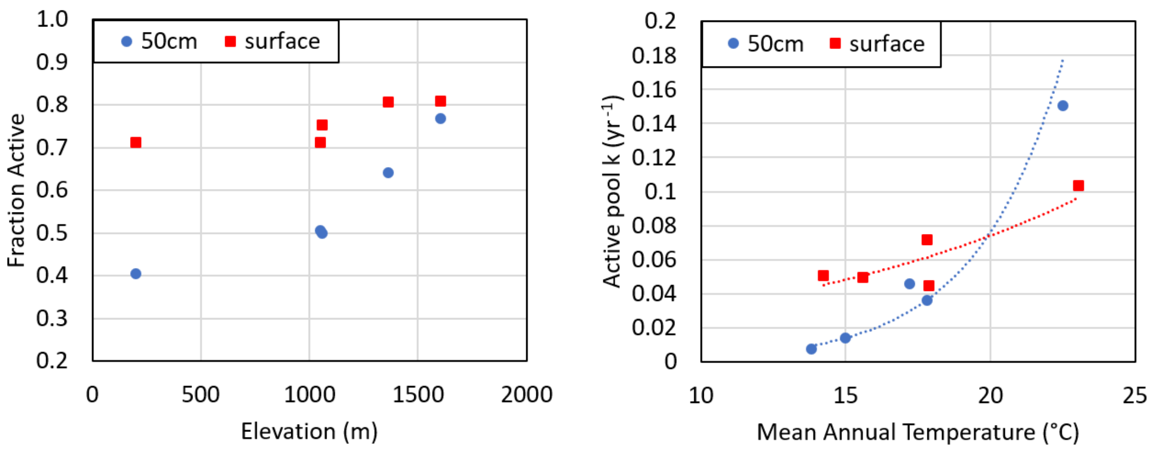


Changes in (a) weight percent organic carbon, (b) organic C/N ratio and (c) $\delta^{15}N$ organic observed in surface (red), upper 20 cm (blue), and upper 50 cm (black) soils from the Mojave radiocarbon climosequence.

Source: University of California, Berkeley

Radiocarbon changes in soil organic matter over time represent the uptake of the changing atmospheric $^{14}CO_2$ over time (as the atmosphere relaxes from a large atomic bomb ^{14}C input in the late 1950s). Thus, the amount of ^{14}C taken up is related to the rate of C cycling. Through the analyses of multiple soils (in differing climates), it is possible to then determine the temperature sensitivity of soil C cycling in a given region. A two-pool (one active, one passive pool with a set residence time [Baisden et al. 2013]), non-steady state carbon model was employed to model C contents and ^{14}C at these sites. This model analysis indicates that (a) the size of the "actively" cycling pool of carbon increases with elevation (declining temperature) and (b) the carbon decomposition rate increases with temperature (Figure 22). This confirms that soil organic carbon decomposition sensitivity to temperature increases with temperature in the Mojave, yielding a positive feedback loop between organic carbon decomposition, CO_2 production, and additional temperature rise as the climate warms.

Figure 22: Radiocarbon Modeling Results



Results from radiocarbon modeling. Model results indicate that (a) the size of the "active" carbon pool increases with elevation (declining temperature)—left panel and (b) the carbon decomposition rate increases with temperature—right panel.

Source: University of California, Berkeley

A caveat to this analysis is that desert soils exhibit a high degree of spatial variability—soil organic carbon and nutrient concentrations can vary up to a factor of two between interspace and under-canopy soils (Titus, Nowak, and Smith 2002). Although it is unlikely that the 1973 soils were sampled directly under vegetation, there is some uncertainty as to the original sampling location and whether the resampled soil profile represents the exact same soil. To address this, a second field campaign was undertaken to quantify the spatial heterogeneity in modern surface soils at these sites. Ten samples of the soil surface horizon were collected from stable landform surfaces randomly distributed within a 100 meter radius at each of the climosequence sites. Sample analysis is still under way, but these results will help determine how much of the observed declines in soil organic carbon and shifts in C/N and $\delta^{15}N$ can be attributed to spatial variability versus systematic changes in the rate of soil carbon cycling over time.

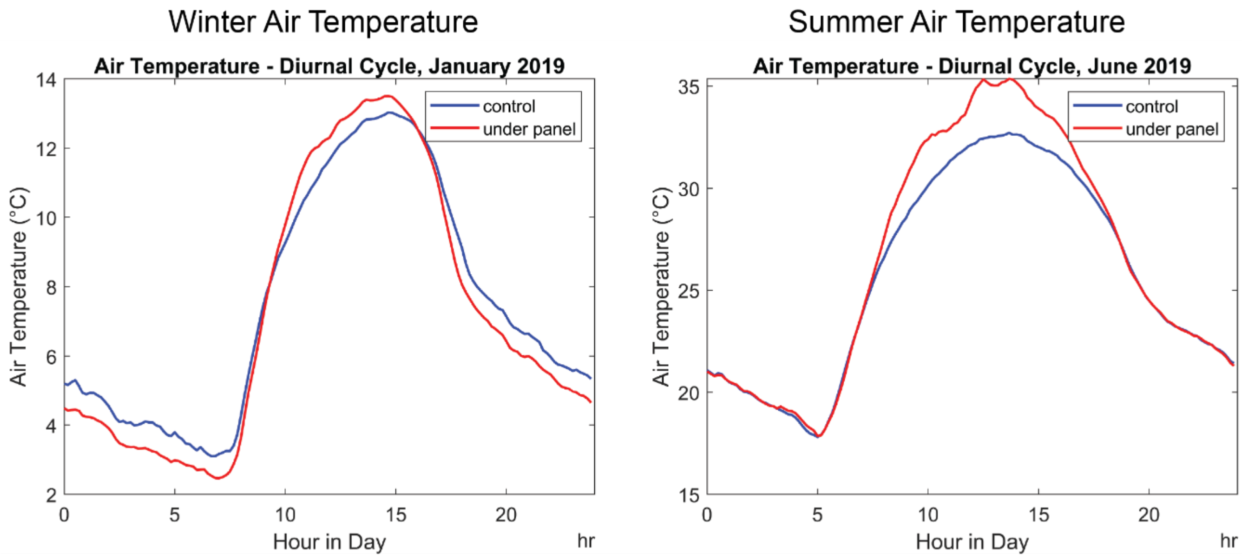
3.3 Investigating and Modeling the Influence of Utility-Scale Solar Installation on Soil Carbon Dynamics

In September 2018, the study of a utility-scale solar plant operated by SunPower in Rosamond, California was initiated (Figure 3). Soil trenches were excavated, and soil horizons were sampled and instrumented for in-situ monitoring beneath a row of solar panels and at a nearby control site immediately adjacent to the panels. The following sections detail observations of how the solar installation influences local micrometeorology and soil conditions, how those changes can be synthesized into changes to model inputs for 1D soil biogeochemical models; and finally, the results of a modeling study examining the potential effect of utility-scale solar installation on soil inorganic carbon dynamics over decadal timescales.

Results from Ex-Situ Soil Analysis and In-Situ Monitoring of the Rosamond Utility-Scale Solar Plant

Changes in micrometeorology due to the presence of panels included changes to air temperature, relative humidity, wind speed, and thus potential evaporative demand. Summertime maximum air temperatures are notably higher under the panels (an average of 5°F (3°C) higher than the control site) while during the winter, air temperature under the panels is ~2°F (1°C) colder at night and 2°F (1°C) warmer during the day (Figure 23).

Figure 23: Influence of Solar Panels on Air Temperature

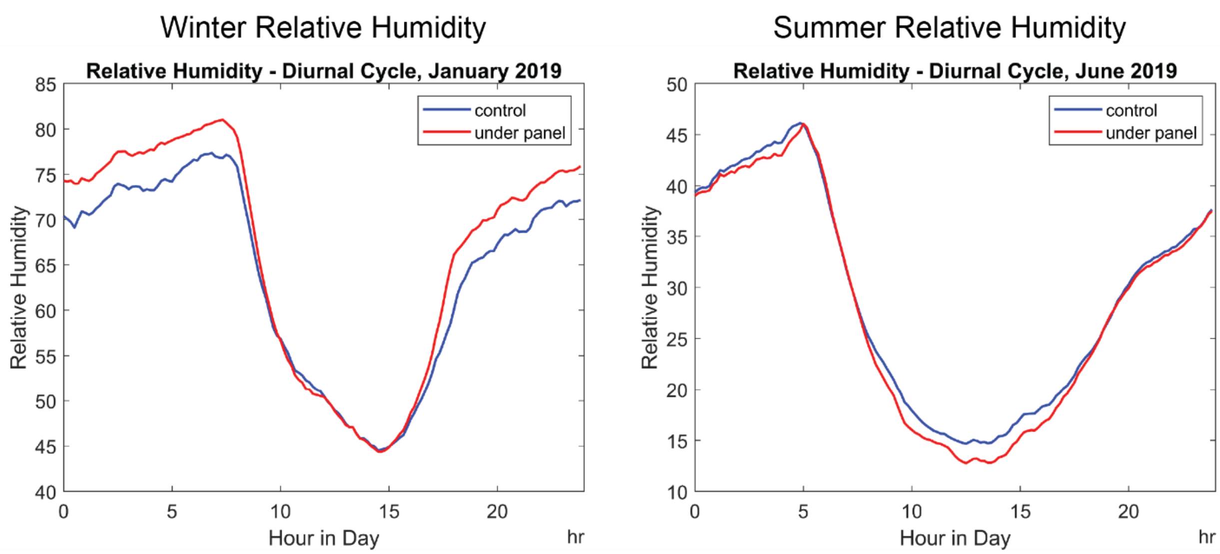


Diurnal cycle in air temperature at the control site (blue) and under the solar panels (red) during winter (left panel) and summer (right) months. The effect of solar panels on air temperature under the panels is especially strong during summer months, when daily maximum air temperature is 5°F (3°C) higher under the panels than at the control site.

Source: University of California, Berkeley

The influence of panels on relative humidity varies by season. During the winter, relative humidity is about 5 percent higher under the panels (Figure 24). If this increased humidity ultimately exceeds dewpoint, then this could stimulate respiration of CO_2 in surface soils if natural vegetation were present (as documented in the 'nighttime pulses' of CO_2 observed in the MNP climosequence). In contrast, during the dry season the relative humidity under the panels is either lower than or similar to that at the control site (Figure 24).

Figure 24: Solar Panel Influence on Relative Humidity is Season-Dependent



Diurnal cycle in relative humidity at the control site (blue) and under the solar panels (red) during winter (left panel) and summer (right) months.

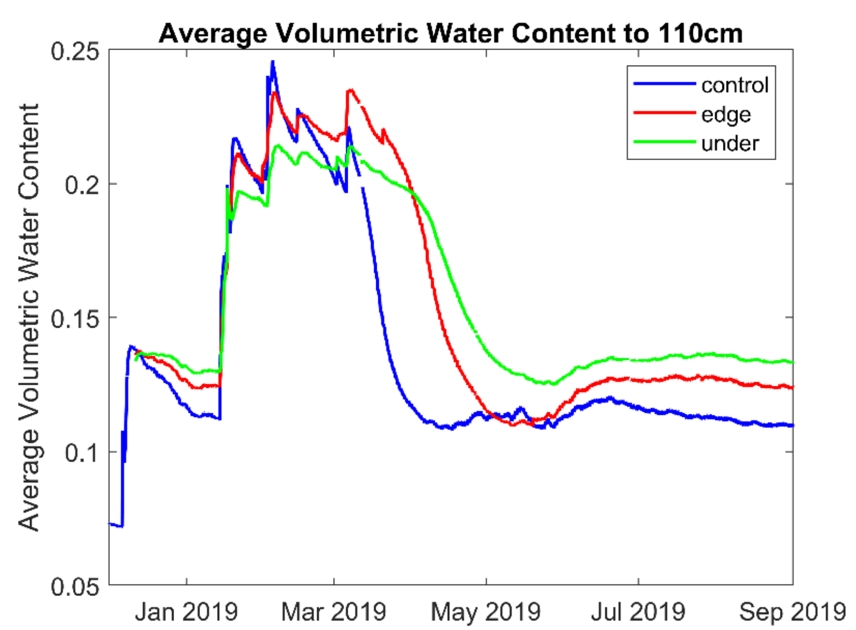
Source: University of California, Berkeley

Average wind speed is damped by the presence of panels: the average wind speed at the control site was 2.5 times higher than that measured under the panels. Combining these observed differences in meteorological conditions with literature estimates of how solar panels decrease incoming solar radiation (the soil under panels receives between 8 percent to 20 percent of incoming shortwave radiation—Adeh et al. (2018); Armstrong et al. (2016)) allowed researchers to calculate how the panels influence *potential evaporation,* a key parameter controlling the soil water balance. The solar site is minimally vegetated, so researchers assumed potential transpiration was negligible, and calculated potential evaporation using the Penman equation. The results indicate that potential evaporation is approximately a factor of two lower under the panels relative to the nearby control site.

Understanding how the installation of solar panels impacts the soil water balance at this site is complicated by the fact that the year of in-situ observations only captures a single wet season near the beginning of the observation period (January – April, 2019; soil trenches were excavated in September 2018). Unlike the dual-monsoon pattern of the eastern Mojave, the western Mojave has a strong single winter rainfall period. Thus, the rain events were recorded while the soil trenches were relatively fresh and had not had sufficient time to compact following the initial trenching disturbance.

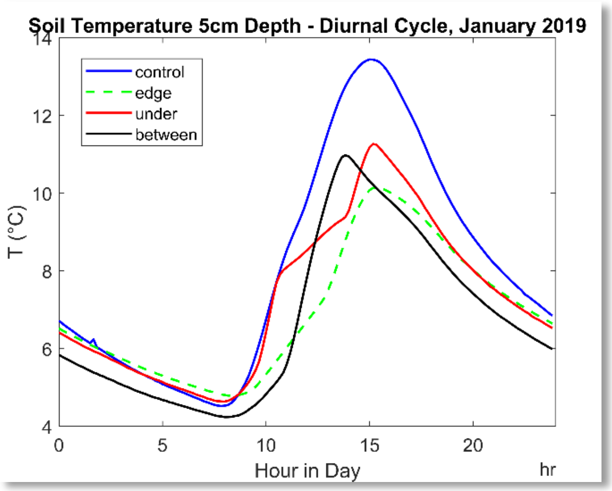
An understanding of how the panels influence soil water dynamics will improve as further data are collected, but a preliminary estimate of water balance differences can be developed by examining how the average water content in the soil profile (integrating water content to 110 cm depth) differs between the under-panel and control profiles (Figure 25). While instantaneous water content at any given depth is highly dependent on water infiltration dynamics that could be affected by preferential flow paths created during soil trenching, averaging water content to 110 cm removes the influence of subtle differences in infiltration. Examining how average soil water evolves through time in the control and under-panel profiles (Figure 25) demonstrates that, as expected, the soil directly under the solar panels receives less water than soils at the control site. During the wet season, the panel edge receives either an amount of water comparable to the control site, or more water than the control site. This is because the solar panels at Rosamond are sun-tracking and their tilt angle changes throughout the day. Observations are consistent with late-season rains occurring in the afternoon when water would be preferentially delivered to the west edge of the panel (where the project has instrumented the profile). Importantly, differences were observed in how the soil profiles dry down after the wet season, driven by differences in evaporative demand. The control site loses water much more rapidly, seen after the first rain in December and in the dry-down after the winter rains. The panel edge also dries out faster than the under-panel profile, consistent with higher potential evaporation at the edge due to higher incoming solar radiation (Figure 25).

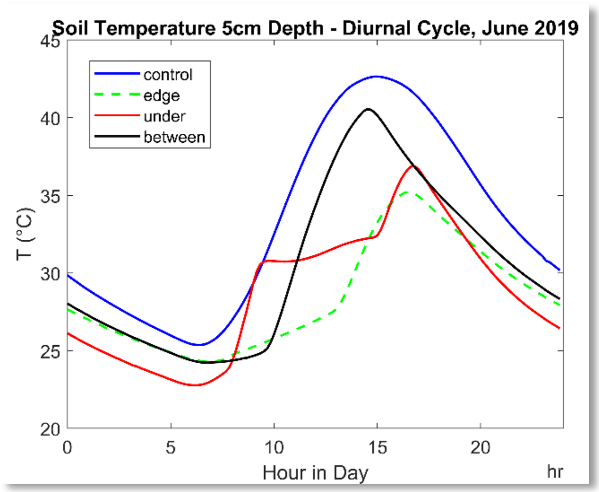
Figure 25: Influence of Solar Panels on Soil Water Dynamics



Average volumetric water content to 110 cm depth at the control site (blue), solar panel edge (red), and under the solar panels (green).

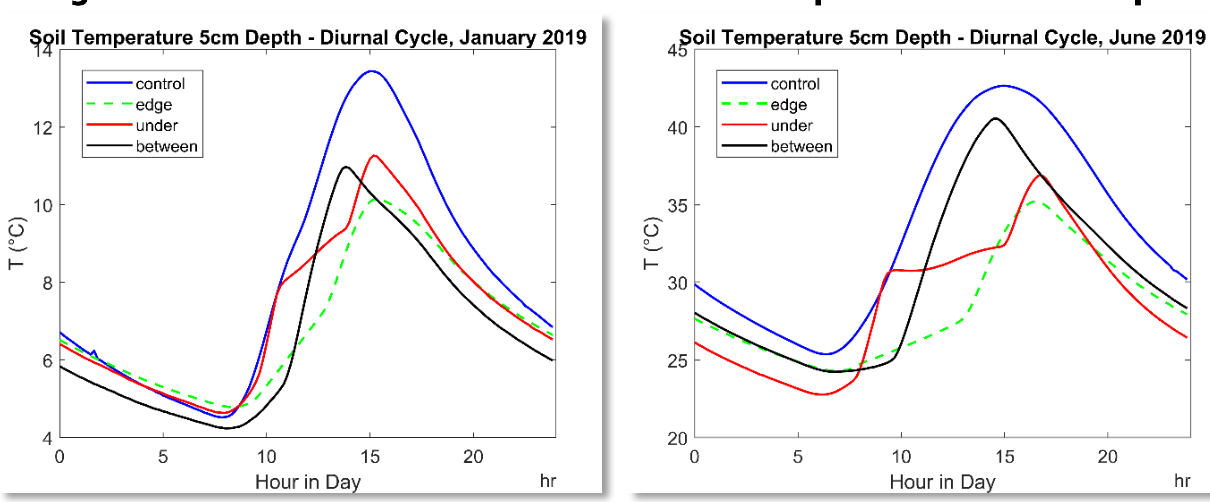
Source: University of California, Berkeley

Changes in heat dynamics (



) are reflected by soil temperature differences.

Figure 26: Influence of Solar Panels on Soil Temperature at 5 cm Depth



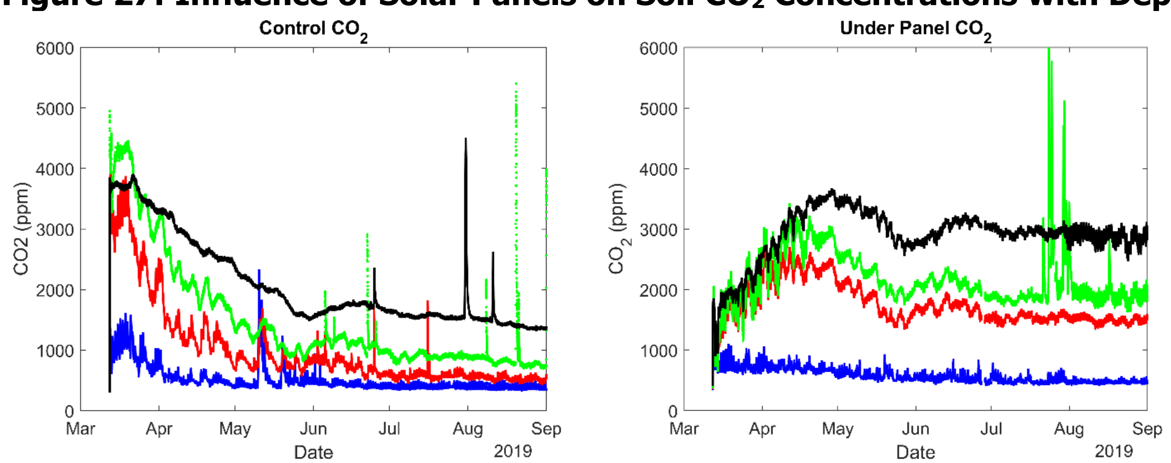
Influence of solar panels on the diurnal cycle of soil temperature at 5 cm depth during the winter wet season (left panel) and summer dry season (right panel) for control (blue), panel edge (green dashed), under-panel (red), and between panel (black). The soils under the soil panels are (a) significantly cooler than those at the control site at comparable depths, (b) have damped daily temperature oscillations and (c) exhibit marked changes to the timing of the diurnal temperature cycle.

Source: University of California, Berkeley

While the solar panels are observed to increase air temperature (Figure 23), the shading effect of the panels significantly reduces soil temperatures. Average daily soil temperatures at the control site are significantly warmer than those observed under the panels at a comparable depth; this pattern holds all the way to 110 cm depth where the control site is between 4°F (2°C)–4.5°F (2.5°C) warmer than the under-panel locations. The amplitude of daily temperature oscillations is also significantly damped by the presence of solar panels. In addition, the presence of solar panels shifts the diurnal temperature cycle (particularly during the summer), pushing the maximum temperature to later in the day relative to the control site, or in the soils between the solar panels.

The effects of soil water and temperature ultimately influence CO_2 dynamics (Figure 27). The in-situ CO_2 measurements exhibit marked differences between the under-panel and control soil profile. Due to instrumentation issues, the in-situ CO_2 measurements are limited to the tail-end of the winter wet season and throughout the summer dry season of 2019. During the winter, the control profile registered higher CO_2 concentrations than the under-panel profile at comparable depths. However, CO_2 concentrations appear to build up over time in the under-panel soils before reaching an apparent steady state during the dry season. In the control soil, CO_2 concentrations decline to an apparent steady state during the dry season. This may represent both soils coming to a steady state after disturbing the soil profile by excavating the soil pits. If the apparent steady states reached during the dry season represent true differences in CO_2 dynamics between the control and under-panel soils, these observations suggest that the under-panel soils exhibit much higher CO_2 production between 10 cm and 40 cm depth relative to the control site. This could be due to the higher soil organic carbon content present in the under-panel soil profile relative to the control soil profile over that depth interval (Figure 28, discussed below). Continued measurements throughout an additional wet season will help elucidate these potential differences in CO_2 production.

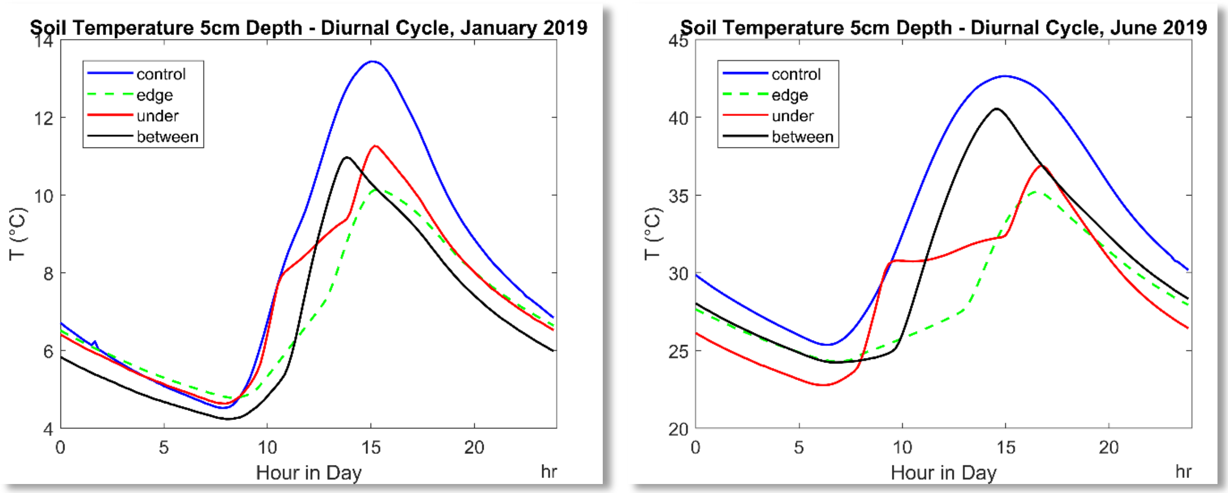
Figure 27: Influence of Solar Panels on Soil CO_2 Concentrations with Depth



CO_2 concentrations with depth (blue–5 cm, red–25 cm, green–50 cm, and black–110 cm) for the control site (left) and under-panel site (right).

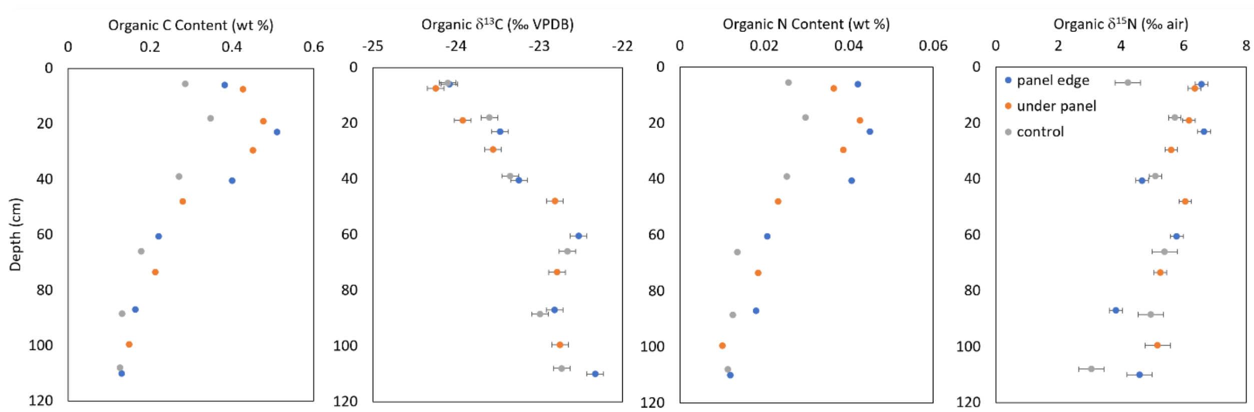
Source: University of California, Berkeley

The soil organic C, organic N, and carbonate content and their stable isotope composition for the soils were measured (Figure 28 and Figure 29) to examine whether measurable changes in the soil carbon pools have occurred in the approximately 4 years since solar panels were installed. The stable isotope composition of soil organic carbon ($\delta^{13}C$) was nearly identical in all three soil profiles, as was the isotopic composition of soil organic nitrogen ($\delta^{15}N$)—with the exception of slightly ^{15}N depleted nitrogen in the surface horizon of the control site (Figure 28). However, the control site had less total soil organic matter in the upper 40 cm (weight percent organic C and N approximately 30 percent lower than that at comparable depths in the under-panel and panel edge profiles). This might reflect natural spatial variability, or a depletion of organic material at the control site due to its higher temperatures (



) which may stimulate microbial respiration.

Figure 28: Soil Organic Matter Content and Isotopic Composition at Rosamond Solar Site



Organic carbon and nitrogen content (weight percent) and stable isotopic composition for three soil profiles at the Rosamond solar site: panel edge (blue), under panel (orange), and control site (grey).

Source: University of California, Berkeley

Depth profiles of soil carbonate content and its stable isotopic composition for the Rosamond solar site are plotted in Figure 29. In general, the shapes of the profiles are expected from soil processes in arid settings. First, the total carbonate in the soil is modest (<1.5 percent) and increases with depth. The depth increase is a nearly universal pattern, as carbonate is dissolved near the land surface by dilute rainwater, and eventually reprecipitates at greater depths as the soil water is lost via evapotranspiration.

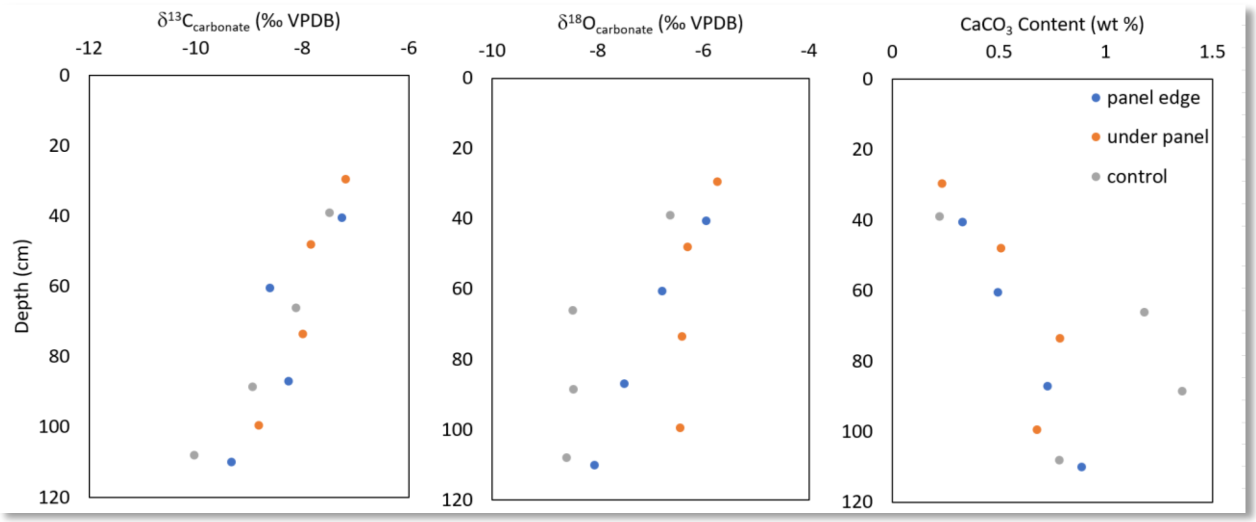
Second, the decrease in $\delta^{13}C$ values with depth reflects the C isotope composition of soil CO_2, which is a mix of biological CO_2 (more negative and identical to the C isotope composition of the plants) and atmospheric CO_2 (about -7‰ for the pre-industrial atmosphere). At equilibrium, there is about a 14‰ offset between soil CO_2 and carbonate; thus, the most negative carbonate values match soil CO_2 with a $\delta^{13}C$ value of -24‰, reasonable for a largely C3 flora in a desert.

Third, the O isotope value tends to decrease with depth (especially the control). In deserts, this is the result of rainwater that undergoes evaporation near the land surface, becoming greatly enriched in ^{18}O. The carbonates at depths of a meter or more commonly have O isotope values reflecting the source water, offset by an equilibrium fractionation of about 30‰. The $\delta^{18}O_{carbonate}$ measured here is indicative of a source water with an isotopic composition of ~39‰ VPDB (-9‰ VSMOW), similar to that reported for rainfall (though rainfall is highly variable) and groundwater, which was used to irrigate the soils for likely several decades (Friedman et al., 1992). Thus, the $\delta^{18}O_{carbonate}$ of the control soil likely reflects the input of isotopically distinctive irrigation water, with evaporative enrichment in the upper 50 cm.

The most striking difference between the three profiles is the oxygen isotopic composition of carbonate: the $\delta^{18}O_{carbonate}$ value of the carbonate in the control soil is 2‰ more negative than that directly under the solar panels, and there appears to be a systematic increase in $\delta^{18}O_{carbonate}$ values from control site to panel edge to the under-panel soil. In addition, the control site has a higher $CaCO_3$ content between 60 cm to 100 cm depth. Assuming the isotopic composition of carbonate was similar in the under-panel and control site soils before the solar installation (both are in the same abandoned agricultural field), this suggests that soil inorganic carbon stocks are dynamic and can undergo measurable dissolution/reprecipitation on a timescale of years. The more negative $\delta^{18}O_{carbonate}$ values at the control site are indicative of the regional groundwater and rainfall, both of which are depleted in ^{18}O (Friedman et al. 1992). The apparent enrichment of carbonate in ^{18}O under panels can be attributed to fact that most soil water there is lost to evaporation, which systematically enriches soil water and any carbonate that forms in it, with ^{18}O. The large differences in ^{18}O between the control and the 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 (Magaritz and Amiel 1981), evidence of the dynamics in more natural settings is limited.

In summary, the carbonate stable isotope values (and depth profiles of concentration) suggest that the panels—whose temperature and moisture contents were discussed above—may be dissolving and reprecipitating inorganic C, and shifting its isotope composition to that now under the panels. Regardless, this process 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.

Figure 29: Soil Carbonate Content and Isotopic Composition at Rosamond Solar Site



Carbonate content and stable isotope data for three soil profiles at the Rosamond solar site: panel edge (blue), under panel (orange), and control site (grey). $\delta^{18}O_{carbonate}$ and $\delta^{13}C_{carbonate}$ are each expressed in standard delta notation relative to VPBD.

Source: University of California, Berkeley

Modeling the Influence of Utility-Scale Solar

The influx of solar installations in the Mojave Desert is largely a 21st-century development, and the observation of geochemical changes under them may take decades to unfold. Thus, the use of geochemical modeling, developed over longer time periods in the region (the climosequence) can be used to conduct numerical experiments that allow a consideration of how soils under panels may develop over time.

Here a 1D reactive transport model is used to examine soil inorganic carbon changes. It was found that the observed differences in heat and water dynamics between the control and under-panel soil profiles could be adequately captured through changes to two input parameters:

- The surface heat boundary condition (that is, changes to the soil surface temperature). Based on observations of the soil temperature at 5 cm depth, it was found that scaling the maximum and minimum soil temperature by 0.86 relative to the control model of soil surface temperature yielded reasonable estimates for the soil surface temperature under the solar panels.
- Evaporative demand. The observed changes in windspeed, relative humidity, and air temperature were coupled to a literature estimate of the reduction in incoming solar radiation (under panels receive between 8 percent to 20 percent of the total incoming radiation) to estimate potential evaporation under the solar panels using the Penman equation (neglecting any potential transpiration). It was found that calculating potential evaporation using incoming solar radiation reduced to 20 percent of the total best-reproduced observed trends in water dynamics under the solar panels. This decreased evaporative demand by approximately a factor of two.

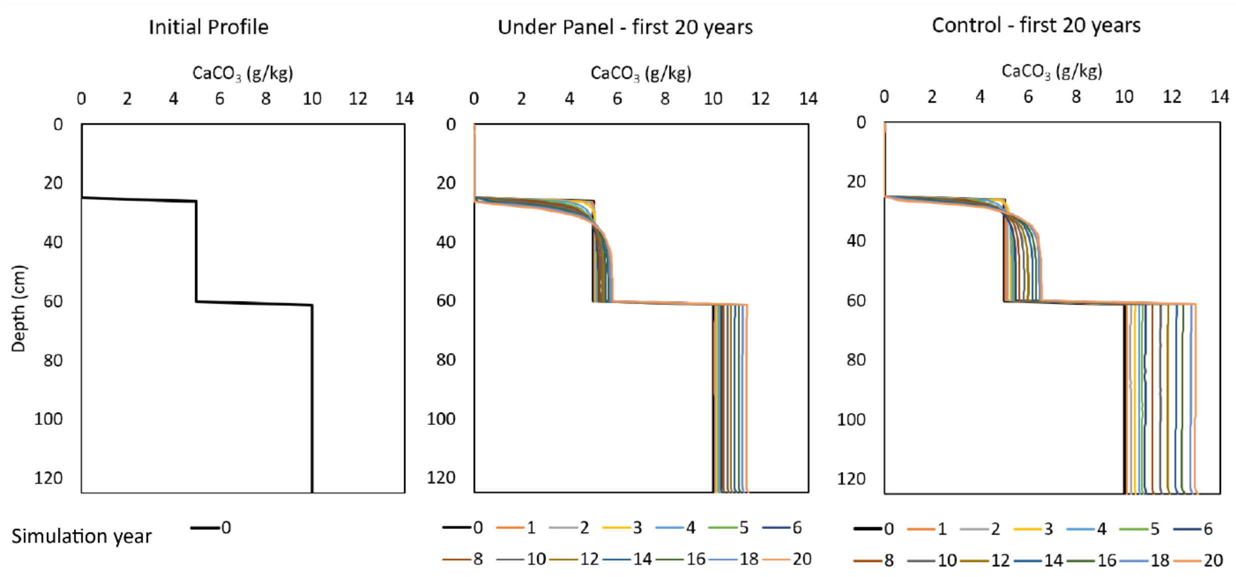
The presence of solar panels will also change the total amount of precipitation delivered to soils directly under the panels simply through shading effects. However, this was difficult to quantify in the context of a 1D model as the water diverted from directly under the panels is delivered to the soil profile at the panel edge (little water is truly intercepted), which will then redistribute to some extent in the subsurface via horizontal transport. Thus, for the purposes of this investigation there was not an attempt to deconvolve the influence of muted precipitation inputs versus decreased evaporative demand. This may be pursued in the future during the development of a 2D model to describe water dynamics at this site.

Impact on Soil Inorganic Carbon Cycling and Carbonate Accumulation

To investigate how the presence of solar panels will influence soil inorganic carbon cycling, soil carbonate accumulation was modeled in a simplified, hypothetical soil with and without the presence of solar panels using the parameterization described above. A reactive transport modeling framework was developed for the Creosote site in the MNP climosequence, which is at a similar elevation and is the most sparsely vegetated site on the climate gradient. The soil profile was assumed to consist of a homogeneous sandy loam (bulk density 1.5), characteristic of abandoned agricultural soils like that found at Rosamond. Daily precipitation and air temperature data for 2018–2098 were derived from the CanESM-2 global climate model (determined by Cal-Adapt to be an "average" climate projection for California). Simulations were run for representative atmospheric CO_2 concentration pathways 4.5 and 8.5. Daily solar radiation was calculated as the theoretical free-sky (cloudless) radiation received at

Rosamond's latitude and elevation. Potential evaporation and soil temperature boundary conditions (temperature at the soil surface and base of the soil profile) were then calculated from this temperature and radiation data as described above. Potential evaporation (transpiration was neglected) was set to zero during periods of precipitation to avoid issues with evaporating observed precipitation before it enters the soil. Soil CO_2 production, precipitation chemistry (including dust inputs), and initial soil water chemistry were all taken from parameters either measured or estimated for the MNP Creosote site (see model description above). The initial $CaCO_3$ distribution was modeled off that observed in the Rosamond soils: 0 to 25 cm depth, then 0.5 weight percent $CaCO_3$ to 60 cm depth, then 1 weight percent $CaCO_3$ for the remainder of the soil profile (Figure 30, left panel). Calcite was assumed to precipitate and dissolve under kinetic control and surface CO_2 concentrations were assumed to be a constant 410 ppm. The only differences between the "under panel" and "control" simulations were the heat boundary conditions (soils cooler under panels) and potential evaporative demand (lower under panels).

Figure 30: Modeled Soil Carbonate Accumulated During 20 Years of RCP 4.5



Patterns in $CaCO_3$ accumulation from 2018–2038 under the solar panel (middle) and control (right) model scenarios.

Source: University of California, Berkeley

Projected Effect of Panels on Soil Inorganic Carbon Cycling and Carbonate Accumulation

The soil on which the panel installation has been constructed is one of the typical or common soils found in the western Mojave Desert. It is likely a late Pleistocene alluvial deposit, comprised of granitic rock sources. As mentioned earlier, the accumulation of $CaCO_3$ in desert soils largely relies on the influx of either Ca ions, or $CaCO_3$ in dust or aerosols. Thus, these soils have modest amounts of $CaCO_3$ (1 percent to 2 percent by weight). It is important to review the entire inorganic carbon cycle to understand how changes in soil processes affect the net storage of soil carbon.

The weathering of Ca-bearing silicate rocks (represented by $CaSiO_3$) in CO_2-bearing solutions (soils, streams, vadose zones, and so forth) is the ultimate sink for atmospheric CO_2:

$$CaSiO_3 + H_2O + 2CO_2 = Ca^{+2} + 2HCO_3^{-1} + SiO_2 \qquad \text{Equation 1}$$

Equation 1 reveals a consumption of 2 moles of CO_2 for every mole of Ca^{+2} released from a rock. The ultimate precipitation of calcite from this solution (either in soil or in the ocean) sequesters one of the moles of CO_2 consumed in a solid form, but releases the other mole back to the atmosphere:

$$Ca^{+2} + 2HCO_3^{-1} = CaCO_3 + CO_2 + H_2O \qquad \text{Equation 2}$$

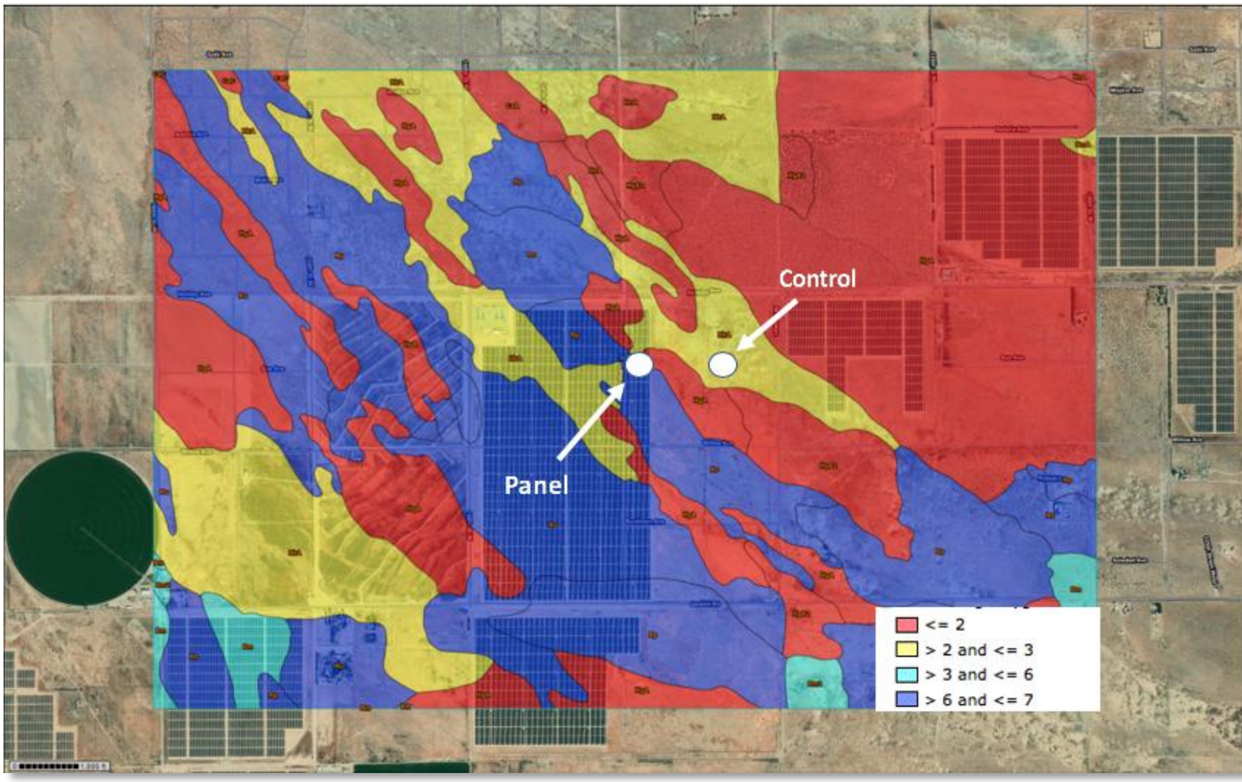
If a strong acid, like HNO_3 from atmospheric pollution, is added, the dissolution of the carbonate mineral undergoes a different trajectory than the reverse of Equation 2, releasing CO_2 to the atmosphere:

$$CaCO_3 + 2H^+ = Ca^{+2} + H_2O + CO_2 \qquad \text{Equation 3}$$

Thus, it is important to understand the source of acidity and the reaction mechanisms that are affecting carbonate equilibria. There seem to be some misconceptions about the effect of forming or dissolving desert soil carbonate on net soil C balances. Allen et al. (2013) imply that the dissolution of carbonate in soil (they cite karst landscapes) results in net releases of CO_2 to the atmosphere. The reverse of Equation 2 clearly shows that the dissolution of carbonate is a net CO_2 neutral unless additional acidity is added to the system (for example, Equation 3). As illustrated in Equation 1, weathering of minerals in soils typically generates alkalinity and buffers pH. The fate of dissolved bicarbonate (HCO_3^-) and calcium is dependent on the flow and chemical reaction path before the carbonate is redeposited. Thus, even the (improbable) dissolution of all carbonate in a desert soil causes no release of CO_2, unless driven by addition of acidity, and under some conditions could serve as a short term C sink until the fluid again reprecipitates the dissolved solutes as solid carbonate.

The changes in soil temperature and moisture under panels may affect the present storage of carbonate, and its changes over time. Figure 31 is the NRCS soil map projection for the average soil carbonate of the sites and the nearby area. While the map projections are a bit higher than those observed, they provide an overview of the expected ranges in carbonate to be found in soils of the area.

Figure 31: NRCS Soil Carbonate Map (Average % in Upper 100 cm)

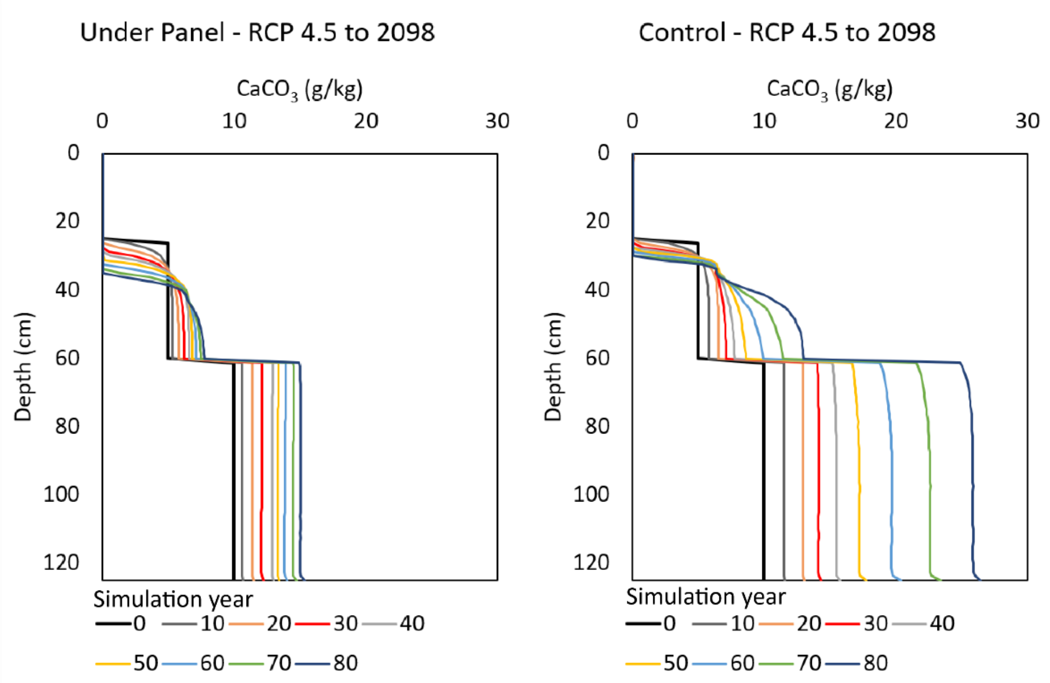


NRCS soil carbonate map showing approximate average weight percent $CaCO_3$ in the upper 100 cm of soils surrounding the Rosamond solar site.

Source: https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx

The way in which the soil carbonate profiles may evolve over the next 20 (Figure 30) and the next 80 (Figure 32) years was modeled using climate projections for these time intervals. The results suggest the following. First, both soils (assuming Ca inputs are the same) would retain all their existing carbonate and continue to gain carbonate over time. The panel soils, due to the changes in water and heat, are projected to undergo a redistribution of carbonate, losing some from the upper horizons, and having it redistributed at greater depths. The reasons for this are that the longer availability of water allows the dissolution of carbonate, and carbonate is more soluble in water as temperatures decline. Second, the projected amounts of carbonate that accumulate under the panels (in the depths being modeled) are less than the control site (see Figure 33 for a summary). As discussed above, this does not indicate a change in the net carbon sequestration potential of the soils since the Ca and accompanying dissolved inorganic carbon are either precipitated at a greater depth or migrate very slowly into the underground aquifer.

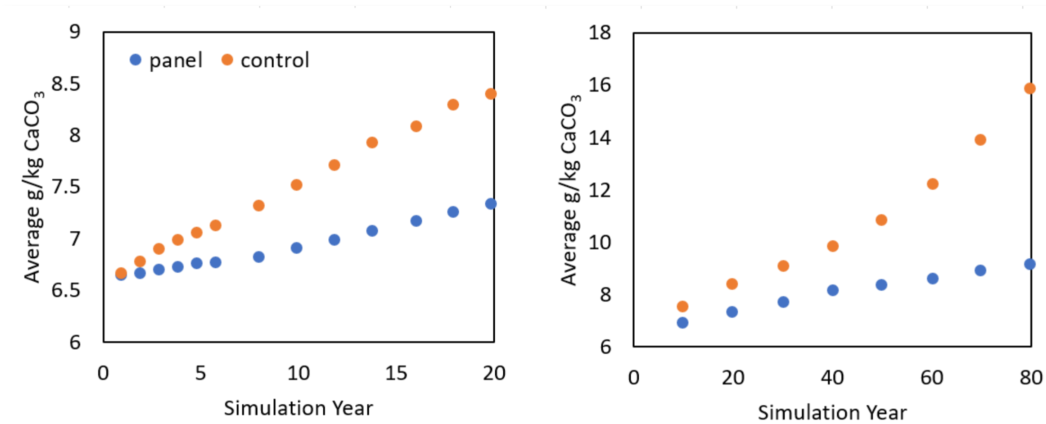
Figure 32: Modeled Soil Carbonate During the Next 80 Years



Patterns in $CaCO_3$ accumulation from 2018–2098 under the solar panel (left) and control (right) model scenarios.

Source: University of California, Berkeley

Figure 33: Evolution of Average $CaCO_3$ Content of Soil Profile DuringTime

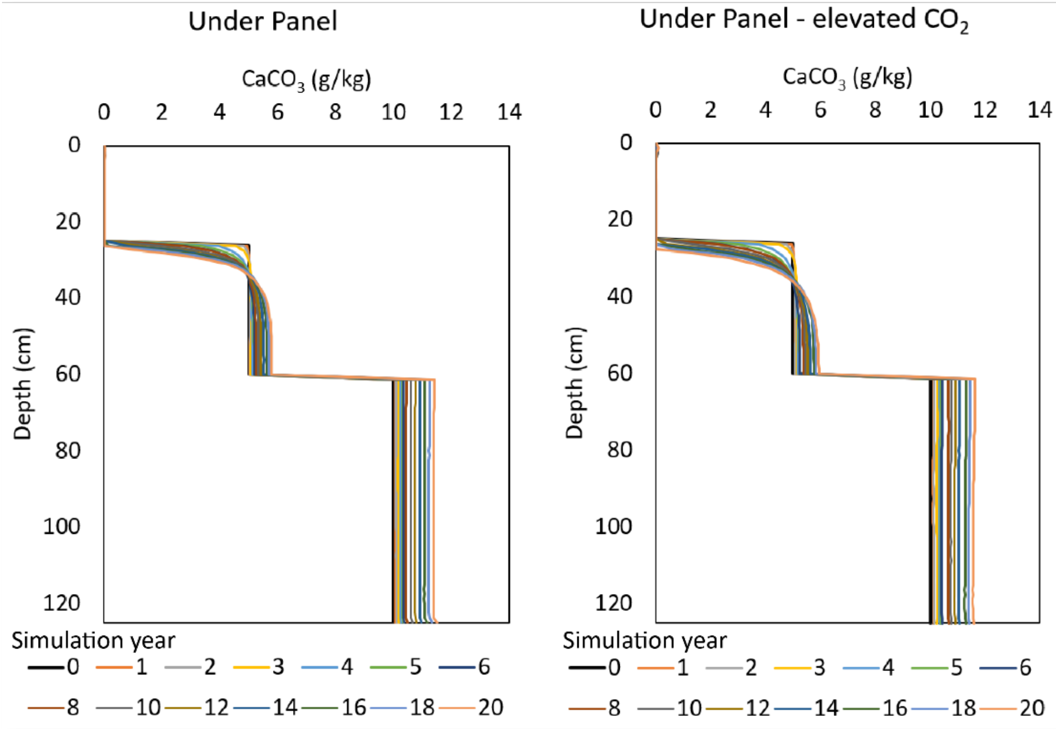


Average g $CaCO_3$ / kg soil to 125 cm depth as a function of time in the solar panel (blue) and control (orange) model scenarios.

Source: University of California, Berkeley

The model projections for the panels assume that there is minimal plant cover under the panels, following the common management strategy practiced by solar operators. To address how the panel profiles might evolve under a plant cover (for example, a rehabilitated desert flora), carbonate accumulation was modeled assuming that the root zone of the soil has double the CO_2 of the projections made above (Figure 34). The effect of elevating soil CO_2 (which invariably happens with vegetation) results in the apparent removal of $CaCO_3$ from the upper part of the soil and its redistribution lower in the profile. The total carbonate accumulation (compared to the no plant scenario) is nearly identical.

Figure 34: Comparison of Soil Carbonate Accumulation With High Rhizosphere CO_2



Patterns in $CaCO_3$ accumulation over 20 years for the initial under-panel scenario (left) and under-panel scenario assuming roughly double rhizosphere CO_2 production (right).

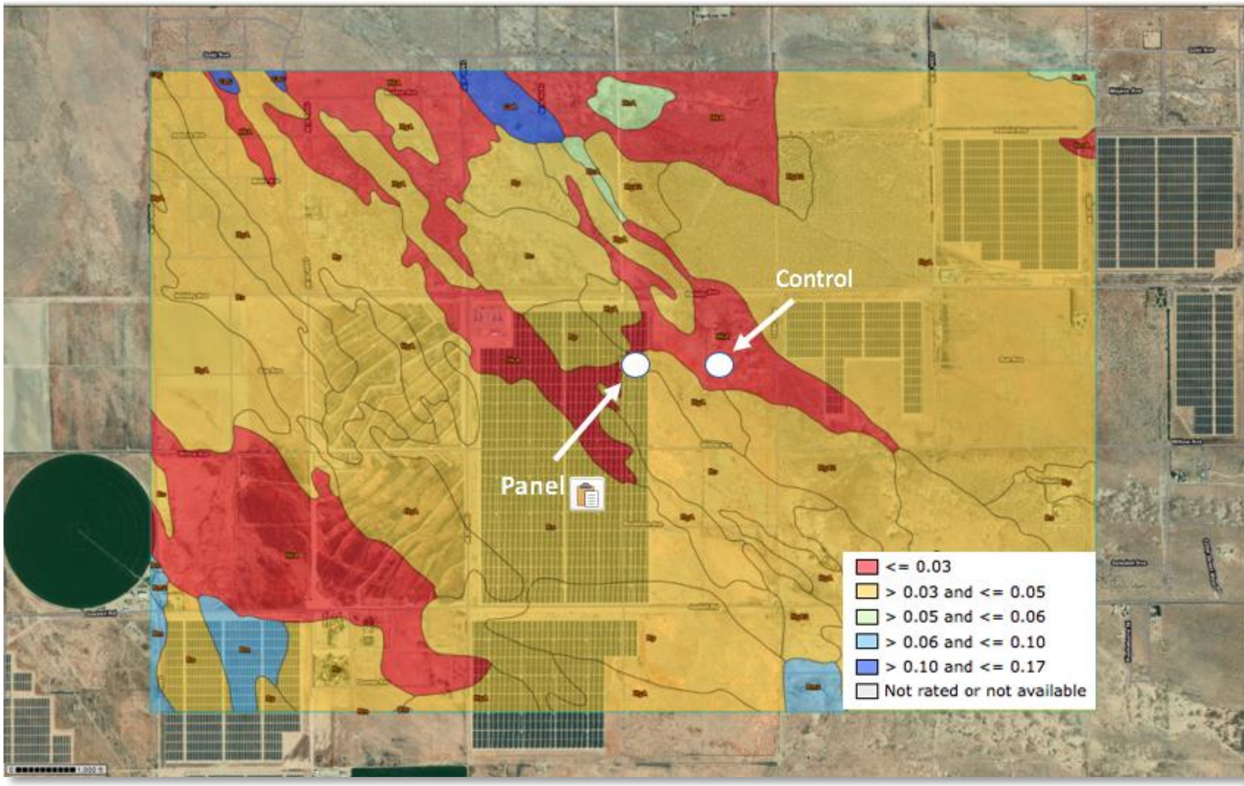
Source: University of California, Berkeley

In summary, the model projections suggest that carbonate is a dynamic and changing soil property, one that will adjust to the microclimate changes under the panels. The panels have the effect of dissolving carbonate near the soil surface and moving it downward. This is consistent with the apparent large O isotope differences between carbonate under the panels and that of the control sites. The panel soil will appear to gain less carbonate than the control soils over time, but this inorganic carbon will either be deposited at a greater soil depth or will migrate into the aquifer. In either case, this does not represent a source of CO_2 to the atmosphere. Finally, model projections indicate that panels will not cause a loss of existing inorganic carbon in the soils.

Potential Impact on Soil Organic Carbon Stocks

The organic carbon in desert soils is naturally very low, due to slow rates of plant carbon inputs and high rates of microbial decomposition. The average soil organic carbon content of the soils, from the NRCS soil map projections, is illustrated in Figure 35. The average values, less than 0.2 percent, are very low and vary slightly across the landscape.

Figure 35: Map of Soil Organic Carbon, NRCS (Average % for Upper 100 cm)



NRCS soil organic carbon map showing approximate average weight percent organic carbon in the upper 100 cm of soils surrounding the Rosamond solar site.

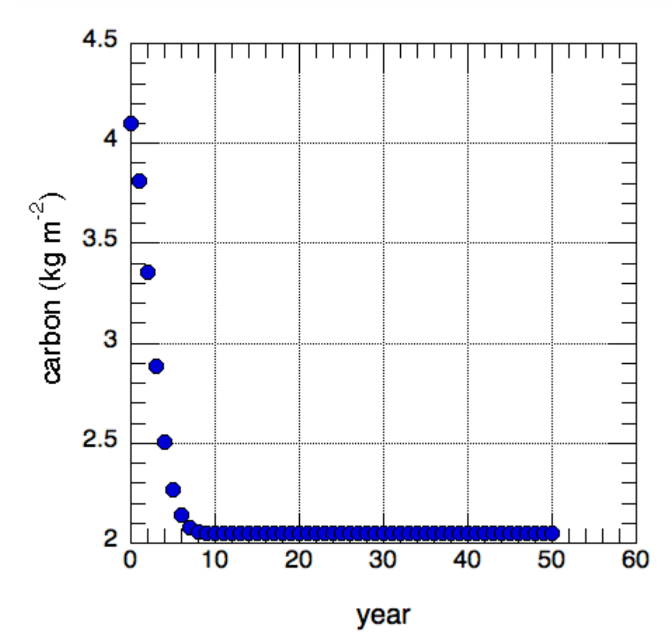
Source: https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx

The storage of soil organic carbon is determined by the balance between organic carbon inputs, generally as dead plant biomass, and losses of organic carbon, largely as respired CO_2. The removal of vegetation under the solar panels removes plant inputs, and thus sets into motion the release of the organic carbon stored in the soils. In degraded soils such as the abandoned agricultural land investigated here, the process of soil organic carbon loss due to disturbance and vegetation removal has likely either already occurred or is already underway, thereby minimizing the potential impact of solar installation on soil organic carbon stocks.

From the measurements (organic carbon content and soil bulk density), the carbon storage in the upper 1 m of the panel soils is 4.1 kg m^{-2}. The radiocarbon research discussed earlier indicates that about half of the total organic carbon cycles occur on decadal time scales, and this has a decomposition rate of about 0.15 y^{-1}. The high rate of decomposition indicates that the soil organic carbon pool will decline rapidly and stabilize as the remaining carbon is stored in soil aggregates and on soil mineral surfaces, and will respond over long time scales (Figure 36).

How large is this potential organic carbon loss? As an example, the Solar Star Projects near Rosamond, California (SunPower, Inc.) is considered. The installation covers a portion of a nearly 10,000-acre property. The facility is reported (for more information on the Solar Star projects, see http://us.sunpower.com/utility-scale-solar-power-plants/solar-energy-projects/solar-star-projects/) to create renewable energy that would avoid 570,000 tons (English units) of CO_2 per year. Converted to metric tons of C per hectare (ha), the site each year saves ~32 metric tons C $ha^{-1}y^{-1}$. Based on the measurements, the soils have about 41 metric tons of organic carbon per hectare, and about half of this is expected to be susceptible to being lost over a decade (20.5 metric tons). Thus, the total pool of C susceptible to loss by disturbance over a decade (approximately) is less than one year of C offsets by solar electrical generation. It is noted that this is likely the maximum rate and amount of soil organic carbon loss, because it is based on a relatively fast decomposition rate, and some vegetation manages to inhabit the solar sites before they are removed by maintenance. Maintaining, or even slightly increasing, this organic C pool is beneficial from a C balance perspective, as well as for the maintenance of desert biodiversity.

Figure 36: Estimated Changes in Soil Organic Carbon Under Panels if All Vegetation is Removed



Worst-case scenario estimate of changes in soil organic carbon stocks at the Rosamond solar site, assuming all vegetation is removed.

Source: University of California, Berkeley

In summary, the research indicates that soils under solar panel installations will continue to store inorganic carbon in the mineral calcium carbonate, and that a fraction of the organic carbon that exists in the soils will invariably be lost as CO_2 due to microbial decomposition. The amount, and rate, was estimated for a worst-case scenario, and is much less than the carbon offsets provided by electrical generation. Additional carbon benefits can be attained by reducing this organic carbon loss, which will require strategies to introduce plants that do not interfere with panel maintenance.

CHAPTER 4: Knowledge Transfer

Over the course of this investigation, the project has produced a spatially and temporally rich dataset of observations detailing the interplay between meteorological forcings, in-situ soil conditions, and soil carbon cycling in the Mojave Desert. All of the in-situ monitoring data has been uploaded to the HydroShare data repository for environmental data, which can be accessed here: https://www.hydroshare.org/. The research team is continuously adding to that shared dataset as the monitoring of these sites is ongoing.

The insights resulting from this extensive field campaign have resulted in the development of several papers that will be submitted for publication in peer-reviewed journals. Two manuscripts based on results are near submission and four others are in preparation. Results from the project have also been presented at multiple international geoscience conferences (three abstracts at the annual meeting of the American Geophysical Union, two at Goldschmidt).

Outputs

The major outputs of this project are peer-reviewed scientific papers, and subsequent research that might be inspired by these initial studies.

- The team has drafted a paper that examines how the widely used soil carbon model DayCent works in arid regions, and documents its deficiencies. Since this model, or models with similar concepts, is embedded in global carbon models, it is important that weaknesses be clearly identified, and ultimately, rectified.
- The team has drafted a paper outlining the changes in soil carbon, nitrogen, and carbon 14 over a 45-year interval in the eastern Mojave Desert. Pending the completion of more sample analyses, the paper will be submitted for review. It will be the first paper to identify a positive feedback loop between climate and soil carbon in temperate environments, and one of the few to observe this response in any environment.
- A future paper will illustrate the two different pathways that soil CO_2 is produced in the Mojave Desert, and will quantitatively articulate the strong differences between near-surface and deep soil processes in arid environments.
- A future paper will quantify and identify the mechanism that causes soils in the driest elevations, in the midst of the summer, to absorb CO_2 at night. This is emerging as one of the big surprises that modern, near-continuous soil instrumentation allows one to observe, and ultimately investigate.
- A future paper will detail the micrometeorological differences between solar installations and the surrounding environment, and its effects (via geochemical modeling) on soil carbon processes.
- A future paper will use the project's observations and geochemical model to examine the carbon cycle in the soils of the climosequence in the Mojave National Preserve.

Impacts

Climate change is possibly the greatest policy issue facing society, and California this century. The policies established by the State, however innovative, require additional evaluation, and expansion, if feedbacks and biotic change in iconic ecosystems, like our deserts, are to be avoided or at least minimized.

This project articulates the environmental changes that likely loom in the near term and provides data on the real impacts of solar installations on landscapes that have been previously degraded by questionable agricultural development. The research can be used as stakeholders and policy makers decide on or zone landscapes for future solar expansion and development.

CHAPTER 5: Conclusions/Recommendations

The Mojave Desert: A Landscape in Flux

The Effects of Changing Climate

The Mojave Desert is rapidly becoming warmer and drier. Water limits many desert soil biological processes, and changes in the frequency and magnitude of water will influence biological processes that dominate the soil surfaces of the region. These short-duration, but large, biological responses to dew and rainfall, overlay a slower set of deeper soil processes that react less rapidly to rainfall, but more strongly to temperature.

The observations made in this study, combined with geochemical modeling, point toward the progressive loss of organic carbon with warming temperatures. This appears to already be occurring. In contrast, a test of an important soil carbon model used in (or adapted to) global ecosystem models shows that it poorly reproduces soil carbon processes in deserts. Identifying this deficiency is important in that it will lead to further improving these models, which have widely divergent predictions of how the Earth's soil carbon balance will change over time—predictions at odds with more empirically based methods.

The Effects of Changing Land Use

To anyone who frequently visits the desert, particularly the western half, it is stunning to observe the continued growth of solar installations. To some, this results in a sense of awe, to others concern or negativity at the changing landscape.

But what does this development do to the soil ecosystem? This study examined a solar installation on abandoned agricultural land, but the moisture and heat flow processes that were observed should also largely be applicable to installations placed on vegetated landscapes. Very simply, it was found that solar panels result in warmer air temperatures versus open space, but cooler soil temperatures (due to shading) and the longer storage of soil water. These changes appear to be readjusting the depth and location of inorganic carbon in the soil, but total soil inorganic carbon stocks will continue to increase under soil panel installations.

The effects on soil organic carbon stocks are primarily driven by vegetation removal, which cuts off carbon inputs. In the absence of these plant inputs, a fraction of the organic carbon that exists in the soils will invariably be lost as CO_2 due to microbial decomposition. The amount, and rate, was estimated for a worst-case scenario, and is much less than the carbon offsets provided by electrical generation. Additional carbon benefits can be attained by reducing this organic carbon loss, which will require strategies to introduce plants or maintain native vegetation in ways that do not interfere with panel maintenance.

In addition, emphasis should be placed on developing solar installations on degraded lands such as the abandoned agricultural lands studied here, where the soil organic carbon cycle is likely already perturbed, instead of converting native ecosystems.

It is important to emphasize that there are differing types of solar installations, located on a variety of landscapes. The observations here may not be directly applicable to these situations. However, it does seem that there are opportunities for research and innovation as these installations evolve to use physical science to help establish or facilitate multiple uses for land used for energy production.

CHAPTER 6: Benefits to Ratepayers

Ratepayers desire affordable and reliable energy, and energy generation that produces limited environmental impacts. As businesses, cities, and states strive to achieve carbon neutrality in the production of electrical power, there will be a corresponding increase in the development of new facilities, such as large-scale solar energy fields.

The research here reveals that in the case of a "business as usual" approach to energy production and use, parts of the state are warming rapidly, initiating feedbacks within desert soil ecosystems that in turn cause them to lose carbon and release it as CO_2. Invariably, though the pace is uncertain, this will affect the configuration of the Mojave Desert flora and fauna. Thus, efforts to replace greenhouse gas-emitting energy generation must be a priority to the inhabitants—human and wildlife—that live in this region.

The replacement of fossil fuel-based electricity with renewables requires the siting of facilities that can take advantage of nature's energy opportunities. Deserts are targeted around the world for solar, due to the abundance of sunlight. These deserts are also environments of very divergent perceived values, and their long histories of exploitation and mismanagement tend to be common across cultures and nations. The newest use of these regions, for energy, can be accomplished more rationally than many previous activities, using the degraded landscape left behind by farming and other activities for solar panels. These panels affect the local environment.

The research in this study found that solar installations trap warm air within and beneath the panels, but the shading of the land surface by the panels in turn keeps the soil cooler and moister than that of the surrounding landscape. These small but—in a dry region—important changes in resources might point to ways in the future that panel installation may coexist with or enhance biodiversity. In addition, the research also indicates that small meteorological changes produce negligible changes in the soil carbon cycle. While there are indeed effects on vegetation and soil organic carbon due to solar installations, there is not a loss of large quantities of inorganic carbon as CO_2. These findings have the potential to inform renewable energy generation policy development and plans.

LIST OF ACRONYMS

Term	Definition
CO_2	Carbon dioxide
MNP	Mojave National Preserve
N	Nitrogen
NRCS	Natural Resource Conservation Service, USDA

REFERENCES

Ahlström, Anders, Michael R. Raupach, Guy Schurgers, Benjamin Smith, Almut Arneth, Martin Jung, Markus Reichstein, et al. 2015. "The Dominant Role of Semi-Arid Ecosystems in the Trend and Variability of the Land CO2 Sink." *Science* 348 (6237): 895 LP – 899. https://doi.org/10.1126/science.aaa1668.

M. Allen, A. McHughen. 2011. Solar power in the desert: are the current large-scale solar developments really improving California's environment? Desert Development Series, 1, University of California, Riverside (2011), pp. 1-11

Amundson, R. 2001. The carbon budget in soils. *Annual Reviews of Earth and Planetary Science.* 29: 535-562. https://doi.org/10.1146/annurev.earth.29.1.535

Amundson, R.G., O.A. Chadwick, and J.M. Sowers. 1989. "A Comparison of Soil Climate and Biological Activity along an Elevation Gradient in the Eastern Mojave Desert." *Oecologia* 80 (3): 395–400. https://doi.org/10.1007/BF00379042.

Amundson, Ronald, A.T. Austin, E.A.G. Schuur, K. Yoo, V. Matzek, C. Kendall, A. Uebersax, D. Brenner, and W.T. Baisden. 2003. "Global Patterns of the Isotopic Composition of Soil and Plant Nitrogen." *Global Biogeochemical Cycles* 17 (1). https://doi.org/10.1029/2002GB001903.

Anderegg, William R.L., and Noah S. Diffenbaugh. 2015. "Observed and Projected Climate Trends and Hotspots across the National Ecological Observatory Network Regions." *Frontiers in Ecology and the Environment* 13 (10): 547–52. https://doi.org/10.1890/150159.

Armstrong, Alona, Nicholas J. Ostle, and Jeanette Whitaker. 2016. "Solar Park Microclimate and Vegetation Management Effects on Grassland Carbon Cycling." *Environmental Research Letters* 11 (7): 74016. https://doi.org/10.1088/1748-9326/11/7/074016.

Baisden, W. Troy, Roger L. Parfitt, Craig Ross, Louis A. Schipper, and Silvia Canessa. 2013. "Evaluating 50 Years of Time-Series Soil Radiocarbon Data: Towards Routine Calculation of Robust C Residence Times." *Biogeochemistry* 112 (1): 129–37. https://doi.org/10.1007/s10533-011-9675-y.

Breecker, D.O., Z.D. Sharp, and L.D. McFadden. 2009. "Seasonal Bias in the Formation and Stable Isotopic Composition of Pedogenic Carbonate in Modern Soils from Central New Mexico, USASeasonal Bias in the Formation of Pedogenic Carbonate." *GSA Bulletin* 121 (3–4): 630–40. http://dx.doi.org/10.1130/B26413.1.

Cable, Jessica M., Kiona Ogle, Richard W. Lucas, Travis E. Huxman, Michael E. Loik, Stanley D. Smith, David T. Tissue, et al. 2011. "The Temperature Responses of Soil Respiration in Deserts: A Seven Desert Synthesis." *Biogeochemistry* 103 (1): 71–90. https://doi.org/10.1007/s10533-010-9448-z.

Cable, Jessica M., Kiona Ogle, Anna P. Tyler, Mitchell A. Pavao-Zuckerman, and Travis E. Huxman. 2009. "Woody Plant Encroachment Impacts on Soil Carbon and Microbial Processes: Results from a Hierarchical Bayesian Analysis of Soil Incubation Data." *Plant and Soil* 320 (1): 153–67. https://doi.org/10.1007/s11104-008-9880-1.

California ISO. "Monthly Renewables Performance Report December 2019." Accessed January 10, 2020. http://www.caiso.com/Documents/MonthlyRenewables PerformanceReport-Dec2019.html.

Cook, Benjamin I., Toby R. Ault, and Jason E. Smerdon. 2015. "Unprecedented 21st Century Drought Risk in the American Southwest and Central Plains." *Science Advances* 1 (1): e1400082. https://doi.org/10.1126/sciadv.1400082.

Fierer, Noah, Andrew S. Allen, Joshua P. Schimel, and Patricia A. Holden. 2003. "Controls on Microbial CO2 Production: A Comparison of Surface and Subsurface Soil Horizons." *Global Change Biology* 9 (9): 1322–32. https://doi.org/10.1046/j.1365-2486.2003.00663.x.

Friedman, Irving, George I. Smith, Jim D. Gleason, Augusta Warden, and Joyce M. Harris. 1992. "Stable Isotope Composition of Waters in Southeastern California: 2. Groundwaters and Their Relation to Modern Precipitation." *Journal of Geophysical Research: Atmospheres* 97 (D5): 5813–23. https://doi.org/10.1029/92JD00183.

Hamerlynck, Erik P., Russell L. Scott, Enrique P. Sánchez-Cañete, and Greg A. Barron-Gafford. 2013. "Nocturnal Soil CO2 Uptake and Its Relationship to Subsurface Soil and Ecosystem Carbon Fluxes in a Chihuahuan Desert Shrubland." *Journal of Geophysical Research: Biogeosciences* 118 (4): 1593–1603. https://doi.org/10.1002/2013JG002495.

Hassanpour Adeh, Elnaz, John S. Selker, and Chad W. Higgins. 2018. "Remarkable Agrivoltaic Influence on Soil Moisture, Micrometeorology and Water-Use Efficiency." *PLOS ONE* 13 (11): e0203256. https://doi.org/10.1371/journal.pone.0203256.

Hernandez, Rebecca R., Madison K. Hoffacker, Michelle L. Murphy-Mariscal, Grace C. Wu, and Michael F. Allen. 2015. "Solar Energy Development Impacts on Land Cover Change and Protected Areas." *Proceedings of the National Academy of Sciences* 112 (44): 13579 LP – 13584. https://doi.org/10.1073/pnas.1517656112.

Houlton, Benjamin Z., and Edith Bai. 2009. "Imprint of Denitrifying Bacteria on the Global Terrestrial Biosphere." *Proceedings of the National Academy of Sciences* 106 (51): 21713 LP – 21716. https://doi.org/10.1073/pnas.0912111106.

Jacques, Diederik, and Jiri Simunek. 2005. "User Manual of the Multicomponent Variably-Saturated Flow and Transport Model HP1, Description, Verification and Examples." Mol, Belgium. https://www.pc-progress.com/Documents/hp1.pdf.

Jenny, Hans. 1941. *Factors of Soil Formation: A System of Quantitative Pedology*. New York: Dover.

Jung, Martin, Markus Reichstein, Christopher R. Schwalm, Chris Huntingford, Stephen Sitch, Anders Ahlström, Almut Arneth, et al. 2017. "Compensatory Water Effects Link Yearly Global Land CO2 Sink Changes to Temperature." *Nature* 541 (7638): 516–20. https://doi.org/10.1038/nature20780.

Kemp, Paul R., Joe M. Cornelius, and James F. Reynolds. 1992. "A Simple Model for Predicting Soil Temperatures in Desert Ecosystems." *Soil Science* 153 (4): 280–87.

Ma, Jie, Zhong-Yuan Wang, Bryan A Stevenson, Xin-Jun Zheng, and Yan Li. 2013. "An Inorganic CO2 Diffusion and Dissolution Process Explains Negative CO2 Fluxes in Saline/Alkaline Soils." *Scientific Reports* 3 (1): 2025. https://doi.org/10.1038/srep02025.

Magaritz, Mordeckai, and Abraham J. Amiel. 1981. "Influence of Intensive Cultivation and Irrigation on Soil Properties in the Jordan Valley, Israel: Recrystallization of Carbonate Minerals1." *Soil Science Society of America Journal* 45: 1201–5. https://doi.org/10.2136/sssaj1981.03615995004500060038x.

Miller, D.M. 2012. Surficial geologic map of the Ivanpah 20′ x 60′ quadrangle, San Bernardino County, California, and Clark County, Nevada. U.S. Geological Survey, Scientific Investigations Map SIM-3206, scale 1:100,000.

Monger, H.C., and R.A. Gallegos. 2000. "Biotic and Abiotic Processes and Rates of Pedogenic Carbonate Accumulation in the Southwestern United States - Relationship to Atmospheric CO 2 Sequestration." In *Global Climate Change and Pedogenic Carbonates*, edited by R. Lal, J.M. Kimbel, H. Eswaran, and B.A. Stewart, 273–89. Boca Raton, FL: CRC.

Oerter, Erik, Jennifer V. Mills, Gregory E. Maurer, Laura Nielsen Lammers, and Ronald Amundson. 2018. "Greenhouse Gas Production and Transport in Desert Soils of the Southwestern United States." *Global Biogeochemical Cycles* 32 (11): 1703–17. https://doi.org/10.1029/2018GB006035.

Parkhurst, D.L., and C.A.J. Apello. 2013. "Description of Input and Examples for PHREEQC Version 3 - A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations." In *U.S. Geological Survey Techniques and Methods, Book 6, Chap. A43*, 497.

Parsons, Andrew N., J.E. Barrett, Diana H. Wall, and Ross A. Virginia. 2004. "Soil Carbon Dioxide Flux in Antarctic Dry Valley Ecosystems." *Ecosystems* 7 (3): 286–95. https://doi.org/10.1007/s10021-003-0132-1.

Parton, William J., Melannie Hartman, Dennis Ojima, and David Schimel. 1998. "DAYCENT and Its Land Surface Submodel: Description and Testing." *Global and Planetary Change* 19 (1): 35–48. https://doi.org/https://doi.org/10.1016/S0921-8181(98)00040-X.

Reheis, Marith C., James R. Budahn, Paul J. Lamothe, and Richard L. Reynolds. 2009. "Compositions of Modern Dust and Surface Sediments in the Desert Southwest, United

States." *Journal of Geophysical Research: Earth Surface* 114 (F1). https://doi.org/10.1029/2008JF001009.

Reynolds, James F., Paul R. Kemp, Kiona Ogle, and Roberto J. Fernández. 2004. "Modifying the 'Pulse–Reserve' Paradigm for Deserts of North America: Precipitation Pulses, Soil Water, and Plant Responses." *Oecologia* 141 (2): 194–210. https://doi.org/10.1007/s00442-004-1524-4.

Schimel, David S. 2010. "Drylands in the Earth System." *Science* 327 (5964): 418 LP – 419. https://doi.org/10.1126/science.1184946.

Schlesinger, William H. 1985. "The Formation of Caliche in Soils of the Mojave Desert, California." *Geochimica et Cosmochimica Acta* 49 (1): 57–66. https://doi.org/http://dx.doi.org/10.1016/0016-7037(85)90191-7.

Seager, Richard, Mingfang Ting, Cuihua Li, Naomi Naik, Ben Cook, Jennifer Nakamura, and Haibo Liu. 2013. "Projections of Declining Surface-Water Availability for the Southwestern United States." *Nature Climate Change* 3 (5): 482–86. https://doi.org/10.1038/nclimate1787.

Šimůnek, Jirí, Martinus Th. van Genuchten, and Miroslav Šejna. 2008. "Development and Applications of the HYDRUS and STANMOD Software Packages and Related Codes." *Vadose Zone Journal* 7 (2): 587 LP-- 600. http://vzj.geoscienceworld.org/content/7/2/587.abstract.

Simunek, Jiří, Donald Suarez, and Miroslav Sejna. 1996. *The UNSATCHEM Software Package for Simulating One-Dimensional Variably Saturated Water Flow, Heat Transport, Carbon Dioxide Production and Transport, and Multicomponent Solute Transport with Major Ion Equilibrium and Kinetic Chemistry*. Riverside, CA: Research Report No. 141, USDA-ARS U.S. Salinity Laboratory.

Šimunek, Jirka, Diederik Jacques, Martinus Th. Van Genuchten, and Dirk Mallants. 2006. "Multicomponent Geochemical Transport Modeling Using Hydrus-1D and HP11." *JAWRA: Journal of the American Water Resources Association* 42 (6): 1537–47. https://doi.org/10.1111/j.1752-1688.2006.tb06019.x.

Soulard, Christopher E., and Benjamin M. Sleeter. 2012. "Late Twentieth Century Land-Cover Change in the Basin and Range Ecoregions of the United States." *Regional Environmental Change* 12 (4): 813–23. https://doi.org/10.1007/s10113-012-0296-3.

Thomey, Michell L., Paulette L. Ford, Matthew C. Reeves, Deborah M. Finch, Marcy E. Litvak, and Scott L Collins. 2014. "Climate Change Impacts on Future Carbon Stores and Management of Warm Deserts of the United States." *Rangelands* 36 (1): 16–24. https://doi.org/https://doi.org/10.2111/RANGELANDS-D-13-00045.1.

Titus, Jonathan H., Robert S. Nowak, and Stanley D. Smith. 2002. "Soil Resource Heterogeneity in the Mojave Desert." *Journal of Arid Environments* 52 (3): 269–92. https://doi.org/https://doi.org/10.1006/jare.2002.1010.

Vargas, Rodrigo, and Michael F. Allen. 2008. "Dynamics of Fine Root, Fungal Rhizomorphs, and Soil Respiration in a Mixed Temperate Forest: Integrating Sensors and Observations." *Vadose Zone Journal* 7: 1055–64. https://doi.org/10.2136/vzj2007.0138.