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LDRD Final Report

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ABBREVIATED FINAL REPORT

Warming Response of Deep Soil Carbon

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21-LW-054

Project Overview

The overarching objective of this LDRD project was to determine the vulnerability of deep soil organic carbon (SOC) to warming in the Sierra Nevada region. Deep soils (>30 cm) store more than 70% of global SOC, and increased SOC decomposition and CO_2 emissions caused by warming are potentially large climate change feedbacks. According to the Intergovernmental Panel on Climate Change, temperatures are expected to increase by 4°C by the year 2100, warming the land and underlying soil, and making understanding of how warming will influence deep SOC storage and persistence critical to projecting the land carbon sink. However, uncertainty remains in our process-level understanding and ability to quantify how projected warming will impact the stability of carbon in deep soils. We investigated warming effects on deep (up to 16 m) SOC stability across climate, vegetation, and soil mineralogy gradients in California. We sampled soils from the surface to bedrock (down to 16 meters) at four sites representing vastly different ecosystems across the Northern and Southern Sierra Nevada mountains. This study quantified the response of SOC concentration, distribution, and vulnerability to warming using a soil incubation experiment to warm the whole soil profile and radiocarbon and stable isotopes to assess which pools are vulnerable to loss under warming. Our results refine our understanding of the terrestrial carbon cycle by revealing the vulnerability of deep SOC to future changes in climate and how minerology may influence that vulnerability.

Mission Impact

Soil is the foundation of all life on Earth. Soil security, resiliency, and health is central to solving big issues of climate change abatement, food security, fresh-water regulation, and biodiversity. Soil is increasingly recognized as a ‘strategic asset’ as its ability to produce food and store carbon (reduce climate change) underpins peace and civil stability. Understanding how soil carbon will respond to a changing future is critical to LLNL’s mission “to enable U.S. security and global stability and resilience by empowering multidisciplinary teams to pursue bold and innovative science and technology.” Our LDRD project results justify the inclusion of deep soils to research and development in climate resilience, a new LLNL mission focus area. It was previously assumed that despite storing more carbon than the atmosphere and plants combined, deep soil is not an active pool of carbon because it is buffered from changes on the surface. In contrast to this paradigm, our results show that warming of the surface could cause a significant amount of deep soil carbon to be respired and released into the atmosphere. Our results highlight a critical need for protection of deep soils and show that deep soils are a critical component of soil response to climate change. Furthermore, the absence of deep soil carbon cycling in previous assessments of terrestrial carbon response to future change adds to the large uncertainties in predictions of the future land carbon sink.

This project supported LLNL's workforce development by hiring Kimber Moreland as a post-doctoral researcher in Karis McFarlane's group at CAMS. This project has given Kimber the opportunity to build internal and external collaborations and contributed to her development as an expert in soil science and biogeochemistry in addition to building LLNL's expertise in this area. This project formed new collaboration between LLNL and UC Riverside and the Southern Sierra Critical Zone Observatory. It also supported an LLNL ROTC summer intern who learned new laboratory skills and will be included on the future manuscript. Kimber has created multiple online videos to educate and engage with other scientists and the public about the importance of deep soils and LLNL research in this area. Furthermore, this research supports LLNL's Science Mission Area in Energy Security & Climate Resilience, the "Energy and Resource Security" Mission Research Challenge, and the soil pillar of the Director's Initiative "Engineering the Carbon Economy," Earth and Atmospheric Science core competency (Climate Change Impacts R&D Priority) and Nuclear, Chemical, and Isotopic Science and Technology core competency.

Publications and Presentations

Presentations:

Moreland, K., McFarlane K. 2022. Digging deeper: sampling to bedrock changes our understanding of soil carbon warming response in the Sierra Nevada. American Geophysical Union (AGU) Fall Meeting 2022. Chicago, IL, USA.

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FULL TECHNICAL REPORT

Warming Response of Deep Soil Carbon

Kimber Moreland, PhD

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Abstract

The overarching objective of this LDRD project was to determine the vulnerability of deep soil organic carbon (SOC) to warming in the Sierra Nevada region. Deep soils (>30 cm) store more than 70% of global SOC, and increased SOC decomposition and CO_2 emissions caused by warming are potentially large climate change feedbacks. According to the Intergovernmental Panel on Climate Change, temperatures are expected to increase by 4°C by the year 2100, warming the land and underlying soil, and making understanding of how warming will influence deep SOC storage and persistence critical to projecting the land carbon sink. However, uncertainty remains in our process-level understanding and ability to quantify how projected warming will impact the stability of carbon in deep soils. We investigated warming effects on deep (up to 16 m) SOC stability across climate, vegetation, and soil mineralogy gradients in California. We sampled soils from the surface to bedrock (down to 16 meters) at four sites representing vastly different ecosystems across the Northern and Southern Sierra Nevada mountains. This study quantified the response of SOC concentration, distribution, and vulnerability to warming using a soil incubation experiment to warm the whole soil profile and radiocarbon and stable isotopes to assess which pools are vulnerable to loss under warming. Our data suggest that depending on minerology SOC from below 2 meters is vulnerable to warming and it is of utmost importance for our science community to sample deeper to understand the role of soils in the future land carbon sink as well as their potential as a climate change solution.

Background and Research Objectives

Climate change is one of the most challenging problems facing humanity today. Millions of human lives and the wellbeing of countless species and ecosystems are at stake as we grapple with global changes that threaten the future habitability of our planet. Fortunately, climate change is solvable with an all-hands-on approach. Soils are a meaningful piece of the solution, but we first need to understand the fate of the massive stores of carbon beneath our feet. Soil stores more carbon, as soil organic carbon (SOC), than the atmosphere and vegetation combined, with deep soils (>30 cm) comprising up to 70% of that pool[1-2]. These SOC stocks represent a balance between carbon addition and removal. Therefore, any climate related factors that impact carbon inputs (e.g., changes in net primary productivity) or outputs (e.g., increased soil respiration) could drastically alter carbon storage[3]. According to the Intergovernmental Panel on Climate Change, atmospheric temperatures are expected to increase by 4°C, warming the land and underlying soil[4]. Soils down to 3 m have already warmed by 2°C since 1961[5] and are expected to continue warming with increasing atmospheric temperatures[4]. Warming increases microbial decomposition of SOC, releasing more CO_2 into the atmosphere, but the amount and rate of this response is highly uncertain because the mechanisms that control microbial accessibility of SOC are not fully understood. Past research has focused on topsoil (30 cm), based on the assumption that deep soils do not interact with the atmosphere[1,6,7]. However, recent studies suggest that subsoil may be as, or more, vulnerable than topsoil to warming[8]. To determine the response of soils to changing temperature, we quantified the vulnerability of deep SOC by combining soil warming incubation experiments, advanced SOC characterization techniques, and computational modeling.

Although decomposition rates are slower in deeper soils than in surface soils, recent studies have shown that deep SOC is more vulnerable to loss than previously thought[7-9]. One soil warming study reported that the mean Q_{10} (increase of soil respiration per 10°C increase) value for carbon utilization rates was 25% higher in deep soil than surface soil, reflecting a higher sensitivity of deep soils to temperature[10]. Another study imposed experimental warming to a depth of 1 m, found that warming increased annual soil respiration by about 35%, and estimated that a 4°C increase, deep soils have the potential to release carbon to the atmosphere at a rate equivalent to 30% of fossil fuel emissions[9]. This increase in emissions has the potential to drastically change our everyday lives by exacerbating global warming. Despite these findings, few studies have investigated relevant factors (*e.g.,* carbon amount, stability, and distribution; mineralogical controls) at depths greater than 1 m[5-10]. Considering that the estimated global average soil thickness is 2 m[11], with some soils extending past 10 m, investigating deep SOC is critical to understanding the global carbon cycle.

The mechanisms controlling temperature sensitivity and SOC turnover rates in deep soil are unknown. It was thought that oxygen limitation restricts microbial activities at depth, decreasing decomposition rates, but newer data indicate this is not the primary control on decomposition in most soils[12]. Current theory suggests that deep SOC is more protected from decomposition than surface SOC through chemical recalcitrance, aggregation, and association with soil minerals[13-14]. Protected (via aggregation or mineral association) SOC pools tend to have longer turnover times than unprotected pools[15]. Stabilization on minerals is likely the most effective mechanism for long-term storage, but different soil minerals have different affinities for binding to SOC[16]. For example, short-range order minerals store more carbon than crystalline minerals[17-18]. However, the importance of mineralogy to temperature sensitivity and SOC mineralization rates remains unknown, especially in deep soils. To anticipate the response of SOC storage to warming and determine if SOC in physically protected or mineral associated pools is less vulnerable, we need to understand the environmental controls on carbon decomposition throughout the entire soil profile.

This project bridged the knowledge gap in deep SOC dynamics by sampling from the surface to bedrock (>16m), as deep SOC vulnerability can have profound implications for accurate accounting of terrestrial C sequestration[7]. We assessed the vulnerability of deep SOC to increasing temperature by combining an environmental gradient approach with a laboratory soil warming incubation experiment in which density fractionation and radiocarbon was used to identify controls on the microbial accessibility of SOC. **We hypothesized that: 1) deep SOC will be more sensitive to warming than surface soils; and 2) deep SOC stability is controlled by mineralogy.** A robust understanding of decomposition with soil depth and its response to warming is needed to create accurate earth system land models to predict our future climate and devise informed and innovative solutions.

Our overarching objective is to determine the vulnerability of deep SOC to warming in the Sierra Nevada region. California is an ideal study location as it pledged to become carbon neutral by 2045 (executive order B-55-18) and is invested in understanding the current and future state of natural carbon storage. In addition, the oak savannah and forested ecosystems in California play a significant and disproportionately large role in regional soil carbon budgets relative to their land area[19]. Specifically, this study addressed four questions:

Q1. How does the rate of CO_2 emissions from deep SOC change with increasing temperature?
Q2. Is SOC preferentially utilized from less-stable SOC pools (e.g., unprotected particulate debris)?
Q3. How does the mineralogy influence vulnerability of deep SOC to warming?
Q4. What will CO_2 emissions from surface and deep soils be by 2100?

Scientific Approach and Accomplishments

To answer our targeted research questions, we used a range of advanced analytical approaches from soil science and biogeochemistry, leveraging LLNL expertise and analytical abilities in radiocarbon analysis, interpretation, and modeling.

Task 1 - Field sampling: This research took place in four sites along two elevation transects, from 400-2000 m, at the Southern Sierra Nevada Critical Zone Observatory[20] (SSCZO) and Northern Sierra Nevada. As elevation increases, oak savannah (low sites) transitions to mixed conifer forest (high sites). Furthermore, our two transects differ in parent rock materials with basalt-derived soils of the Northern Sierra storing up to 60% more SOC than granitic soils of the Southern Sierra because of differences in the amount of short-range-order minerals[17]. This allowed us to **test our second hypothesis that the soil mineralogy controls the vulnerability of SOC to warming**. We collected intact soil cores from each site from the soil surface to bedrock (~ 16 m) with a Geoprobe team.

Task 2 - Incubation: To address how the rate of CO_2 emissions from deep SOC changes with increasing temperature, intact soil core sections were incubated in a climate-controlled incubation chamber for a total of 100 days at two different temperatures: site soil mean annual temperature, and 4 °C above ambient temperature at LLNL. The amount of CO_2 respired, and its radiocarbon age was assessed during the incubation. The radiocarbon age of the emitted CO_2 indicate the mean age of respired SOC and addressed if warming increases the microbial availability of more stable SOC pools with longer residence times.

Task 3 - Density fractionation, radiocarbon, chemical composition, and mineralogy: To investigate if SOC in less-stable pools is preferentially utilized and to better understand the controls on SOC vulnerability with depth, we performed density fractionation to separate soil carbon into three operationally defined pools that exemplify the proposed SOC protection mechanisms[22-23]. These pools include: SOC that is physically protected from microbes by the soil structure (in aggregates), SOC bound to minerals, and SOC that is unprotected[15]. Radiocarbon measurements of the density fractions indicated the relative cycling rates of SOC in these pools. Mineralogical correlations to deep SOC stability remain unexplored and revealed that mineral types may influence the amount of soil carbon storage. Finally, we assessed how mineralogy influences vulnerability of deep SOC to warming using quantitative X-ray diffraction[25].

***Task 4 - CENTURY modeling*:** To predict the levels of CO_2 emissions from surface and deep soils by the year 2100, our data and the CENTURY model will estimate long-term CO_2 respiration rates and turnover times. Because of pandemic-related delays, this task will be completed as part of K Moreland's third year as a postdoc as this activity will enable Kimber to continue developing her skills in soil carbon modelling. The CENTURY model is a reduced complexity soil carbon model driven by climate that includes carbon inputs and decomposition. This model and its derivations serve as the foundation for the soil carbon models in earth system models and the land models within them. It can be customized to the site, analyze multiple depths, model both bulk carbon and radiocarbon, and run on a desktop computer. In the most commonly used version of CENTURY, SOC is grouped into three different pools based on average turnover time: active (<1yr), slow (10^1-10^2 yrs), and passive (>10^2yrs)[26]. The active pool will be parameterized as the SOC respired after incubating for 1 month under ambient temperature while the passive pool will be parameterized as the SOC in the mineral associated C before incubation. The slow pool will be calculated by difference, using the light density fractions as an additional constraint[27]. This modeling approach allows for a three-pool, non-steady-state system with respect to turnover time, which accounts for the heterogeneity of soil and captures different SOC cycling rates.

Mission Impact

Soil is the foundation of all life on Earth. Soil security, resiliency, and health is central to solving big issues of climate change abatement, food security, fresh-water regulation, and biodiversity. Soil is increasingly recognized as a 'strategic asset' as its ability to produce food and store carbon (reduce climate change) underpins peace and civil stability. Understanding how soil carbon will respond to a changing future is critical to LLNL's mission "to enable U.S. security and global stability and resilience by empowering multidisciplinary teams to pursue bold and innovative science and technology." Our LDRD project results justify the inclusion of deep soils to research and development in climate resilience, a new LLNL mission focus area. It was previously assumed that despite storing more carbon than the atmosphere and plants combined, deep soil is not an active pool of carbon because it is buffered from changes on the surface. In contrast to this paradigm, our results show that warming of the surface could cause a significant amount of deep soil carbon to be respired and released into the atmosphere. Our results highlight a critical need for protection of deep soils and show that deep soils are a critical component of soil response to climate change. Furthermore, the absence of deep soil carbon cycling in previous assessments of terrestrial carbon response to future change adds to the large uncertainties in predictions of the future land carbon sink.

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Carbon Economy," Earth and Atmospheric Science core competency (Climate Change Impacts R&D Priority) and Nuclear, Chemical, and Isotopic Science and Technology core competency.

Main findings:

Q1. How does the rate of CO_2 emissions from deep SOC change with increasing temperature?

- Our data suggest that depending on minerology deep SOC is sensitive to warming, with the warmed subsoil respiring significantly more total C compared to the control group in the andesite parent material.

Q2. Is SOC preferentially utilized from younger (less-stable) SOC pools?

- Our data suggest that regardless of temperature, older C is respired with depth, but there is no difference with warming.
- In the deep soil both control and experimental groups respired on average younger organic carbon than the bulk soil organic carbon indicating that microbe were mineralizing the fresher (younger) material that could be coming from the less-stable SOC pools. How does the rate of CO_2 emissions from deep SOC change with increasing temperature?

Q3. How does minerology influence amount of C respired?

- Minerology does influence the total amount of C respired with the andesite releasing more total C, especially in the deep soil.

Q4. What will the CO2 emissions from the surface and deep soils be by 2100?

- Subsoil C to bedrock is vulnerable to warming depending on minerology.
- Ongoing work includes use of the Century model (task 4) to calculate this.

Conclusion

This study of SOC vulnerability to warming rewrites our understanding of the role of deep soils in global carbon cycles and carbon sequestration. This is the first study to determine the vulnerability of deep SOC to warming in the Sierra Nevada region across gradients in climate, vegetation, and mineralogy to 16 meters. The few relevant studies currently available suggest that deep SOC is an important contributor to total soil CO_2 flux to the atmosphere and may be more sensitive to warming than surface soils. However, the sensitivity of deep SOC to climate change is not well constrained and improved model parameterizations of the sensitivity of deep SOC to climate change are needed to make accurate predictions of future CO_2 emissions. This work provides the first robust set of model parameterizations of vertically resolved temperature sensitivity of soil respiration for land surface models to 16 meters and we intend to work with Earth system land modelers to leverage the data to inform and improve the accuracy of these model predictions.

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