UNIVERSITY OF CALIFORNIA, SANTA CRUZ

SOIL CARBON CONTENT OF *SEQUOIA SEMPERVIRENS* FOREST HABITAT

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BACHELOR OF ARTS

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ENVIRONMENTAL STUDIES

by

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ABSTRACT: Climate change is one of the most pressing, multi-dimensional, and disputed contemporary global issues. Land use changes and deforestation for agricultural and developmental purposes enhance climate change effects. Coastal California is home to the world's tallest, and especially long-lived tree, the Coast Redwood (*Sequoia sempervirens).* Some individuals are over 2,000 years in age. Redwoods have been theorized to have one of the highest rates of above ground carbon storage. To understand how their carbon storage potential is influenced by temperature, and precipitation, I investigated redwood forests soil carbon content from their most southern range to their most northern range in California. I collected a total 120 samples and found that soil carbon content decreased as you move higher in latitude from south to north.

KEYWORDS: California, soil carbon, climate change, redwoods, *Sequoia sempervirens,* forest ecology

6/12/19

Student signature *Date*

"The redwoods, once seen, leave a mark or create a vision that stays with you always. The feeling they produce is not transferable. From them comes silence and awe. It's not only their unbelievable stature, nor the color which seems to shift and vary under your eyes, no, they are not like any trees we know, they are ambassadors from another time."

John Steinbeck, Travels with Charley: In Search of America

Introduction

1.1 Climate Change

Climate change is one of the most pressing, multi-dimensional, and disputed contemporary global issues. Over 50 years of research has confirmed that anthropogenic activity has accelerated the rate at which greenhouse gases (GHG) like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are released into the atmosphere, resulting in global climate change. However, GHG emissions are not the only influence humans have on global climate. Land use changes and deforestation for agriculture and development enhance climate change effects (Henderson, Reinert, Dekhtyar, Migdal, 2018). Habitats like forests, grasslands, and wetlands perform valuable ecosystem services, including carbon sequestration, the capturing of carbon from the atmosphere and subsequent storage in plants and soil (Bedsworth, Cayan, Guido, Fisher, Ziaja, 2018). When natural habitats are converted for agriculture or development, their carbon capturing services are greatly diminished, and a positive feedback loop is enhanced. Climate change results in the acceleration of global atmospheric and sea-surface warming resulting in sea-level rise, regional drought and flooding, food insecurity due to extreme and unpredictable weather, water insecurity due to drought and/or outdated water infrastructure damage, and irreversible habitat and ecosystem damages (Allen et al. 2018). Climate change is regarded as a national security issue by the U.S Department of Defense, due to its contribution to increased natural disasters, resulting in large refugee flows, and conflicts over basic vital resources (Henderson, Reinert, Dekhtyar, Migdal, 2018). While research indicates that climate change naturally occurs over long periods of time, there is no evidence suggesting that it has happened this quickly before. According to a recent report by the Mauna Loa observatory in Hawaii, the atmosphere has now reached carbon dioxide levels of 415 parts per million (ppm). This level of atmospheric CO_2 has never knowingly happened in human history (Nugent, 2019)(HNN Staff, 2019). According to the Intergovernmental Panel on Climate Change (IPCC), human-induced warming has reached approximately 1 °C above pre-industrial levels, since the Industrial Revolution. The IPCC has suggested a wide array of emissions reduction options, and carbon dioxide removal (CDR) possibilities. Facilitating and enhancing carbon sequestration in soil has dual benefits for both CDR and soil health (Allen et al. 2018), and a range of conservation, restoration and land management methods can also increase terrestrial carbon uptake (Allen et al. 2018). However, with an increasing human population and need for food and housing, the importance of conservation and restoration has been largely overlooked as a climate change mitigation strategy. Picking and choosing which habitats to conserve and restore can pose complex challenges, and is a unique and location specific decision. However, research can aid in understanding just how much carbon sequestration and carbon storage potential certain habitats have. For instance, the Coast Redwood (*Sequoia sempervirens)* is theorized to have one of the highest rates of above ground carbon storage (Van Pelt, Sillet, Kruse, Freund, & Kramer, 2016).

1.2 The Coast Redwood

Coastal California is home to the Coast Redwood, the world's tallest, and especially long-lived tree. Some individuals are over 2,000 years in age (Johnstone, Dawson & Fung, 2010). The Coast Redwood is an iconic and beloved tree of the western, coastal United States, attracting millions of annual visitors (NPS 2018). With a range of ~600 km long and ~35 km wide, this species requires a unique set of abiotic factors, making it endemic to a small, coastal range from ~42°N to ~36°N (Johnstone, Dawson & Fung, 2010). The southernmost distribution of Coast Redwoods is near Big Sur and its northern limit is along the Chetco River, in the western fringe of the Klamath mountain range in Oregon (UCANR 2018). The most notable habitat requirement for the species is summer time fog. The Coast Redwood is limited to the California Current upwelling zone due to its reliance on humid marine conditions (Johnstone, Dawson & Fung, 2010). During summer months, coastally exposed zones rely on the water drip from canopy to root zones, and on direct foliar uptake (Johnstone, Dawson & Fung, 2010). This unique evolutionary trait facilitates redwood growth and water conservation during the dry summer season (Johnstone, Dawson & Fung, 2010). Due to their size, long lifespans, ability to withstand dry summer months, and slow decomposition rates relative to tropical habitats, Coast Redwoods have been theorized to have one of the highest rates of above ground carbon storage (Van Pelt, Sillet, Kruse, Freund, & Kramer, 2016). However, to understand how their carbon storage potential is influenced by temperature, and precipitation, I investigated redwood forest soil carbon content (SCC) from their most southern range to their most northern range in California. I analysed 120 soil samples from 10 forests. I used soil organic matter and total mass of carbon to measure soil carbon content. I also measured $\boldsymbol{\delta}^{13}$C to $\boldsymbol{\delta}^{12}$C ratio to understand redwood water use efficiency (WUE) along their range. Additionally, I collected abiotic variable data including average temperature, and average rainfall. With these data there is an opportunity to determine whether there are correlations between SCC, temperature, and rainfall, and learn more about how SCC may respond to climatic changes over time.

1.3 Soil Carbon Content as a Study System

More carbon is stored in the Earth's soil, including wetlands, peatlands, and permafrost, than is currently present in the Earth's atmosphere (Davidson & Janssens, 2006). However, due to changing climatic variables, the current and potential soil carbon release could result in an intensification of the positive feedback loop to climate change. Today, there still remains much dispute regarding whether it would accelerate plant-derived carbon inputs, and facilitate a negative feedback. The intensification and acceleration of global warming due to terrestrial carbon-cycle feedbacks is an essential element of current and future climate change (Melillo et al. 2002). Climate change models have predicted that carbon-cycle feedbacks could either accelerate or slow climate change affects (Melillo et al. 2002). The uncertainty in feedback outcomes is partly due to the lack of knowledge about terrestrial ecosystems and their processes, like soil microbes response to long-term temperature changes (Melillo et al. 2002). It is thought that atmospheric warming and drought due to climate change can influence increased soil warming, and subsequent loss of soil carbon would generally turn ecosystems towards a source of CO_2 to the atmosphere, rather than a sink (Melillo et al. 2002)(van der Molen et al. 2011).

There are several reasons why I chose to study soil carbon content in redwood forests for this project. One reason includes the importance of soil as a carbon sink and the unknown response of soils to climate change (switch from carbon sink to carbon source). Another reason is that the results of analysing soil carbon content can allude to the entire redwood forest subterranean carbon content, rather than just the tree itself. And finally, the feasibility of taking soil samples is more realistic to the scope of this project than taking carbon content measurements from branches of the world's tallest tree.

1.4 Climatic Data

Impacts of climate change are attributed to environmental drivers, such as rising temperatures, changes in rainfall patterns, rising atmospheric CO_2, rising sea level, etc. (Allen et al. 2018). These climatic and environmental drivers can result in overall habitat changes, like plant productivity, or ocean acidification (Allen et al. 2018). Thus, the relationship between temperature, rainfall, and in the case of coast redwoods, fog, is a vital one to understand. Mapping the response of soil carbon content to changes in climatic trends from redwood's southern range to their northern range can aid in further understanding the habitat's relationship to climatic variables and how it might change over time.

1.5 Hypothesis

I predicted that due to higher average rainfall and cooler average temperatures, the northern sites would have more soil carbon content. Because redwoods are less stressed when there is more rainfall and cooler average temperatures, I expected redwoods in the Northern range to have higher rates of photosynthesis, leading to higher carbon uptake. This would result in more biomass accumulation, greater soil organic matter content, and higher carbon content in soils.

For the WUE analysis, I predicted that WUE would increase with lower latitudes and less rainfall. This is because WUE is thought to be greater where water availability is limited due to partial stomatal closure restricting transpiration, in order to preserve moisture (Abbate et al. 2004).

Methods

2.1 Forest Sites & Field Methods

From December of 2018 to March of 2019, I conducted the field methods portion of my research. I visited ten forests from Monterey County to Del Norte County including State Parks (SP), UC Natural Reserves (UCNR), and land trust sites held by the Sempervirens Fund. My sites from south to north are shown in Figure 1:

Figure 1: Forest sites sampled (from south to north): Limekiln SP, Landels-Hill Big Creek Reserve (UCNR), UCSC Campus Natural Reserve (UCNR), Sempervirens Fund Property: SFV 236, Sempervirens Fund Property: Lompico, Mt. Tamalpais SP, Samuel P. Taylor SP,

Navarro River Redwoods SP, Humboldt Redwoods SP,
Jedediah Smith Redwoods SP.

At each forest location, I collected a total of 12 samples, three from each subsite, with a total of four subsites each represented by a cardinal direction. Once at a forest location, my field methods were conducted in chronological order as follows: travel by foot to the furthest cardinal direction. Once there, randomly select a tree that visually appears to be larger than three meters in diameter at breast height (DBH). Then, geotag the “tree” using the application Avenza Maps. Next, pick a random spot next to the chosen tree to dig a hole and move entirety of duff layer to the side. Proceed to dig a hole the length of the shovel, excluding the wooden handle (between 15-30 cm deep). Take a small hand trowel and fill the trowel with soil, placing the soil in plastic ziplock bag. After, measure and log hole depth and cover the hole. Take canopy density readings using a densiometer mirror (see Figure 2), and measure DBH of the tree. Lastly, select the next tree about 20 m away from the last tree. Repeat 119 times.

Figure 2: Densiometer Mirror, used to take canopy cover density measurements.

2.2 Soil Sample Analysis

I collected a total of 120 soil samples. I assessed soil organic matter (SOM) to use it as a proxy for organic soil carbon content. I ran isotope analysis for total carbon content (organic and inorganic carbon content) and WUE.

SOM methods happened in two phases: a drying phase and a burning phase. The drying phase included: thawing out frozen soil samples, then taring metal tins. Then placing about 10 g of soil in metal tin. Repeat for each sample. Weigh again with soil in tin to obtain wet weight. Place tins in oven at 110 °C for 24 hours to dry. Weigh to obtain dry weight. Sieve samples with 2000, 1000, and 500 micrometer sieves and eliminate larger rocks, roots and leaves, then weigh again. The burning phase included: cleaning crucibles by placing in furnace at 500 °C for two hours, then let cool. Weighing crucibles, place soil in crucibles and weigh again. Place crucibles in the furnace for 4 hours at 500 °C, take out; let cool then weigh again. The difference in pre-burn weight and post-burn weight, divided by pre-brun weight gives the SOM content of the sample. Isotope analysis was conducted by the UCSC Stable Isotope Lab. The preparation steps included: placing about 10 g of wet soil in smaller ziplock bags, send to isotope lab on campus. There they are freeze dried and returned to me, I then prepare samples in tin capsules along with standards. They are returned to the lab where total carbon, and $\boldsymbol{\delta}^{13}C$ to $\boldsymbol{\delta}^{12}C$ ratio is assessed.

2.3 Geographic Data Collection: Latitude and Elevation

To understand the relationship between climatic variables, soil carbon content and WUE, and geographic variables, latitude and elevation was logged using Avenza Maps and Google Earth.

2.4 Abiotic Data Collection: Precipitation, and Temperature

To find possible correlations between total carbon content, WUE and climate, historical precipitation and temperature data in the areas where soil was collected, I used data from the Western Regional Climate Center and the National Oceanic and Atmospheric Administration.

2.5 Statistical Analysis

Statistical analysis was conducted using JMP Pro 14. Statistically significant relationships between climatic, geographic, trees, soil and other habitat variables were tested using a multivariate analysis. Spearman's rho was used as the test statistic. In order to better understand the relationships between variables, I conducted a Principal Components Analysis.

2.6 Communication

To make my research accessible and easy to understand for people outside of the scientific community I utilized social media, National Geographic Open Explorer, attended a conference, including the 6th Annual UC Santa Cruz Climate Conference, and reached out to be interviewed for podcasts and articles. I made sure to use language that was simple and free of field specific jargon (Figure 3, 4).

Figure 3: Lilianne talking about her project with community members at the UCSC Climate Conference.

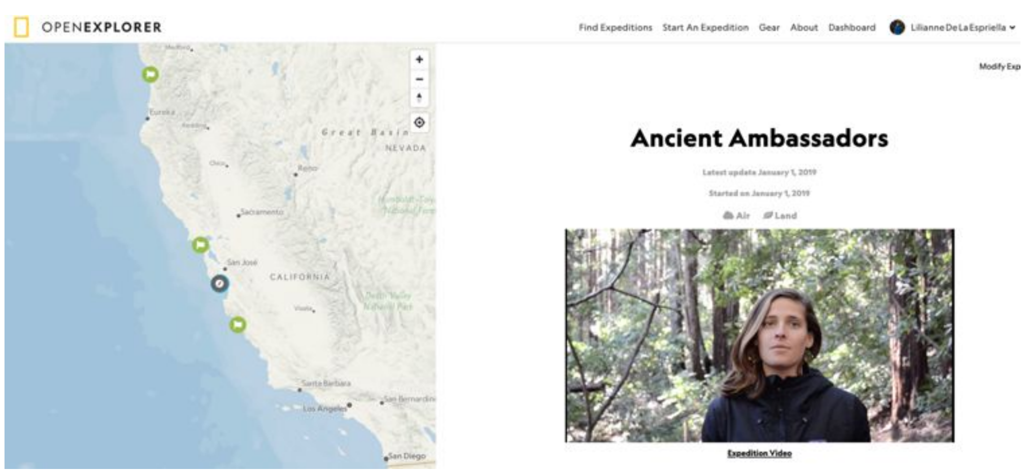

Figure 4: National Geographic Open Explorer Page.

Results:

3.1 Soil Carbon Content Response to Geographic Variables

Estimated mass of total carbon (from here on referred to as "total carbon") decreased as latitude moved northward (N=120, Spearman ρ = -0.4602, Prob>|ρ|= <.0001) (Figure 5). Soil organic matter also decreased as latitude moved northward (N=120, Spearman ρ = -0.2842, Prob>|ρ|= 0.0017) (Figure 6). Total carbon increased in higher elevation sites (N=120, Spearman ρ = 0.4839, Prob>|ρ|= <.0001). Soil organic matter also increased with an increase in elevation (N=120, Spearman ρ = 0.3961, Prob>|ρ|= <.0001).

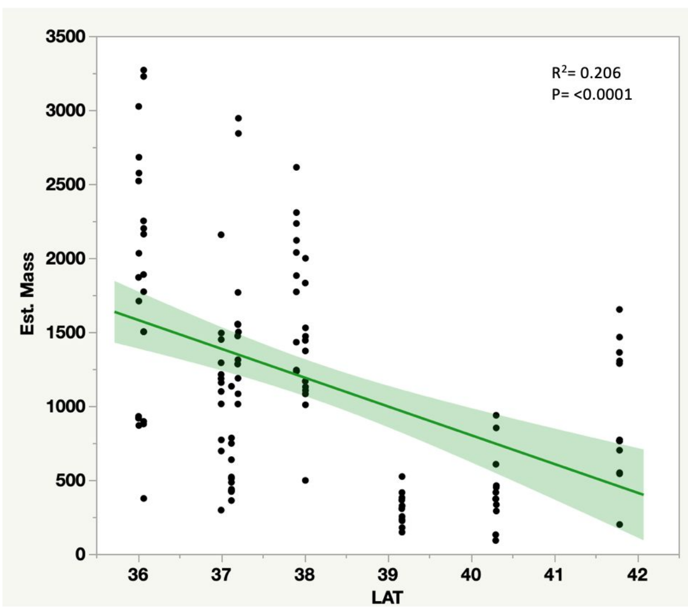

Figure 5: Total carbon response to latitude. Total carbon responded negatively to latitude.

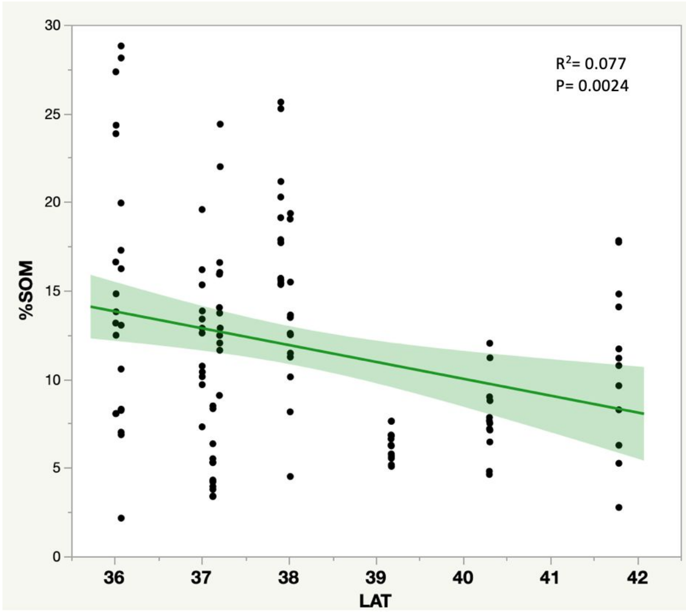

Figure 6: Soil organic matter response to latitude. Soil organic matter responded negatively to latitude.

3.2 Soil Carbon Content Response to Climatic Variables

Total carbon decreased with an increase in average precipitation (N=120, Spearman ρ = -0.2404, Prob>|ρ|= 0.0082). Soil organic matter also decreased as average precipitation increased (N=120, Spearman ρ = -0.3888, Prob>|ρ|=<.0001).

Total carbon decreased with an increase in average temperature, although not significantly (N=120, Spearman ρ = -0.0331, Prob>|ρ|= 0.7195). Soil organic matter also decreased with an increase in average temperature, although not significantly (N=120, Spearman ρ = -0.1034, Prob>|ρ|= 0.2611).

3.3 Soil Carbon Content Response to Habitat Specific Variables

Total carbon responded negatively with increased canopy cover, although not significantly (N=120, Spearman ρ = -0.2717, Prob>|ρ|= 0.0028). Soil organic matter also decreased with an increase in canopy cover, although not significantly (N=120, Spearman ρ = -0.1217, Prob>|ρ|= 0.1875).

Total carbon decreased with an increase in diameter at breast height of redwood trees, although not significantly (N=120, Spearman ρ = -0.1652, Prob>|ρ|= 0.0725). Soil organic matter also decreased with an increase in diameter at breast height of redwood trees, although not significantly (N=120, Spearman ρ = -0.0799, Prob>|ρ|= 0.3874).

3.4 WUE Response to Geographic, Climatic, and Habitat Specific Variables

WUE decreased as latitude moved northward (N=120, Spearman ρ = -0.2253, Prob>|ρ|= 0.0133). WUE increased as elevation increased (N=120, Spearman ρ = -0.2535, Prob>|ρ|= 0.0052).

WUE decreased as precipitation increased, although not significantly (N=120, Spearman ρ = -0.0245, Prob>|ρ|= 0.7908). WUE increased as temperature increased, although not significantly (N=120, Spearman ρ = 0.0772, Prob>|ρ|= 0.4018).

WUE decreased as canopy cover increased (N=120, Spearman ρ = -0.2391, Prob>|ρ|= 0.0088). WUE decreased as DBH increased (N=120, Spearman ρ = -0.2495, Prob>|ρ|= 0.0062).

Variable	by Variable	Spearman ρ	Prob>|ρ|
%SOM	LAT	-0.2842	0.0017
Total C (µg)	LAT	-0.4602	<.0001
WUE	LAT	-0.2253	0.0133
%SOM	Elevation (M)	0.3961	<.0001
Total C (µg)	Elevation (M)	0.4839	<.0001
WUE	Elevation (M)	0.2535	0.0052
%SOM	Avg. Precip	-0.3888	<.0001
Total C (µg)	Avg. Precip	-0.2404	0.0082
WUE	Avg. Precip	-0.0245	0.7908
%SOM	Avg. T (C)	-0.1034	0.2611
Total C (µg)	Avg. T (C)	-0.0331	0.7195
WUE	Avg. T (C)	0.0772	0.4018
%SOM	Canopy Cover	-0.1217	0.1875
Est. Mass	Canopy Cover	-0.2717	0.0028
WUE	Canopy Cover	-0.2391	0.0088
%SOM	DBH	-0.0799	0.3874
Est. Mass	DBH	-0.1652	0.0725
WUE	DBH	-0.2495	0.0062

Figure 7: Summary of statistical analysis results. This table includes the results mentioned in the results sections above. It also includes and additionally includes the response of water use efficiency to latitude, elevation, Precipitation temperature, canopy cover, and diameter of tree at breast height, and other non significant results.

Discussion:

Overall, the results did not match the original hypothesis that soil carbon content would increase in northern latitudes with higher average rainfall. The results suggest quite the opposite: soil carbon content was higher in southern latitudes, and in sites with lower average rainfall. One explanation could be attributed to the higher rates of decomposition or soil organic matter runoff due to more average rainfall in the northern limit forests. It is understood that more rainfall can result in nutrient poor soils due to heavy rains washing organic materials from the soil (Avissar et al. 2018). Additionally, just days before the northern limit forests were sampled (including Jedediah Smith, Humboldt, and Navarro) there was a major storm and flooding event that affected the three northern sites and inundated the sites sampled at Humboldt and Navarro. This major storm and subsequent flooding may have changed the soil composition.

WUE results did match the original hypothesis. WUE decreased as latitude increased and as water availability became more limited and is consistent with current research findings. One study on wheat crops found that WUE was higher in water limited crops, possibly because of stomatal closure to restrict transpiration (Abbate et al. 2004).

Total carbon and soil organic matter responded negatively to canopy cover. This is consistent with the findings of less total carbon and soil organic matter in the northern range because the northern range had higher canopy cover than the southern range. However, more research is required to investigate whether canopy cover itself has an effect on total carbon and soil organic matter. Additionally total carbon and soil organic matter responded negatively to DBH. The northern range redwood trees had larger average diameter trunks, however this study did not reveal whether diameter of redwood tree trunks are indeed correlated to total carbon and soil organic matter. More research would be required in order to find a possible relationship. However, soil organic matter and total carbon decreased with an increase in average temperature. This finding is consistent with relevant literature regarding soil carbon response to changes in temperature, in particular, atmospheric warming. While there is much debate, and more research required, many studies have found that as the atmosphere warms, soil warming can switch soils from being a carbon sink to a carbon source (Melillo et al. 2002)(van der Molen et al. 2011).

There is speculation around the topic of soil carbon content and how climatic, geographic, and habitat specific variables may influence it. Countless environmental factors play a role in whether soils store carbon or become a potential carbon source. To better understand soil carbon storage, the forest ecosystem response to a changed climate must also be considered. The carbon storage in woody tissue would be affected by water availability, changing temperatures, and photosynthesis potential (Melillo et al. 2002). Consistent and long term research is required to better understand what may influence soil carbon content. One reason a consensus among research has not been reached is due to the wide range of kinetic properties diverse soil organic compounds exhibit (Johnstone, Dawson & Fung, 2010). Additionally, because varying habitats are unique and season dependent in their own way, each habitat must be investigated individually and carefully. For example, soil warming studies conducted on mid-latitude grassland ecosystems have shown little change in carbon storage (Melillo et al. 2002). But soil warming studies in high-latitude, dominant woody vegetation ecosystems in colder habitats may have a greater carbon loss potential (Melillo et al. 2002).

Coast Redwood ecosystem response to climate change effects is largely unknown. However, delving deeper into specific areas of the ecosystem can begin to paint a clearer picture. One study investigated redwood's response to a decline in summer time fog occurrence, and found a 33% decline in fog frequency since the early 20th century (Johnstone, Dawson & Fung, 2010). The study suggested that long-term reductions in fog likely have an impact on the water and carbon economy of the redwood forest and other coastal endemic species (Johnstone, Dawson & Fung, 2010). Another study found that in *Sequoia* forests, whether the majority of above ground carbon storage is in dead or live trees depends on whether the habitat is predominantly wet or fire prone. They found that in wet habitats where fire disturbance events are unlikely, the majority of above ground carbon storage is in dead wood (Van Pelt, Sillet, Kruse, Freund, & Kramer, 2016). Reviewing and combining studies like these and piecing together the complexities of forest ecosystems can aid in better understanding how forest's soil ecosystems will respond to changed climates. Additionally, above ground ecological studies are just as vital to understanding how soil carbon will respond under climate change scenarios, as subterranean studies are to understanding how above ground organisms will respond to climate change effects.

For future studies, more time, sampling the same sites and subsites during different times of the year, collecting reliable climatic data, and having a team of researchers would be essential. Doing this research over at least a few years could give the time needed to sample throughout different seasons, in order to control for an odd year (like a drought year or unusually wet year), and to understand short term and immediate changes in soil carbon content in relation to climatic variables. Sampling during different seasons would also allow researchers to understand how soil carbon content changes throughout the year, in general. For instance, does the soil carbon content gradient switch after summer or stay the same as during winter?

A team of researchers would facilitate quicker data collection in the field, and quicker sample analysis in the lab. It would aid in avoiding burnout and would also create a collaborative environment where different strengths and skill sets compliment each other. Unfortunately, due to time and reliable data availability, fog data was not included in this study. Before beginning a new study, I would secure a reliable system for collecting fog occurrence data. Finding weather data, especially for fog, was a challenge. If data were available, they would be inconsistent with many gaps. In order to properly study redwoods, monitoring fog and having access to reliable weather data is vital.

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