# FIRE HISTORY AND SOIL CARBON IN OLD GROWTH COAST REDWOOD FORESTS ACROSS THE LATE HOLOCENE


by

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A THESIS

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THESIS ABSTRACT

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Title: Fire History and Soil Carbon in Old Growth Coast Redwood Forests across the Late Holocene

Fire is an important ecological feature across temperate forests, yet characteristics of the coast redwood fire regime remain uncertain due to generally few fire histories. This study examines legacies of fire in redwood forests in northern California through radiocarbon dating and quantification of soil macro-charcoal, soil carbon and pyrogenic carbon in old growth redwood stands. We sampled soils in the Headwaters Forest Reserve, a protected fragment of old growth redwood in Humboldt County, California. Radiocarbon dates from macro-charcoal indicate fire events occurring a maximum of 6,840 calibrated years BP, predating existing records. Composite 14C dates show increased fire activity within the last 1,000 years in synchrony with existing dendrochronological records. Soil C averaged 928 g/m2, of which a high proportion was pyrogenic C (15-30%). Information from this multi-proxy reconstruction clarifies our understanding of the nature of coast redwood fires, contributing to ongoing discussions of coast redwood fire management.

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# CHAPTER I

# INTRODUCTION

## Fire in Redwoods

Fire is an important ecological process in a variety of ecosystems worldwide, shaping characteristics like forest structure and composition, yet uncertainty remains regarding how fire interacts with and influences the characteristics of coast redwood (*Sequoia sempervirens)* forests. These forests present a conundrum: the mesic nature of redwood forest structure and the frequent precipitation in Northern California has been thought to prevent frequent burning, yet existing tree ring records of fire reveal 30-year fire intervals prior to Euro-American settlement (Stuart 1987, Brown and Swetnam 1994, Brown et al. 1999, Brown and Baxter 2003, Stephens and Fry 2005, Norman 2007). Additionally, coast redwoods possess traits such as basal and epicomics sprouting, cone morphology, and thick back; traits that are typically characterized as adaptations to fire (Sawyer et al. 2000). Furthermore, lightning has been associated with wildfires in the area between 1986-2013, but past frequencies or probabilities remain relatively unknown (Hostetler et al. 2018, Lorimer et al. 2009, Carroll et al. 2018, Stuart and Stephens 2006, Lorimer et al. 2009). Anthropogenic ignition sources remain relatively unclear, but some studies suggest that the decadal fire intervals prior to Euro-American settlement are the result of First Nations burning habits (Sawyer et al. 2000). Understanding the context of fire in redwoods across the Late Holocene is important given current increases in the intensity and frequency of wildfires across the western United States (Westerling et al. 2006, Fried at al. 2004). The role to which fire shapes and impacts coast redwood forests must be investigated to better inform management efforts under warming climatic conditions of the next century (Long 2009).

The longevity of redwoods signifies that existing stands of old growth are legacies of different climatic and environmental conditions. Subsequently, the context of long-term environmental change within coast redwoods remains poorly documented; existing research on disturbance regimes, particularly fire, in redwood forests is largely dependent on tree-ring records, which can be difficult to obtain from coast redwood trees, due to the poor preservation of fire scars (Fritz 1940, Brown 2007). Furthermore, tree-ring records are confined to the lifespan of the tree, and so even with optimal preservation of scars, the average 2,000 year lifespan of a coast redwood does not access enough of a long-term context to provide an adequate fire history record. Existing fire scar records typically cover 300-400 years at most. Finally, there has been limited record synchrony between reported fire frequencies, partly explained by both regional gradients and differences in methods, but still a problem for understanding how fire operates differently across different regions of redwood (Norman et al. 2009, Baxter and Brown 2003).

Clarifying existing uncertainties requires accessing additional fire proxies and archives within coast redwood ecosystems that can complement existing tree-ring research. One such proxy is soil charcoal and carbon: charcoal incorporated into forest soil systems is thought to have a potential residency time of thousands of years, meaning it has the potential to serve as an archive of fire history that both overlaps and predates tree-ring records (Bird et al. 2015). Furthermore, soil carbon levels, and the proportion of that carbon that is pyrogenic, may provide an indication of the influence of fire on coast redwood ecosystem function, expanding our understanding of the role of fire within coast redwood ecosystems.

**Fire and Carbon Cycling**

Forest fires can influence the carbon cycle through pathways in two directions: Total combustion of carbon-based biomass may emit carbon dioxide into the atmosphere, while partial combustion may produce charcoal or other pyrogenic carbon (PyC) that, if incorporated into forest soil systems, may reside for hundreds to thousands of years, potentially contributing to long-term carbon sequestration (Bird et al. 2015, DeLuca and Aplet 2008, Law et al. 2001, Preston and Schmidt 2006). Baseline levels of carbon in redwood soils remain unknown, as does the proportion of soil carbon that is pyrogenic.

We refer to both charcoal and PyC in this study: PyC is a broader term for the physical residue and productions of fire (including soot, char, partially charred material and individual compounds altered on a molecular level), while charcoal refers specifically to macroscopic fragments ( Knicker 2001, Bird et al. 2015, Schmidt and Noack 2000). Existing research on the fraction of PyC relative to soil organic matter (SOM) in other ecosystems have produced ratios of 0.15 for fire-prone ecosystems, 0.1 for temperate ecosystems and a nominal 0.01 for tropical wet forests (Bird et al. 2015). Determining the ratio of PyC to SOM in coast redwoods will be important for contextualizing the role of fire in redwoods compared to other ecosystems. For example, coastal Douglas-fir forests in Southwest Oregon, a potential comparison to Northern California's redwoods, have an estimated 700 g/m2 of pyrogenic carbon (Pingree et al. 2012).

No previous research has evaluated charcoal content of coast redwood mineral soils, an ecosystem with dramatic levels of carbon-based biomass. Advances in charcoal and carbon quantification methods present a unique opportunity to investigate how fire has influenced characteristics of soil and carbon cycles within old growth coast redwood forests, and to compare carbon and fire patterns of redwoods to other ecosystems.

**Research Questions**

This research takes advantage of the newly established peroxide acid charcoal C quantification method to evaluate charcoal within coast redwood mineral soils. The study addresses the following questions:

- **A.** Is there a charcoal stratigraphy within mineral soils in old growth coast redwood forests?
- **B.** What can be inferred about Holocene fire history in redwood forests from radiocarbon dated charcoal fragments?
- **C.** What quantity of soil organic carbon is pyrogenic carbon?

**Study Area**:

We conducted this research in the old growth coast redwood forests within the Elk River and Salmon Creek watersheds at the Headwaters Forest Reserve in Humboldt County, California. Elevation ranges from 100 to 2,000 feet. Soils are mostly shallow (>1m), and are a mix of alfisols and ultisols. Climate is characterized by maritime conditions: cool and wet winters are followed by warm, cloudy summers.

The Headwaters Forest Reserve, a 7,000 acre parcel of mixed old growth and second growth, is managed by the Bureau of Land Management as part of the National

Landscape Conservation system. Sites sampled were all in old-growth stands of coast redwoods, an ecosystem dominated by coast redwood in the overstory, but with occasional Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*) and western red cedar (*Thuja plicata*) individuals. The understory of these old growth forests is characterized by ferns and small shrubs.

Due to the particular cultural and political history of Headwaters, the reserve has a history of disturbance: the remaining old growth is protected, but edges of both second and old growth are in close proximity to timber roads and the reserve boundaries themselves. Unpublished data shows that fires occurred in the reserve between every 10-42 years since the 1760s, and that earlier fires occurred but were not dateable. They also found fire increased after 1850 until 1936 when fire suppression management went into effect. Levels of tree survival indicate low to moderate fire severity, strongly controlled by topography (Norman et al. 2009).

# CHAPTER II

# METHODS

## Site Selection and Sampling

Sites were selected based on access to groves of old-growth. Effort was made to select sites at a distance from past disturbances such as logging, road construction or fire events.

Forest soil sampling was primarily confined to ridgetops of old growth redwood stands, excluding steep slopes or valley bottoms. Multiple volumetric soil cores were obtained contiguously at each site using a 5-cm split core sampler driven into the soil up to 30 centimeters deep. Samples are referred to using alphabetic depth categories of A-G, each representing 5-centimeter soil cores. Sampler rings had a volume of 98.2 cubic centimeters. Coarse litter was removed prior to sampling, but there was no effort to distinguish between O, A, and B horizons as there was often no distinct boundaries, and the soil-coring method did not permit diagnosing soil horizons. Corresponding soil pits were dug adjacently in order to sample charcoal fragments opportunistically at exact depths from a clean soil profile between 0 and 45 centimeters deep. Soil cores were taken in duplicate in order to compare the two methods of quantifying charcoal concentration: physical sieving and peroxide-acid digestion. One valley-bottom site (EELS_01) was sampled opportunistically for comparison.

At two sites (GOV_01 and WORM_03), debris-flow deposits were exposed by stream or road cuts, allowing for deeper sampling. Charcoal fragments were sampled by hand at exact depths from a clean soil profile and soil cores were subsequently obtained vertically from the face of the soil profile at 10 cm increments.

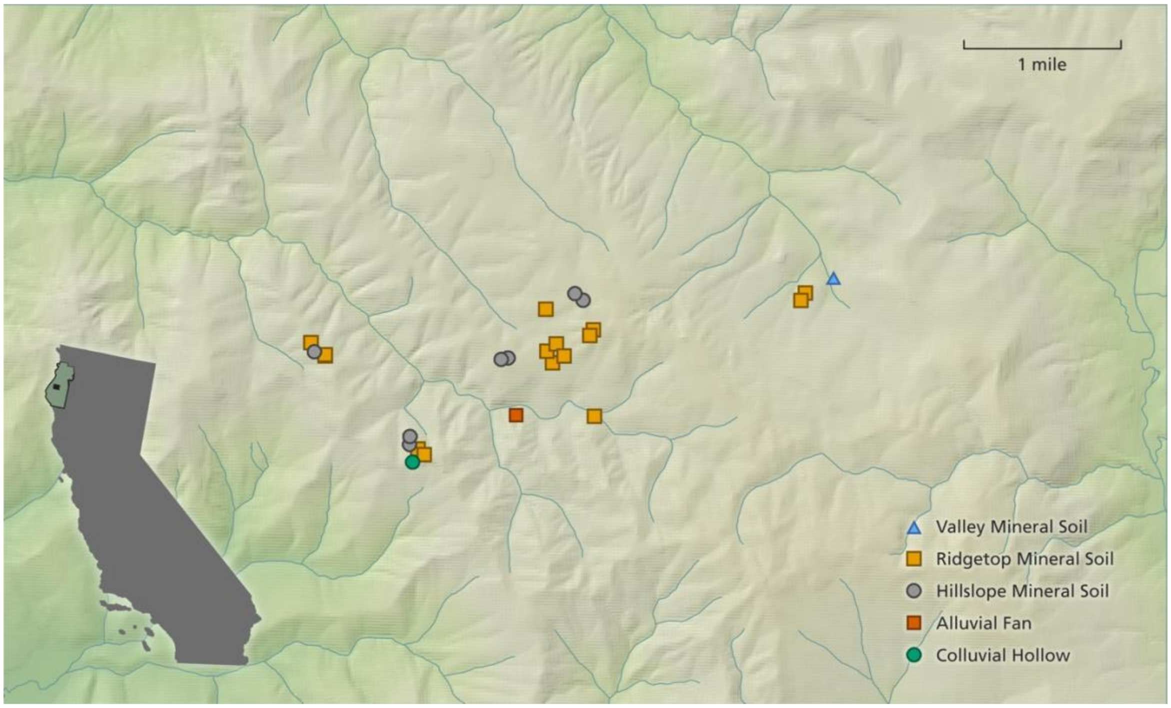


**Figure 1. Map of Study Sites in the Headwaters Forest Reserve, Humboldt County, CA.**

### *Radiocarbon Dating*

Charcoal samples from each sample site were selected for accelerator mass spectrometry (AMS) radiocarbon dating based on depth and quality of sample. These dates came entirely from charcoal hand-picked from opportunistic samples. Samples were cleaned using alternating heated 10% KOH and 10% HCL rinses. Radiocarbon dating was performed at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory in Livermore, California on 45 samples from 17 sites (Table 1).

Radiocarbon dates were calibrated using the CALIB 5.0.1 program and the INTCAL13 calibration curve (Reimer et al. 2013), and modern dates were estimated with Oxcal. Estimates of site activity were determined using the Bayesian Gaussian mixture model provided in the BchronDensity function within the Bchron R package.

***Physical Charcoal Quantification***

In the laboratory, soil-core sections were soaked overnight in a 10% KOH solution to disperse organic clumps, and then rinsed through 2 mm and 0.5 mm test sieves. Both the 2 mm and 0.5 mm fractions were removed and treated with 3% hydrogen peroxide for over 24 hours. Once oven-dried, charcoal was identified under a microscope and weighed to obtain total mass for each soil-core section for each site. Charcoal concentration from sieved samples was calculated using the following equation:

$$\frac{mg\ charcoal}{g} = \frac{Mass\ of\ charcoal\ (mg)}{Dry\ weight\ of\ bulk\ sample\ (g)}$$

***Acid-peroxide digestion***

Acid-peroxide digestion was completed following the methods of Kurth et al. (2006) as modified by Pingree et al. (2012). Each 5-cm soil core segment was dried for 24 hours at 60°C, weighed, and stored in plastic sample bags. Five grams from each sample was ground in a ball mill to <0.76 μm. One gram of soil per sample was placed in a 50 ml Erlenmeyer flask to which 20 ml of 30% H2O2 and 10 ml of 1 M HNO3 was added and swirled by hand at room temperature for 30 minutes. Flasks were heated in a water bath to 90°C for 16 hours. After digestion, the samples were filtered through pre-weighed filter papers, which were dried at 60°C for over 24 hours and weighed to obtain the mass of residual material after digestion and filtration.

A charcoal standard was created by combusting dry western red cedar (*Thuja plicata*) wrapped in aluminum foil at 450°C. A 1:9 ratio of charcoal and charcoal-free rock (Condrey Mountain Schist from SW Oregon) was ground to <0.76 μm in a ball mill, resulting in a 10% charcoal standard. Each batch of acid-peroxide digestion included one sample standard and duplicates of at least two samples.

***Elemental Analysis***

Percent carbon of original and digested materials was determined on a GV Isoprime Isotope Ratio Mass Spectrometer at the Laboratory of Stable Isotope Ecology, University of Miami. Samples were prepped and weighed at the University of Oregon, before analysis at the Stable Isotope Facility. Total C following digestion is reported as charcoal C and assumes that all non-charcoal organic C was consumed during peroxide-acid digestion.

Charcoal C concentration (PyC) of digested soil samples was determined using the following equation:

$$\frac{mg\ PyC}{g\ soil} = \left(\frac{(C1 * M1)}{M2}\right) * 1000$$

where M1 = mass of digested sample, C1 = C concentration of digested sample, and M2 = mass of original sample.

PyC mass per square meter was estimated as the product of PyC concentrations, bulk density, and soil depth sampled (5 cm), summed over all depth increments. Specifically, grams of PyC per square meter was calculated with the following equation:

$$\frac{g\ PyC}{m^2} = \left(\frac{\%\ PyC}{100} * BD * 5\right) * 10{,}000$$

where BD = bulk density (total dry weight of sample divided by the volume of the sampler as $g/cm^3$).

CHAPTER III

RESULTS

## Results from Radiocarbon Dates

### *A. Forest Mineral Soil Sites*

The median ages of calibrated mineral soil carbon radiocarbon dates ranged from modern to 3,805 years BP. Across the study area, the relationship between age and depth in charcoal samples in mineral soils is statistically significant (Figure 2A). The cumulative probability distribution of radiocarbon dates from mineral soil was greatest in the last 1,000 years, with a peak of 0.008 at 800 years before present, and a subsequent decline (Figure 2B).

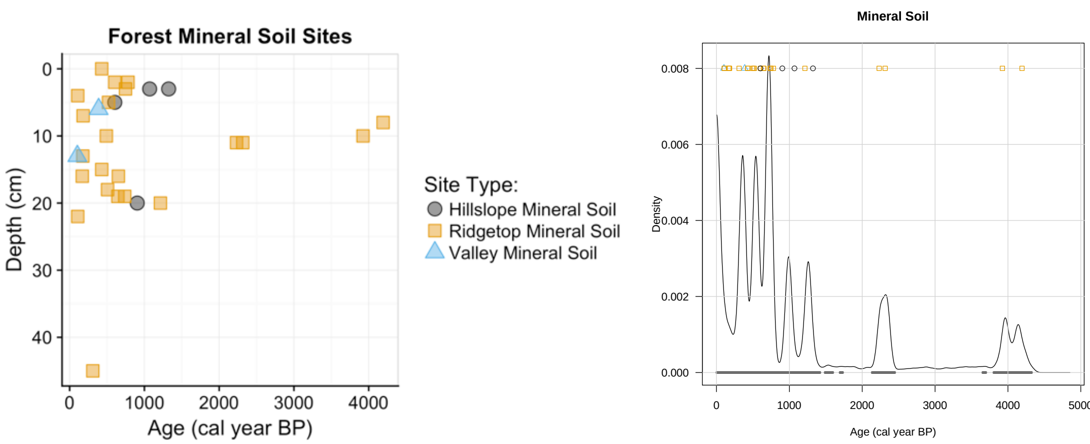


**Figure 2. Radiocarbon dates of mineral soil.** 43 dates shown from 20 sites (average 2 dates per site). (A) Radiocarbon dates of forest mineral soil profiles. (B) Bayesian Gaussian mixture model estimation of site activity for mineral soil sites.

### *B. Alluvial Fan and Colluvial Hollow Sites*

Radiocarbon dates from soil-charcoal sampled from alluvial fans and colluvial hollows ranged in age from 931 to 6,839 years BP. Two charcoal fragments from the WORM_03 site dated at 6,666 and 6,839 year BP, though they were located at depths a meter apart (Figure 3A). The density of radiocarbon dates from depositional sites was greatest around 5,000 years BP, with smaller peaks at 1,000 and 7,000 years BP (Figure 3B).

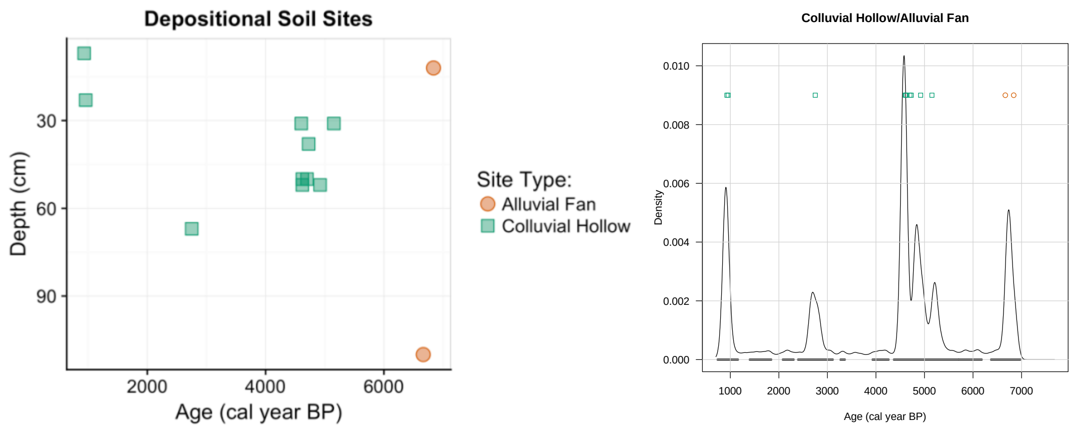


**Figure 3. Radiocarbon dates at depositional sites.** (A) Radiocarbon dates of soil profiles found within a colluvial hollow and an alluvial fan. (B) Bayesian Gaussian mixture model estimation of site activity for non-mineral soil sites.

### *C. Charcoal Stratigraphy*

All adjacent dates were compared pairwise (up to 9 dates or 8 comparisons per core), for a total of 21 comparisons from 14 cores, showing that the majority of dates are not in stratigraphic order; 13 out of the 22 comparisons display an age reversal (Figure 4).

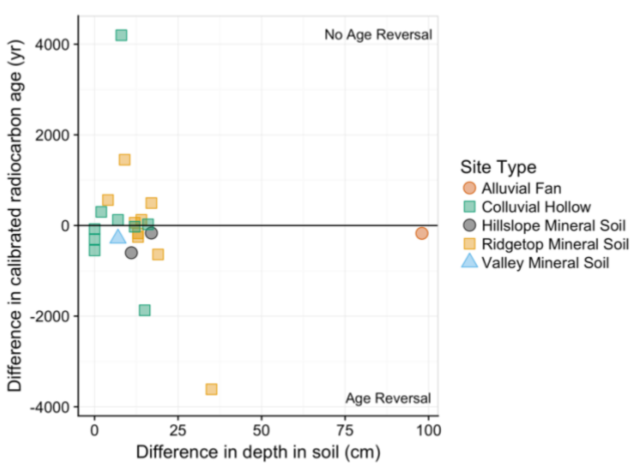

**Figure 4. Soil-charcoal radiocarbon dates compared within single cores**. Stratigraphic relationships across soil-charcoal radiocarbon dates from sites with at least two radiocarbon dates from the same core.

### *D. Synchrony with Tree-ring Records*

Comparing soil charcoal dates to tree-ring records of fire shows some overlap between fire events ca. 100 and 175 years BP (Figure 5). Tree-ring records are reported as given by Norman and Jennings, and fire scar records are grouped for all areas in Headwaters.

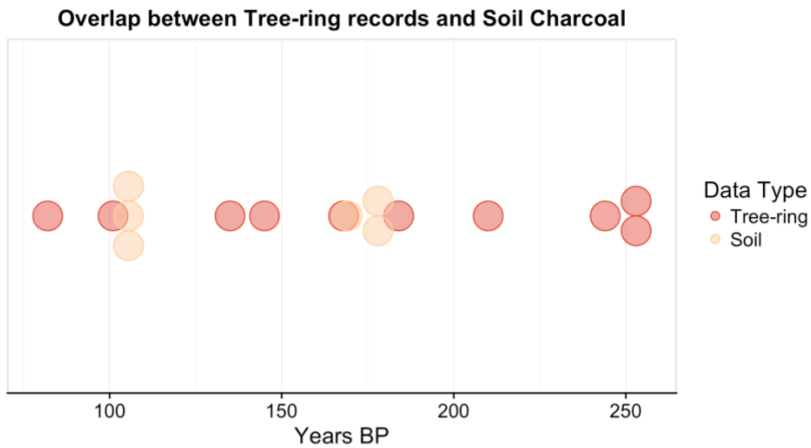


**Figure 5. Overlap between tree-ring records of fire and soil charcoal dates from the Headwaters Forest Reserve.**

**Table 1. Radiocarbon dates of individual pieces of soil charcoal from Headwaters Forest Reserve, California.**
MS=Forest mineral soil.

| *Site Name* | *Site Type* | *CAMS #* | *Sample ID* | *Depth (cm)* | *C14 Age* | *Error* | *Cal yr BP* |
|---|---|---|---|---|---|---|---|
| *Governor's Grove* | Colluvial Hollow | 175998 | GOV-01 | 17 | 1010 | 35 | 798-1040 |
| | | 177582 | GOV-01 | 23 | 1050 | 30 | 924-1050 |
| | | 177078 | GOV-01 | 31 | 4490 | 60 | 4891-5313 |
| | | 177079 | GOV-01 | 38 | 4185 | 30 | 4618-4837 |
| | | 177080 | GOV-01 | 50 | 4155 | 30 | 4580-4826 |
| | | 177081 | GOV-01 | 52 | 4355 | 35 | 4848-5036 |
| | | 175999 | GOV-01 | 67 | 2615 | 40 | 2543-2844 |
| | Ridgetop MS | 177460 | GOG-01 | 1 | Modern | | |
| | | 177461 | GOG-01 | 18 | 445 | 30 | 465-534 |
| | Ridgetop MS | 177462 | GOG-02 | 4 | 90 | 30 | 22-265 |
| | | 177463 | GOG-02 | 16 | 155 | 35 | 1-285 |
| *Worm Trail* | Ridgetop MS | 177084 | WORM-01 | 11 | 2285 | 35 | 2315 |
| | Alluvial Fan | 175996 | WORM-03 | 12 | 6000 | 30 | 6839 |
| | | 175997 | WORM-03 | 110 | 5845 | 30 | 6666 |
| *Salmon Creek Trail* | Ridgetop MS | 177082 | SCT-01 | 16 | 680 | 30 | 561-680 |
| | | 177083 | SCT-01 | 20 | 1255 | 30 | 1083-1278 |
| | Ridgetop MS | 177458 | SALM-01 | 0 | 365 | 30 | 316-501 |
| | | 177459 | SALM-01 | 13 | 175 | 40 | 1-298 |
| | Ridgetop MS | 177580 | SALM-03 | 3 | 840 | 30 | 686-891 |
| | | 177581 | SALM-03 | 22 | 90 | 30 | 22-265 |
| *Worm Trail* | Ridgetop MS | 177453 | WOMT-01 | 5 | 480 | 30 | 499-542 |
| | | 177454 | WOMT-01 | 19 | 680 | 40 | 556-687 |
| | Ridgetop MS | 177455 | WOMT-02 | 2 | 575 | 30 | 503-648 |
| | | 177455 | WOMT-02 | 15 | 365 | 30 | 316-501 |
| *Ridge Trail* | Ridgetop MS | 177577 | RIDG-01 | 19 | 830 | 30 | 688-789 |
| | Ridgetop MS | 177465 | RIDG-02 | 2 | 875 | 30 | 709-907 |
| | | 177457 | RIDG-02 | 11 | 2245 | 35 | 2153-2343 |
| *Elk River* | Valley MS | 177578 | EELS-01 | 6 | 305 | 30 | 299-462 |
| | | 177579 | EELS-01 | 13 | 75 | 30 | 27-259 |
| *Left fork of Worm trail* | Hillslope MS | 177586 | WOLF-01 | 5 | 580 | 30 | 533-649 |
| | | 177587 | WOLF-01 | 16 | Modern | | |
| | Hillslope MS | 177588 | WOLF-02 | 3 | 1420 | 35 | 1287-1377 |
| | Ridgetop MS | 177589 | WOLF-03 | 10 | 3615 | 30 | 3841-4062 |
| | | 177590 | WOLF-03 | 45 | 265 | 30 | 1-433 |
| | Ridgetop MS | 177591 | WOLF-04 | 10 | 420 | 30 | 333-523 |
| *Right fork of Worm Trail* | Hillslope MS | 177592 | WORF-02 | 3 | 1155 | 30 | 982-1175 |
| | | 177593 | WORF-02 | 20 | 985 | 30 | 797-959 |
| | Ridgetop MS | 177594 | WORF-03 | 8 | 3805 | 30 | 4089-4291 |
| | Ridgetop MS | 177595 | WORF-05 | 7 | 200 | 30 | 1-303 |

**Results from Bulk Soil Analysis**

***A. Physical Soil Analysis***

Bulk density of soil samples increases with depth from ca. 0.3 g/cm3 at the soil surface to ca. 1 g/cm3 at 30 cm. (Figure 6A). Charcoal concentrations determined by physical charcoal quantification decreases significantly with depth (Figure 6B).

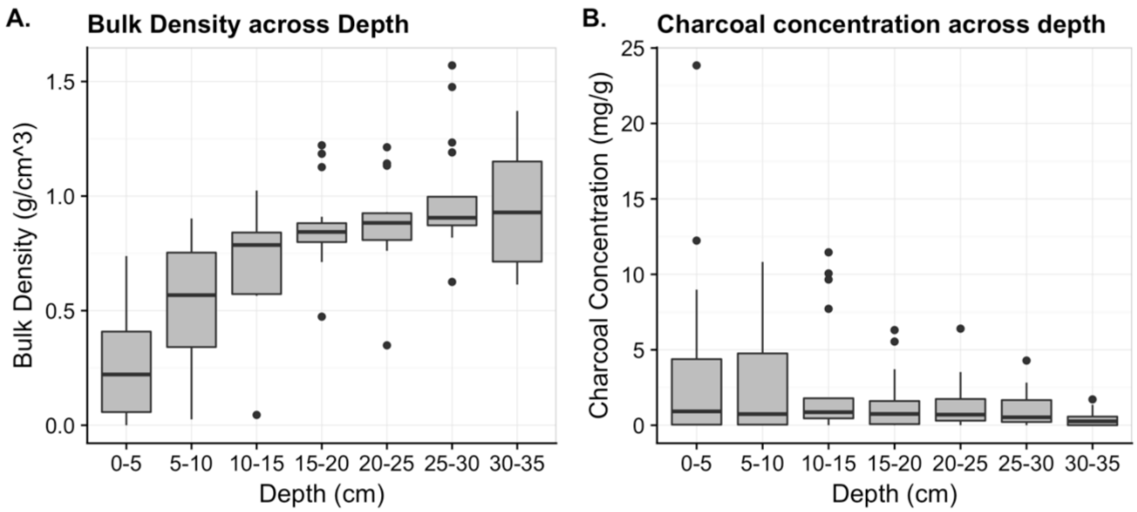


**Figure 6. Soil Sample Characteristics**. Physical analysis of volumetric soil samples, expressed by depth category. (A) Bulk density across depth. Calculated as dry weight of soil sample/volume of soil sampler. (B) Charcoal concentration (expressed as milligram per gram) across depth. Charcoal mass measurements obtained from sieving volumetric soil samples at 2 mm and 0.5 mm.

***B. Acid-Digestion Pyrogenic Carbon***

Twenty-six duplicates were run during elemental analysis, showing machine accuracy to be within 0.15%. Inter-sample variability was 0.015% within each tray of 92 samples, and 0.03% between each tray (4 total). The 10% charcoal standard (from western red cedar) had a 34% loss of PyC during digestion.

Total C of undigested bulk soil samples decreases with depth (Figure 7A). The ratio of PyC to total C slightly increases with depth, indicating the effect of preservation ability (Figure 7B). Average proportions of PyC to total C per depth increment range from 0.089 – 0.199. The total average ratio of PyC was 0.159.

Total PyC in grams per square meter ranged from 620 to 1,488 g/m2 per site, with an average of 928 g/m2 across all sites, or 9,280 kg/ha (Figure 8). Mass of PyC increased across depth in all site types.

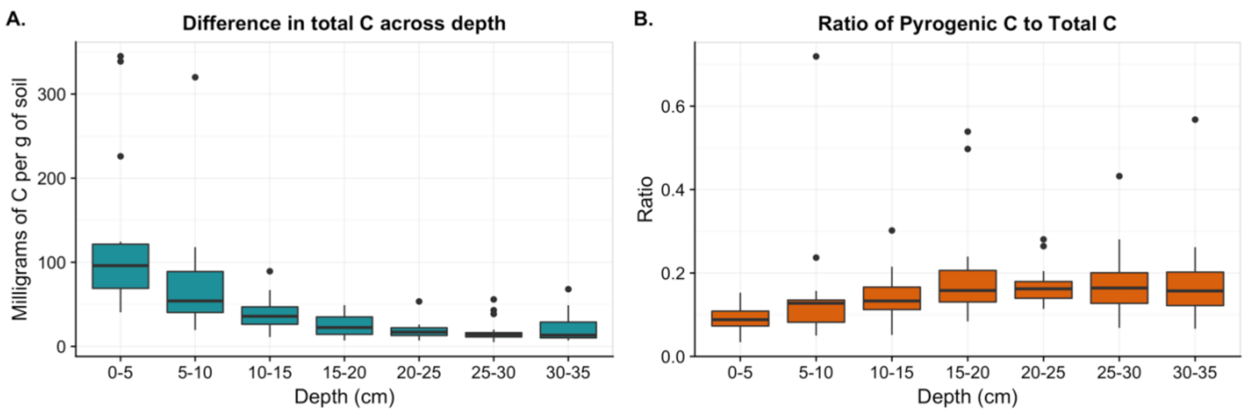


**Figure 7. Carbon levels determined by elemental analysis.** Results from elemental analysis of undigested soil and digested soil samples. (A) Total C levels for undigested soil samples across depth. (B). Ratios of PyC to total C.

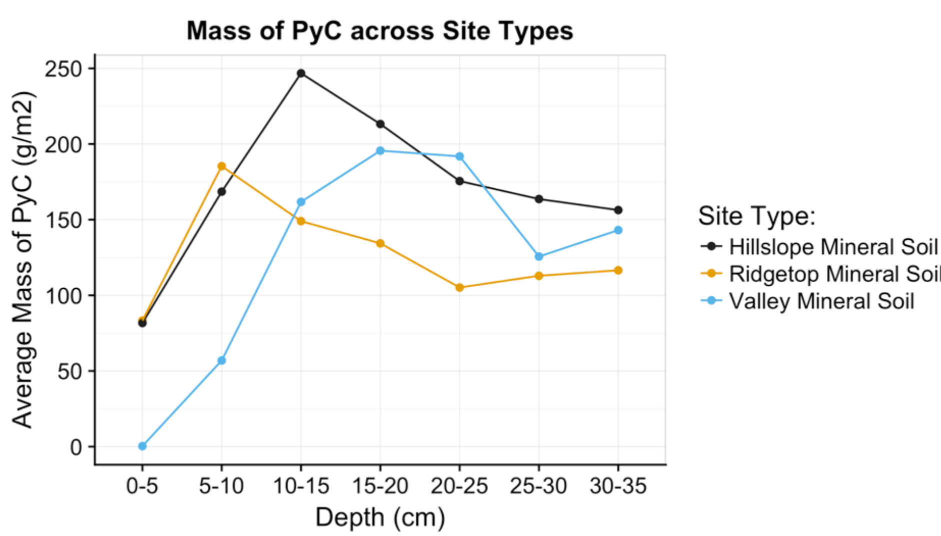


**Figure 8. PyC in grams per square meter across site types.** 16 ridgetops were sampled, along with 7 hillslopes and 1 valley for context.

### *C. Comparisons between physical and chemical-based methods*

Charcoal concentrations given by physical and chemical quantifications of soil charcoal both decreased over depth. Charcoal concentrations produced through the chemical quantification of PyC were on average greater than those produced by physical quantification (Figure 9).

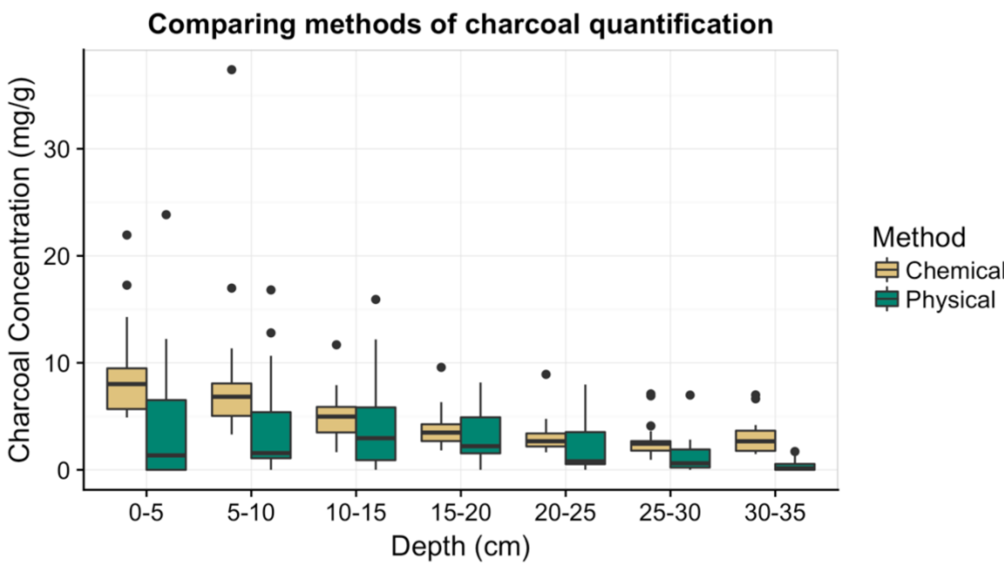


**Figure 9. Charcoal concentration results for chemical and physical quantifications of charcoal.** Chemical here refers to the acid-digestion method, while physical refers to the traditional method of sieving (>0.5 mm) and manual separation of charcoal fragments.

# CHAPTER IV

# DISCUSSION

## Fire history in coast redwood from soil charcoal radiocarbon dates

The soil charcoal record in coast redwood mineral soils contains records of fire history that precede tree-ring records of fire. Charcoal is abundant and has the capacity to preserve over thousands of years across different depths. Concentrations of charcoal are most abundant in the top 10 cm of redwood soils and decline with depth, though charcoal is still found 30-35 cm deep. The age reversals of radiocarbon-dates soil profiles indicates there is not a stratigraphy within mineral soils within coast redwood forests, indicating that redwood soils experience mixing to a relatively large degree. This may be a result of disturbance events occurring at various spatial or temporal scales, including both human and natural (such as tree tip-ups or down-slope soil movement) disturbance events. The size of redwood root systems should mean that a redwood tree tip-up would upturn relatively large amounts of soil in a single event. Redwood charcoal stratigraphy may also suggest that redwood soil horizons may not accumulate continuously, and that soil mixing is relatively common.

The ages of the charcoal fragments from the alluvial fan would indicate that the material in the alluvial fan sampled was likely transported by a depositional event (Figure 3A). Due to the nature of the site and the unusual age of the samples, these dates were not included in subsequent analysis. However, these fragments are evidence that fire occurred within the area in the early Holocene, followed by a depositional event of some kind.

There is some overlap between the fire scars dated by the unpublished Norman and Jennings data and the soil charcoal radiocarbon dates that occur within the last few hundred years. Specifically, fire events at ca. 100 and ca. 175 years BP registered in both the soil charcoal and tree ring records (Figure 5). Dated fires from the Norman and Jennings project only extend back to 250 years BP, so it is likely that fire scars from earlier may reflect events registered by soil charcoal dates. Furthermore, the soil charcoal radiocarbon dates that registered as "modern" may be from settler/logger-induced broadcast burns that took place in the 1900s and earlier in order to expose the landscape for easier harvesting.

**Pyrogenic Carbon**

The average proportion of PyC relative to total soil C in redwood ecosystems was comparable to estimates for ecosystems with frequent fire (0.15), and proportions at deeper depths were distinctively higher (0.20). This suggests that fire may have an impact on carbon cycling within coast redwood forests comparable to ecosystems with frequent fire regimes (fires occurring somewhere between 5 to 30 years). The extreme levels of biomass in redwood forests may contribute to the large quantity of charcoal produced, and hillslope erosion and tree-tip-up bioturbation promotes the burial and preservation of charcoal. The acid digestion may actually underestimate the PyC content of soil, as the charcoal standard lost 34% of the PyC during digestion. However, this recently-created charcoal may have components that would have been lost by normal soil-respiration activity had it been in a soil environment for decades. Decomposition rates for younger, artificially-made charcoal may be higher and Kurth et al. (2006) reported PyC loss of less than 10% (Douglas-fir charcoal) using the same acid-peroxide digestion. Therefore it is not clear to what degree the acid-digestion underestimates the actual PyC concentration.

The average g/m2 of PyC across sites was higher than estimates produced for coastal Douglas-fir forests in Southwest Oregon, boreal forest soils, Sierra Nevada soils and dry Ponderosa Pine forest soils (Ball et a. 2010, Kurth et al. 2006, Pingree et al. 2012, Bélanger and Pinno 2008, Mackenzie et al. 2008). Pingree 2012 found ca. 700 g/m2 of PyC in the Siskiyou Mountains, constituting nearly 20% of total C in surface and subsurface mineral soils. Comparing across ecosystems, the system with the most similar mass of PyC is a boreal forest in Saskatchewan with a reported 4,000-11,000 kg charcoal C $ha^{-1}$ (Bélanger and Pinno 2008). Mass of PyC across redwood soil sites ranged from 6,000-14,000 kg per hectare, suggesting similarities in charcoal dynamics. Our results suggest redwood ecosystems contain greater pyrogenic carbon in mineral soils than comparable sites with frequent fire, which may be a result of the abnormally high aboveground biomass in redwood forests and efficient burial and preservation of charcoal into mineral soils.

The average mass of PyC was highest in hillslope sites, though not enough valley sites may have been sampled for adequate comparison. The higher levels of hillslope PyC compared to ridgetop is a strong indication of PyC transportation through erosion (Abney and Berhe 2018).

**Charcoal Quantification Methods**

Comparison between physical and chemically-based methods of charcoal quantification show higher charcoal concentration results from the acid-digestion method. Given that samples were taken in duplicates, this would indicate that the acid-digestion method may be more accurate, or that more than half of the charcoal in the soils is of a size class less than 0.5 mm. Considering the time and labor associated with sieving soils for charcoal, these results suggest that acid digestion methods may be a better alternative, which would improve our ability to quantify charcoal and PyC across various ecosystem types.

# CHAPTER V

## CONCLUSIONS

Fire appears to be an important ecological process in old growth coast redwood forests, occurring across the Late Holocene and strongly impacting belowground carbon storage within redwood mineral soils. The radiocarbon chronology indicates a major increase in fire starting 1,000 years ago, which may be the result of both human and climate effects. High levels of mixing may improve the capacity of charcoal to persist within soil, allowing for preservation of fire history records. Levels of PyC are comparable to other fire-prone ecosystems, suggesting coast redwood forests act as a significant sink of belowground carbon.

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