*Soil carbon and charcoal show fire was abundant in prehistoric coast redwood forests*

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**Manuscript Hightlights** (each 85 characters)

**Some points to consider regarding the long-term history of fire…i.e. how to interpret the pattern of dates over >3000 years.**

It is hard to see the overall temporal pattern of dates. I suggest making summed probability distributions using spd function in the rcarbon package, using spdnormalized=FALSE. This is a common approach. You could run it for the different subsets of charcoal, or at least for hillslopes, ridgetops, and all mineral soils. You can then plot some general pattern of fire from fire scars (Norman) next to the spd output. This will hopefully provide support for the statement of increased fire in the last 1000 years.

The longer term pattern…that of few mineral soil dates > 1500 years old. Is it an increase in fire, OR a loss of soil from soil movement (colluvium movement downslope), OR a loss of charcoal (from fragmentation, respiration, erosion, etc). Finding older charcoal buried in deep colluvium and in fans makes it hard to support that it is an actual increase in fire. These soils are "active' in that trees uproot, animals burrow, etc., and it may be that there is a generally a 1000-year half-life for large charcoal particles. The high proportion of C that is pyC is a sign that older charcoal may have been fragmented.

There are papers by Asmeret Behre about the burial of charcoal after fire…and the C cycle implications.

A methods point about the KMD method: plotting %PyC as a function of total C….I think shows a slight positive correlation. A priori, there should be no correlation. This happened for Lauren too. It is because some proportion of total C is as recalcitrant as the PyC. Over the Holocene, a lot of carbon cycles in the soil, but some forms of organic matter may simply be less likely to be lost to respiration. Lauren corrected for this by creating a corrected PyC number by subtracting off a proportion of the total C for the same sample (assuming there is a PyC and total C for every sample). For Lauren it was about 10% of the total C.

**New comments (March 21)**

I think there can be a paragraph about inbuilt ages (or inherited ages) that can summarize (briefly) findings from recent studies. I think an analysis of similarity of ages at the same site **might** be a way to address inbuilt age, but given the frequency of fire, it would be hard to claim the charcoal was from the same fire (esp since it is buried in mineral soil). The Streig paper is in redwoods, the Frueh paper is in the Oregon Coast Range.

Streig, A.R., Weldon, R.J., Biasi, G., Dawson, T.E., Gavin, D.G., Guilderson, T.P., 2020. New insights into paleoseismic age models on the northern San Andreas Fault: Charcoal inbuilt ages and updated earthquake correlations. Bulletin of the Seismological Society of America 110, 1077–1089. <https://doi.org/10.1785/0120190307>

Frueh, W.T., Lancaster, S.T., 2014. Correction of deposit ages for inherited ages of charcoal: implications for sediment dynamics inferred from random sampling of deposits on headwater valley floors. Quaternary Science Reviews 88, 110–124. <https://doi.org/10.1016/j.quascirev.2013.10.029>

**Abstract:** (279/250 words)

The fire disturbance regime, a process affecting the structure and composition of most temperate forests, is often best described and informed by long-term records. Yet determining basic attributes of a fire regime, such as frequency and severity, may be difficult in ecosystems that have limited available fire proxies (such as multi-century tree-ring fire scar records or high-resolution lake sediments), complicating our ability to contextualize modern changes in fire occurrence against a historic or prehistoric baseline range of variability. Here, we establish long-term records of fire in coast redwood forests, an important temperate forest ecosystem with limited information on past fire regimes. We use radiocarbon dating and quantification of both soil macro-charcoal, pyrogenic carbon, and soil total carbon, in the Headwaters Forest Reserve, protected old-growth coast redwood in Humboldt County, California. We investigate the multi-millennial record of fire preserved in soil charcoal and determine the amount of pyrogenic carbon stored in soils. Radiocarbon dates from macro-charcoal indicate fire events occurring a maximum of 6,840 calibrated years BP, predating existing records. Summed probability distributions of 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%), indicating that fire was a frequent feature of prehistoric coast redwood fire regimes. Age-depth reversals within charcoal dates indicates mixing of surficial soils, which may limit the time depth of soil C. However, C burial by soil movements show the potential for residency times of 6-7 thousand years. Information from this multi-proxy reconstruction clarifies our understanding of the nature of coast redwood fires, contributing to ongoing discussions of both past and present coast redwood fire regimes.

**Key words**: Fire, Coast Redwood, Pyrogenic Carbon, Charcoal, Soil Carbon, Paleofire

# Introduction

Fire as a disturbance is a key ecosystem process undergoing shifts in severity and frequency in many systems because of climate change. Characterizing shifts in modern fire regimes, however, requires an understanding of the baseline patterns of fire in each system prior to anthropogenic warming. Specifically, contextualizing fire in modern ecosystems under changing climatic and fire conditions requires the spatial and temporal insights provided by long-term (millennial-scale or longer) records of fire (Gavin et al., 2007; Whitlock et al., 2003). Paleoecological records of fire provide insights into the interactions of fire, vegetation and climate over longer time scales, enabling investigation of the functional mechanisms and relationships driving changes in fire regimes (Conedera et al*.*, 2009). Additionally, millennial-scale fire records clarify historic and pre-historic ranges of fire variability, providing context for modern shifts in variability. Clarifying uncertainties in millennial-scale fire patterns in ecosystems without reliable, appropriate, or accessible paleoecological archives, such as lacustrine depositional environments or suitable tree ring records, will require insight from novel fire proxies and archives. Methods such as radiocarbon dating of soil charcoal may enable reconstructing spatially-specific fire history if there is a reliable record in soils that have little recent human disturbance.

The distribution and abundance of pyrogenic carbon and charcoal stored within soil can provide insight into local long-term fire dynamics (Thevenon et al., 2010). Pyrogenic carbon is the physical residue and productions of fire and includes soot, char, partially charred material and any organic compounds altered on a molecular level by combustion (Bird et al., 2015). Here, we use the term pyrogenic carbon to capture the full spectrum of combusted material present in soil and reserve the term ‘charcoal’ specifically to refer to macroscopic fragments of partially combusted material (Bird et al., 2015; Knicker, 2011; Schmidt and Noack, 2000). The presence and distribution of soil charcoal within soil is a meaningful proxy of fire history since it reveals the age (when dated) and spatial location of past fires (Gavin et al*.*, 2007) and quantifies the amount of the soil carbon stock that is sequestered into a long-lived recalcitrant stock (Schmidt and Noack, 2000). Soil charcoal fragments are also spatially constrained : in systems without substantial soil movement, the presence of soil charcoal reflects the specific location of a fire (Gavin et al. 2007, Clark 1988, Ohlson and Tryterud 2000). Furthermore, charcoal incorporated into forest soils may reside for centuries to millennia (Criscuoli et al., 2014; Hammes et al., 2008), allowing charcoal to serve as an archive of fire history that both overlaps and predates tree-ring and anthropogenic records (Bird et al., 2015). In this study, we quantify soil charcoal, pyrogenic carbon, and total soil carbon in old-growth coast redwood (*Sequoia sempervirens*) forest where lacustrine records do not exist and tree-ring fire scar records are sparse and difficult to collect.

Using soil charcoal as a proxy of fire relies on radiocarbon dating charcoal fragments found within specific soil contexts and depths (i.e., Gavin et al. 2007). Radiocarbon dating, however, is an imperfect approach: the technique is expensive, and may overestimate the realistic age of a fire if the wood material itself is old enough at the time of burning (referred to as the inbuilt age or inherited age). In addition, soil disturbance, from bioturbation, colluvial soil movement, and debris flows affect the soil stratigraphy and time-depth preserved at a site. Despite those limitations, the use of radiocarbon dated charcoal as a proxy of fire activity persists, particularly in systems without alternative reliable archives (Talon et al., 2005).

The characteristics and dynamics of the coast redwood fire regime across millennium remains uncertain (Varner and Jules 2017). The mesic environment of redwood forest and the frequent precipitation and fog in coastal northern California suggest fire should be infrequent, yet existing tree ring fire scar records reveal 30-year intervals between fire prior to Euro-American settlement (Brown et al., 1999; Brown and Swetnam, 1994; Norman, 2007; Stephens and Fry, 2005; Stuart, 1987). Some suggest that the decadal fire intervals prior to Euro-American settlement are the result of First Nations burning habits (Greenlee and Langenheim, 1990; Jones and Russell, 2015; Lorimer et al., 2009; Stephens and Fry, 2005). In addition, coast redwoods possess fire-adapted traits such as basal and epicormic sprouting and thick bark that suggest a long co-existence with frequent fire (Noss, 1999). Current increases in the intensity and frequency of wildfires across the western United States have sparked concern about the consequences of frequent burning in coast redwood stands (Buma et al., 2020; Westerling et al., 2006). Nearby upslope areas, often < 2 km away, are much drier oak and chaparral environments; fire may spread from these areas. Despite their importance for contextualizing modern trends in variability, few traditional paleoecological records of fire in coast redwood are available. Additionally, redwood tree rings can be difficult to date (Roden, 2008), and few lakes exist in the region with adequate sediment deposition, highlighting the importance of using alternative techniques to reconstruct stand-level fire history.

No previous research has evaluated either the pyrogenic carbon content of coast redwood mineral soils. Advances in charcoal and carbon quantification methods present a unique opportunity to investigate how fire has influenced characteristics of soil and carbon cycling within old growth coast redwood forests. To establish a baseline understanding of soil carbon and charcoal dynamics within coast redwoods, we asked the following research questions: 1) what is the abundance and age of charcoal and pyrogenic carbon deposited within old growth coast redwood soils? 2) does the abundance and age of charcoal and pyrogenic carbon differ according to landscape position or depth of soil? 3) How does the abundance and age of charcoal and pyrogenic carbon in redwood soils compare to similar ecosystem types? To address those questions, we used radiocarbon dating and elemental analysis to evaluate the ages and distribution of soil charcoal and pyrogenic carbon across a gradient of landscape positions in an old growth coast redwood forest in northern California.

# Methods

## Study Area

We sampled organic and mineral soils in 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 (BLM data, unpublished). The climate is maritime: cool and wet winters (mean annual precip, mean jan temp) are followed by warm, cloudy summers (mean July temp – get for Arcata or from PRISM website). We sampled only old-growth stands of coast redwood, an ecosystem dominated by coast redwood in the overstory, with occasional Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*) and western red cedar (*Thuja plicata*) individuals.

The Headwaters Forest Reserve has a history of disturbance: remaining old growth is protected, but edges of both second and old growth stands are in close proximity to logging roads and the reserve boundaries themselves. A tree ring fire scar study extending to the 1760s showed that fires occurred in the reserve between every 10-42 years and suggests fire frequency increased after 1850 until 1936 when fire suppression management went into effect (Norman and Jennings, unpublished - Check the Lorimer review paper on redwoods—there is a list of citations…maybe you can cite Stuart 1987. You can cite published studies from nearby, too.).

Sites were selected based in old growth stands at a minimum of 50-m from past disturbances such as logging or road construction. We established 20 sample sites, primarily on ridgetops (n =14), with fewer sites on hillslopes (n=3), hollows (n = 1), alluvial fans (n = 1) or valley bottoms (n=1) to limit the possibility of sampling charcoal that was transported to the site via erosion, runoff, or debris flows (Fig 1). This focus of sampling intentionally provided a more conservative estimate of charcoal occurrence and abundance. We opportunistically sampled two sites with clear evidence of mass movement: a deep colluvium exposure on a road cut and an alluvial fan. At each site, we dug soil pits up to 45 cm in depth and sampled charcoal fragments for radiocarbon dating at exact depths from a clean soil profile between 0 and 45 cm deep. For the colluvial hollow and alluvial fan, we sampled exposures from a road cut and incised stream channel, respectively.

To estimate the abundance of total pyrogenic carbon and overall carbon content of soil, we took two volumetric soil cores, spaced 0.5 m apart at each site using a 5-cm diameter AMS split core sampler fitted with six 5-cm deep (98.2 cm3) sampling rings, which was driven into the soil up to 30 cm deep. At the colluvial road cut and the alluvial fan sites, we sampled from the face of the exposure at 10 cm increments. We removed coarse litter prior to sampling, but did not distinguish between O, A, and B horizons due to a lack of distinct boundaries.

## Pyrogenic carbon Quantification

To quantify the abundance of pyrogenic carbon, we relied on two methods of soil pyrogenic carbon and charcoal quantification methods: physical charcoal quantification (Clark, 1988) and acid-peroxide digestion. Physical quantification is a traditional approach to manually identify large particles, requiring more time and labor (Clark, 1988; Whitlock and Larsen, 2005), while acid-peroxide digestion, established by Kurth et al. (2006) and Pingree et al. (2012), requires no physical counting of particles, and captures a greater range of pyrogenic materials and size ranges, but may also digest charcoal. Prior to both quantification procedures, we dried the 5-cm bulk soil sample increments in an oven at 60°C for 24 hours and measured bulk density for each 5-cm sample increment (Pingree et al., 2012).

### Physical Charcoal Quantification

We soaked soil-core samples overnight in a 10% KOH solution to disperse organic clumps, and then rinsed through 2 mm and 0.5 mm test sieves. We removed material from both size classes and treated each with 3% H2O2 for over 24 hours. Once oven-dried, we counted charcoal fragments under a stereoscope, and weighed the total mass of identifiable charcoal within each soil-core section for each site. Charcoal concentration from sieved samples was calculated by dividing mass of charcoal by the dry weight of the sample.

### Chemical Charcoal Quantification

To estimate pyrogenic carbon concentrations chemically, we completed an acid-peroxide digestion on the mineral soil samples (n = 18) following the methods of Kurth et al. (2006) as modified by Pingree et al. (2012). We ground soil samples in a ball mill to <0.76 μm before weighing ca. 1 gram. Digestions were run in batches of 45. The gound soil was added to a 50 ml flask with 20 ml of 30% H2O2 and 10 ml of 1 M HNO3. We swirled samples by hand to promote effervescence at room temperature across a 30-minute period, before heating in a water bath to 90°C for 16 hours. After digestion, we filtered samples through pre-weighed filter papers and dried at 60°C for over 24 hours before weighing to obtain the mass of the residual material after digestion and filtration. We determined the percent of carbon present in undigested and digested soil samples using a mass spectrometer at the Laboratory of Stable Isotope Ecology, University of Miami.

To evaluate pyrogenic carbon estimates produced by acid-peroxide digestion and compare results among batches of digestions, we created charcoal standards by combusting dry western red cedar samples (*Thuja plicata*) wrapped in aluminum foil at 450°C. We ground a 1:9 ratio of charcoal and charcoal-free rock (Condrey Mountain Schist from Southwestern Oregon) to <0.76 μm in a ball mill, creating a 10% charcoal standard.

## Radiocarbon Dating

To estimate the range of ages of charcoal, we selected charcoal samples with known depths at each sample site for accelerator mass spectrometry (AMS) radiocarbon dating based on depth, size, and quality of sample such that dates are based on a single piece of charcoal. We prioritized dating the uppermost and deepest charcoal at each site. We cleaned samples with alternating heated 10% KOH and 10% HCL rinses prior to radiocarbon dating at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory in Livermore, California.

## Data Analysis

We determined charcoal C concentration (pyrogenic carbon) of digested soil samples using )\* 1000, where M1 = mass of digested sample, C1 = C concentration of digested sample, and M2 = mass of original sample. We estimated PyC mass per square meter as the product of PyC concentrations and bulk density summed over all depth increments ( \* 10,000, where BD = bulk density (g/m3)).

We calibrated radiocarbon dates with the rCarbon program in R (Crema and Bevan 2021) using the INTCAL20 calibration curve (Muscheler et al., 2020; Reimer et al., 2020).

To investigate the presence of a stratigraphy of charcoal dates within redwood soils, we compared calibrated radiocarbon ages of charcoal fragments from the same soil core but different depths where such pairings existed (n = 21). A stratigraphy existed if the fragment from the deeper depth had an older calibrated radiocarbon age. To summarize the timeline of charcoal ages, radiocarbon ages from mineral soils (i.e., excluding the alluvial fan and the colluvial site) were combined into a summed probability distribution (SPD) using the spd function of the rcarbon package in the R programming environment (Rstudio 2021). No calibration normalization was applied.

# Results

## Soil and pyrogenic carbon

Bulk density of soil samples increases on average with depth from 0.3 g/cm3 at the soil surface to 1 g/cm3 at 30 cm (Figure S1). Total carbon of undigested bulk soil decreases with depth from 100 mg/g to x mg/g (Fig 2A). Total pyrogenic carbon in grams per square meter ranged from 620 to 1,488 g/m2 per site across all depths, with an average of 928 g/m2 across all sites (Fig. 7). The ratio of pyrogenic carbon to total C slightly increases with depth, indicating the effect of preservation ability (Figure 2B). Average proportions of pyrogenic carbon to total C per depth increment range from 0.089 – 0.199. The total average ratio of pyrogenic carbon was 0.159. The average mass of pyrogenic carbon was highest in hillslope sites, though not enough valley sites may have been sampled for adequate comparison. The higher levels of hillslope pyrogenic carbon compared to that found on ridgetops is a strong indication of PyC transportation through erosion (Abney and Berhe 2018).

## Charcoal stratigraphy

All adjacent dates were compared pairwise for a total of 21 comparisons. 13 out of the 22 paired dates display an age reversal (older samples at shallower depths), indicating a lack of stratigraphy within those sites (Fig 3).

## Radiocarbon Dates

Charcoal deposited within the debris flow displayed an older range of calibrated radiocarbon dates (931 to 6,839 years BP) than charcoal deposited within mineral soils on ridgetops, hillslopes, and valleys (modern to 3,805 calibrated median years BP). Due to the distinct difference in age between landscape types, results from the debris flow are reported separately. Two charcoal fragments from the WORM\_03 site dated at 6,666- and 6,839-year BP, though they were located a meter apart in depth (Fig 2). Due to the nature of the site and the unusual age of the samples, these dates were not included in subsequent analysis, but their presence indicates the potential longevity of charcoal within redwood soils.

# Discussion

The abundance, distribution, and age of soil charcoal within old growth coast redwood soil differs across landscape position. Charcoal and carbon concentrations are greatest in the top 10 cm of redwood soils and decline with depth, though charcoal is still found 30-35 cm deep. Radiocarbon dates demonstrate charcoal has the capacity to preserve over thousands of years across different depths within redwood soils, though not always within a stratigraphy. However, the soil charcoal record in coast redwood mineral soils contains evidence of fire history that precede tree-ring records of fire.

The age reversals of radiocarbon dated soil profiles indicate stratigraphy within mineral soils within coast redwood forests is relatively arbitrary, signaling that redwood soils experience mixing across a variety of spatial scales. On a fine-scale, bioturbation driven by earthworms and other creatures mix soils consistently over time (Gabet et al., 2003). On a larger scale, tree tip-ups upturn large amounts of soil, creating mounds up to 1-meter high (Norman et al., 1995), that can take several thousand years to completely disappear (Schaetzl and Follmer, 1990). Given the size of redwood root systems (Phillips *et al.*, 2013), this process may be even more exaggerated. Across greater spatial scales, soil mixing may be driven by erosion or depositional events: the ages and depths of charcoal fragments from the alluvial fan indicates that material in the alluvial fan sampled was likely transported by a depositional event (Fig 2). While alluvial fan dates were not included in analysis because of their distinct age and source, these fragments are evidence that charcoal can persist in coast redwood soils for thousands of years, perhaps especially when buried deeply in depositional events.

The highest density of radiocarbon dates from mineral soils occurred within the last 1,000 years, suggesting a number of things: either a shift in the frequency of fire, optimized charcoal preservation or a bias in sampling. Two soil charcoal radiocarbon dates registered as “modern” (~1950 or more recent) and may be from settler/logger-induced broadcast burns that took place in the region in the 1900s and earlier in order to expose adjacent landscapes for easier harvesting (Table 1). Overlap exists between the fire scars dated by unpublished Norman and Jennings work 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, emphasizing that the higher density of radiocarbon density may reflect fire frequency. While greater investigation is needed to fully constrain fire activity across the last millennium in coast redwood forests, dated fires from the Norman and Jennings project only extend back to 250 years BP, again emphasizing the value of the temporal extent of soil charcoal.

## Pyrogenic Carbon

The average proportion of pyrogenic carbon relative to total soil C in redwood ecosystems was comparable to estimates for ecosystems with frequent fire (15%), and proportions at deeper depths were distinctively higher (20%). Specifically, the average g/m2 of pyrogenic carbon 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, all systems that undergo regular fire at different temporal intervals (Ball et al., 2010; Bélanger and Pinno, 2008; Kurth et al., 2006; MacKenzie et al., 2008; Pingree et al., 2012). Pingree 2012 found ca. 700 g/m2 of pyrogenic carbon 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 pyrogenic carbon is a boreal forest in Saskatchewan with a reported 4,000-11,000 kg charcoal C ha−1 (Bélanger and Pinno, 2008). Mass of pyrogenic carbon across redwood soil sites ranged from 6,000-14,000 kg per hectare, suggesting similarities in the processes leading to charcoal production and preservation. 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 a testament to efficient burial and preservation of charcoal into mineral soils.

Our estimates of pyrogenic carbon abundance suggest 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). High levels of biomass in redwood forests may contribute to the large quantity of charcoal produced, and hillslope erosion and tree-tip-up bioturbation may promote the burial and preservation of charcoal. Acid digestion may underestimate pyrogenic carbon soil content, as charcoal standards lost 34% of pyrogenic carbon during digestion. However, the extremely young age (weeks-months) of standards means they contain components that will be lost through normal soil-respiration activity while in a soil environment for decades or longer. Decomposition rates for younger, artificially made charcoal are often higher and Kurth et al. (2006) reported pyrogenic carbon 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 pyrogenic carbon concentrations, meaning more work is needed to clarify the effect of charcoal age on digestion estimates.

Furthermore, interpreting past fire activity from soil charcoal requires a series of assumptions about the various processes impacting soil charcoal deposition and persistence: charcoal degradation within soil may occur at different rates between systems or across depth (), subsequent fires may consume charcoal in upper soil layers () and erosion may transport particles across large distances (Conedera *et al.*, 2009; Doetterl *et al.*, 2016). Due to the myriad of factors that induce soil mixing and movement (erosion, cryoturbation, tree tip ups, bioturbation, etc), few soil systems display a stratigraphy signaling a consistent age-depth relationship (older soil at deeper depths), limiting our ability to extrapolate results (Carcaillet and Brun, 2000; Conedera et al., 2009). However, recovering individual dates within mixed soils still allows for individual records of fire across a longer time scale than that available currently in redwood fire proxies.

Soil charcoal in old growth redwood forests provide a record of fire activity inaccessible through tree-ring or anthropogenic records. High levels of mixing may improve the capacity of charcoal to persist within soil, allowing for preservation of fire history records, though not in sequence. Levels of pyrogenic carbon in old growth coast redwood forests are comparable to other fire-prone ecosystems, suggesting fire is a feature of coast redwood ecosystems over thousand-year time scales.

**Data Availability:** The data and code used in this manuscript have been made available for reproducibility purposes and are accessible at the following DOI: [10.5281/zenodo.4455777](https://doi.org/10.5281/zenodo.4455777).

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# References

Ball PN, MacKenzie MD and DeLuca TH (2010) Wildfire and charcoal enhance nitrification and ammonium‐oxidizing bacterial abundance in dry Montane forest soils. *Journal of*. Wiley Online Library. Available at: https://acsess.onlinelibrary.wiley.com/doi/abs/10.2134/jeq2009.0082?casa\_token=z7b2lu0TfTcAAAAA:tSub3R2l0v7hQ6U8sDDRAIgE0eUEnaFu2VdxbgPnbi9puBUnmzo5NHPcbMGt0Hfj0WmyPIaSy2AHAGA.

Bélanger N and Pinno BD (2008) Carbon sequestration, vegetation dynamics and soil development in the Boreal Transition ecoregion of Saskatchewan during the Holocene. *Catena* 74(1). Elsevier: 65–72.

Bird MI, Wynn JG, Saiz G, et al. (2015) The pyrogenic carbon cycle. *Annual review of earth and planetary sciences* 43(1). Annual Reviews: 273–298.

Brown PM and Swetnam TW (1994) A cross-dated fire history from coast redwood near Redwood National Park, California. *Canadian journal of forest research. Journal canadien de la recherche forestiere* 24(1). NRC Research Press: 21–31.

Brown PM, Kaye MW and Buckley D (1999) Fire history in Douglas-fir and coast redwood forests at Point Reyes National Seashore, California. *Northwest Science* 73: 205–216.

Buma B, Weiss S, Hayes K, et al. (2020) Wildland fire reburning trends across the US West suggest only short-term negative feedback and differing climatic effects. *Environmental research letters* 15(3). IOP Publishing: 034026.

Carcaillet C and Brun J-J (2000) Changes in landscape structure in the northwestern Alps over the last 7000 years: lessons from soil charcoal. *Journal of vegetation science: official organ of the International Association for Vegetation Science* 11(5). John Wiley & Sons, Ltd: 705–714.

Clark JS (1988) Particle motion and the theory of charcoal analysis: Source area, transport, deposition, and sampling. *Quaternary research* 30(1). Cambridge University Press (CUP): 67–80.

Conedera M, Tinner W, Neff C, et al. (2009) Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. *Quaternary science reviews* 28(5). Elsevier: 555–576.

Criscuoli I, Alberti G, Baronti S, et al. (2014) Carbon sequestration and fertility after centennial time scale incorporation of charcoal into soil. *PloS one* 9(3). Public Library of Science (PLoS): e91114.

Doetterl S, Berhe AA, Nadeu E, et al. (2016) Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. *Earth-science reviews* 154. Elsevier BV: 102–122.

Gabet EJ, Reichman OJ and Seabloom EW (2003) The effects of bioturbation on soil processes and sediment transport. *Annual review of earth and planetary sciences* 31(1). Annual Reviews: 249–273.

Gavin DG, Hallett DJ, Hu FS, et al. (2007) Forest fire and climate change in western North America: insights from sediment charcoal records. *Frontiers in ecology and the environment* 5(9). John Wiley & Sons, Ltd: 499–506.

Greenlee JM and Langenheim JH (1990) Historic fire regimes and their relation to vegetation patterns in the Monterey bay area of California. *The American midland naturalist* 124(2). JSTOR: 239.

Hammes K, Torn MS, Lapenas AG, et al. (2008) Centennial black carbon turnover observed in a Russian steppe soil. *Biogeosciences* 5(5). Copernicus GmbH: 1339–1350.

Jones GA and Russell W (2015) Approximation of Fire-Return Intervals with Point Samples in the Southern Range of the Coast Redwood Forest, California, USA. *Fire Ecology* 11(3). fireecology.springeropen.com: 80–94.

Knicker H (2011) Pyrogenic organic matter in soil: Its origin and occurrence, its chemistry and survival in soil environments. *Quaternary international: the journal of the International Union for Quaternary Research* 243(2). Elsevier BV: 251–263.

Kurth VJ, MacKenzie and DeLuca TH (2006) Estimating charcoal content in forest mineral soils. *Geoderma* 137(1). Elsevier: 135–139.

Lorimer CG, Porter DJ, Madej MA, et al. (2009) Presettlement and modern disturbance regimes in coast redwood forests: Implications for the conservation of old-growth stands. *Forest ecology and management* 258(7). Elsevier: 1038–1054.

MacKenzie MD, McIntire EJB, Quideau SA, et al. (2008) Charcoal distribution affects carbon and nitrogen contents in forest soils of California. *Soil Science Society of America journal. Soil Science Society of America* 72(6). Wiley: 1774–1785.

Muscheler R, Adolphi F, Heaton TJ, et al. (2020) Testing and improving the IntCal20 calibration curve with independent records. *Radiocarbon* 62(4). Cambridge University Press (CUP): 1079–1094.

Norman SA, Schaetzl RJ and Small TW (1995) Effects of slope angle on mass movement by tree uprooting. *Geomorphology (Amsterdam, Netherlands)* 14(1). Elsevier BV: 19–27.

Norman SP (2007) A 500-year record of fire from a humid coast redwood forest. *Save the Redwoods League*. savetheredwoods.org. Available at: http://www.savetheredwoods.org/wp-content/uploads/pdf\_norman.pdf.

Noss RF (ed.) (1999) *The Redwood Forest*. Washington, D.C., DC: Island Press.

Phillips CJ, Marden M, Lambie S, et al. (2013) Observations of below-ground characteristics of young redwood trees (Sequoia sempervirens) from two sites in New Zealand – implications for erosion control. *Plant and soil* 363(1–2). Springer Science and Business Media LLC: 33–48.

Pingree MRA, Homann PS, Morrissette B, et al. (2012) Long and Short-Term Effects of Fire on Soil Charcoal of a Conifer Forest in Southwest Oregon. *Forests, Trees and Livelihoods* 3(2). Molecular Diversity Preservation International: 353–369.

Reimer PJ, Austin WEN, Bard E, et al. (2020) The IntCal20 Northern hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62(4). Cambridge University Press (CUP): 725–757.

Roden J (2008) Cross-dating of tree ring δ18O and δ13C time series. *Chemical geology* 252(1–2). Elsevier BV: 72–79.

Schaetzl RJ and Follmer LR (1990) Longevity of treethrow microtopography: implications for mass wasting. *Geomorphology* 3: 113–123.

Schmidt MWI and Noack AG (2000) Black carbon in soils and sediments: Analysis, distribution, implications, and current challenges. *Global biogeochemical cycles* 14(3). John Wiley & Sons, Ltd: 777–793.

Stephens SL and Fry DL (2005) Fire history in coast redwood stands in the northeastern Santa Cruz mountains, California. *Fire ecology* 1(1). Springer Science and Business Media LLC: 2–19.

Stuart JD (1987) FIRE HISTORY OF AN OLD-GROWTH FOREST OF SEQUOIA SEMPERVIRENS (TAXODIACEAE) FOREST IN HUMBOLDT REDWOODS STATE PARK, CALIFORNIA. *Madroño* 34(2). California Botanical Society: 128–141.

Talon B, Payette S, Filion L, et al. (2005) Reconstruction of the long-term fire history of an old-growth deciduous forest in Southern Québec, Canada, from charred wood in mineral soils. *Quaternary research* 64(1). Cambridge University Press (CUP): 36–43.

Thevenon F, Williamson D and Bard E (2010) Combining charcoal and elemental black carbon analysis in sedimentary archives: Implications for past fire regimes, the pyrogenic carbon cycle, and the human …. *Global and planetary change*. Elsevier. Available at: https://www.sciencedirect.com/science/article/pii/S0921818110000202?casa\_token=do4uCT\_uN-wAAAAA:kJmV8sylhMIxAY7PrI0PkLVI3lHr5jhMlMq0Q-8aiM2vGtJWQdkObECziC1Er72eOqvjQJ\_4M60.

Westerling AL, Hidalgo HG, Cayan DR, et al. (2006) Warming and earlier spring increase western U.S. forest wildfire activity. *Science (New York, N.Y.)* 313(5789). American Association for the Advancement of Science (AAAS): 940–943.

Whitlock C and Larsen C (2005) Charcoal as a fire proxy. In: *Tracking Environmental Change Using Lake Sediments*. Dordrecht: Kluwer Academic Publishers, pp. 75–97.

Whitlock C, Shafer SL and Marlon J (2003) The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. *Forest ecology and management* 178(1–2). Elsevier BV: 5–21.

Ball, P. N., et al. "Wildfire and charcoal enhance nitrification and ammonium-oxidizing bacterial abundance in dry montane forest soils." *Journal of Environmental Quality* 39.4 (2010): 1243-1253.

Baxter, W. T., and P. M. Brown. "Fire history in coast redwood forests of the Mendocino Coast, California." (2003).

Brown, Peter M., and William T. Baxter. "Fire history in coast redwood forests of the Mendocino Coast, California." *Northwest Science* 77.2 (2003): 147-158.

Carroll, A. L., S. C. Sillett, and R. Van Pelt. "Tree-ring indicators of fire in two old-growth coast redwood forests." *Fire Ecology* 14.1 (2018): 85-105.

DeLuca, Thomas H., and Gregory H. Aplet. "Charcoal and carbon storage in forest soils of the Rocky Mountain West." *Frontiers in Ecology and the Environment* 6.1 (2008): 18-24.

Fried, Jeremy S., Margaret S. Torn, and Evan Mills. "The impact of climate change on wildfire severity: a regional forecast for northern California." *Climatic change* 64.1-2 (2004): 169-191.

Law, B. E., et al. "Carbon storage and fluxes in ponderosa pine forests at different developmental stages." *Global Change Biology* 7.7 (2001): 755-777.

Long, James N. "Emulating natural disturbance regimes as a basis for forest management: a North American view." *Forest Ecology and Management* 257.9 (2009): 1868-1873.

Preston, Caroline M., and M. W. I. Schmidt. "Black (pyrogenic) carbon in boreal forests: a synthesis of current knowledge and uncertainties." *Biogeosciences Discussions* 3.1 (2006): 211-271.

Schmidt, Michael WI, et al. "Persistence of soil organic matter as an ecosystem property." *Nature* 478.7367 (2011): 49-56.

# Figures

Map

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**Figure 1. Map of study sites within Headwaters Forest Reserve.**

Because the geomorphic context of some sites (Colluvium and fan sites) will be important to interpreting them, then lidar hillshade map will help a lot. Maybe only the colluvium and fan sites need enlargements with the lidar.

In the map above, the key has red circle for the fan, but a red square on the map.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Table 1. Radiocarbon dates of individual pieces of soil charcoal from Headwaters Forest Reserve, California. MS = Forest mineral soil. CAMS is the Center for Accelerator Mass Spectrometry and Lawrence Livermore National Laboratory. Radiocarbon dates were calibrated using the INTCAL20 calibration curve, and only the total 2σ age range is shown.** | | | | | | | | | |
| Location | Site Type | CAMS # | Site ID | Depth (cm) | C14 Age | | Error | Cal yr BP  (2σ age range) |
| Governor’s Grove | Colluvial Hollow | 175998  177582  177078  177079  177080  177081  175999 | GOV-01  GOV-01  GOV-01  GOV-01  GOV-01  GOV-01  GOV-01 | 17  23  31  38  50  52  67 | 1010  1050  4490  4185  4155  4355  2615 | 35  30  60  30  30  35  40 | | 798-1040  924-1050  4891-5313  4618-4837  4580-4826  4848-5036  2543-2844 |
| Ridge MS | 177460  177461 | GOG-01  GOG-01 | 1  18 | Modern  445 | 30 | | 465-534 |
| Ridge MS | 177462  177463 | GOG-02  GOG-02 | 4  16 | 90  155 | 30  35 | | 22-265  1-285 |
| Worm Trail | Ridge MS | 177084 | WORM-01 | 11 | 2285 | 35 | | 2315 |
| Alluvial Fan | 175996  175997 | WORM-03  WORM-03 | 12  110 | 6000  5845 | 30  30 | | 6839  6666 |
| Salmon Creek Trail | Ridge MS | 177082  177083 | SCT-01  SCT-01 | 16  20 | 680  1255 | 30  30 | | 561-680  1083-1278 |
| Ridge MS | 177458  177459 | SALM-01  SALM-01 | 0  13 | 365  175 | 30  40 | | 316-501  1-298 |
| Ridge MS | 177580  177581 | SALM-03  SALM-03 | 3  22 | 840  90 | 30  30 | | 686-891  22-265 |
| Worm Trail | Ridge MS | 177453  177454 | WOMT-01  WOMT-01 | 5  19 | 480  680 | 30  40 | | 499-542  556-687 |
| Ridge MS | 177455  177455 | WOMT-02  WOMT-02 | 2  15 | 575  365 | 30  30 | | 503-648  316-501 |
| Ridge Trail | Ridge MS | 177577 | RIDG-01 | 19 | 830 | 30 | | 688-789 |
| Ridge MS | 177465  177457 | RIDG-02  RIDG-02 | 2  11 | 875  2245 | 30  35 | | 709-907  2153-2343 |
| Elk River | Valley MS | 177578  177579 | EELS-01  EELS-01 | 6  13 | 305  75 | 30  30 | | 299-462  27-259 |
| Worm Trail (Left fork) | Hillslope MS | 177586  177587 | WOLF-01  WOLF-01 | 5  16 | 580  Modern | 30 | | 533-649 |
| Hillslope MS | 177588 | WOLF-02 | 3 | 1420 | 35 | | 1287-1377 |
| Ridge MS | 177589  177590 | WOLF-03  WOLF-03 | 10  45 | 3615  265 | 30  30 | | 3841-4062  1-433 |
| Ridge MS | 177591 | WOLF-04 | 10 | 420 | 30 | | 333-523 |
| Worm Trail (Right fork) | Hillslope MS | 177592  177593 | WORF-02  WORF-02 | 3  20 | 1155  985 | 30  30 | | 982-1175  797-959 |
| Ridge MS | 177594 | WORF-03 | 8 | 3805 | 30 | | 4089-4291 |
| Ridge MS | 177595 | WORF-05 | 7 | 200 | 30 | | 1-303 |

**A screenshot of a cell phone

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**Fig. 2. Total soil carbon (mg) and the ratio of pyrogenic carbon to total soil carbon across depth (0-35 cm) in old growth redwood soils.** Results from elemental analysis of undigested soil and digested soil samples. A) Total C levels for undigested soil samples across depth (0-35 cm). B). Ratios of pyrogenic carbon to total C across depth (0-35 cm). [drop 30-35]

**Chart, box and whisker chart

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**Figure 3. Comparing charcoal concentration estimates produced by physical and chemical quantification methods.**

A close up of a map

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**Figure. 4. Radiocarbon dates of charcoal samples according to depth of sample**. [add error bars] 43 dates are shown from 20 sites (average 2 dates per site), plotted according to site type and against depth within soil profile. Site type indicated with color and shape of point.

A close up of a map

Description automatically generated**Figure 5. Age-depth relationships of paired soil-charcoal radiocarbon dates**. Stratigraphic relationship between calibrated radiocarbon age and depth in soil across soil-charcoal radiocarbon dates from individual sites with at least two radiocarbon dates. Line at y = 0 represents no difference in age between paired samples. Points above y = 0 display no age reversal, indicating charcoal samples at deeper depths produced older calibrated radiocarbon ages, while points below y = 0 indicate charcoal samples at deeper depths were found to be younger, indicating a lack of stratigraphy.

Fig. 6 SPD figure…compared to fire scars?

# Appendix S1

Chart, box and whisker chart

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**Figure S1: Bulk density of soil samples across depths.**