Reconstructing fire history using soil charcoal and pyrogenic carbon in an old growth coast redwood forest

Katherine Hayes1 ¶, Dan Gavin2 ¶

1Department of Integrative Biology, University of Colorado Denver, Denver, Colorado, USA

2Department of Geography, University of Oregon, Eugene, Oregon, USA

\* Corresponding author

Email: [Katherine.hayes@ucdenver.edu](mailto:Katherine.hayes@ucdenver.edu) (KH)

¶ These authors contributed equally to this work.

**Abstract:** (172/300 words)

Fire is an important ecological feature in temperate forests that is often best described or informed by long-term records yet determining past fire regimes may be difficult in ecosystems with limited available fire proxies or histories. We use radiocarbon dating and quantification of both soil macro-charcoal and soil and pyrogenic carbon in old growth redwood stand to examine legacies of fire in redwood forests, an ecosystem with few fire records. We sampled charcoal fragments, soil carbon and soil pyrogenic carbon of 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 regimes.

**Introduction**

Understanding fire in modern ecosystems under changing climatic and fire conditions requires knowledge of the spatial and temporal context of long-term (millennial-scale) patterns of fire within a system (Whitlock et al. 2003, Gavin et al. 2007). 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, contextualizing modern shifts in variability.

However, reconstructing paleoecological histories of fire remains difficult in ecosystems without traditional paleoecological proxies such as lake sediment cores or tree rings which limits our ability to make inferences regarding fire in certain regions and systems. Methods such as radiocarbon dating and pyrogenic carbon estimates may serve to reconstruct estimates of fire activity in locations without reliable lacustrine depositional environments or suitable tree ring records, but also remain dependent on access to the appropriate physical archive (appropriate sample material and soil charcoal, respectively). Clarifying existing uncertainties regarding millennial-scale fire patterns in ecosystems without reliable fire records, tree rings or appropriate and accessible lacustrine depositional settings will require accessing and compiling insights from novel fire proxies and archives.

The distribution and abundance of pyrogenic carbon and charcoal stored within soil can provide insight into local long-term fire dynamics. Pyrogenic carbon (henceforth referred to as 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 by combustion) (Bird et al. 2015). The term ‘charcoal’ specifically refers to macroscopic fragments of partially combusted material (Knicker 2001, Bird et al. 2015, Schmidt and Noack 2000). The presence and distribution of soil charcoal and pyrogenic carbon within local soils is a meaningful proxy of fire history (Gavin et al. 2007, Ohlson and Tryterud 2000). Soil charcoal is often both spatially constrained and temporally persistent: in systems without substantial soil movement, the presence of soil charcoal can indicate specific fire locations (Gavin et al. 2007, Clark 1988). Furthermore, charcoal incorporated into forest soils has a potential residency time of thousands of years, allowing charcoal to serve as an archive of fire history that both overlaps and predates tree-ring and anthropogenic records (Bird et al. 2015).

Traditional use of soil charcoal as a proxy of fire involves radiocarbon dating of charcoal fragments found within specific soil contexts and depths. Application of radiocarbon dating, however, is limited: the technique is expensive, and dates themselves may overestimate the realistic age of a fire if the wood material itself is old enough at the time of burning (often referred to as the inbuilt age error) (Gavin et al. 2003, Harmon et al. 1986). Furthermore, reliance on soil charcoal as an indication of past fire activity requires acknowledging the various processes impacting soil charcoal deposition and persistence: degradation of charcoal within soils may occur at different rates, 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 an age-depth relationship, limiting our ability to extrapolate results (Conedera et al. 2009, Carcaillet et al. 2000). Even given those limitations, the use of radiocarbon dated charcoal material as a proxy of fire activity persists, particularly in systems without alternative reliable archives (Gavin et al. 2003).

Paragraph on PYC: The investigation of pyrogenic carbon dynamics in soils can supplement and strengthen the use of radiocarbon dates as a proxy of past fire activity (Thevenon et al. 2010). The proportion of PyC in local soils relative to soil C is a meaningful paleoecological inference: WHY. Furthermore, PyC has the potential to be widely available and temporally extensive. According to some estimates, over 80% of all PyC produced is incorporated into soil (Preston and Schmidt 2006), and >90% remains close to the location of production, at least initially (Kuklbusch et al. 1996). Given the ubiquity and longevity of PyC, the proportion of PyC present in soils in conjunction with radiocarbon dates can provide insights regarding past biomass burning and fire activity.

To test the application of soil-based fire reconstruction methods, we investigated soil charcoal and PyC dynamics within an old growth coast redwood (*Sequoia sempervirens)* forest in Northern California. Considerable uncertainty remains regarding how fire interacts with and influences the characteristics of coast redwood forests (Varner and Jules 2017). The 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 and thick bark; traits that are typically characterized as adaptations to fire (Sawyer et al. 2000). Furthermore, lightning has been associated with wildfires in the area in recent decades (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 unclear: 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).

No previous research has evaluated either the carbon or 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 cycles [maybe provide more background on carbon cycle in context of paleoecological reconstruction] within old growth coast redwood forests, and to test the application of soil-based fire reconstruction methods. To establish a baseline understanding of soil carbon and charcoal dynamics within coast redwoods, we asked the following research questions: 1) Is there a charcoal stratigraphy within mineral soils in old growth coast redwood forests?, 2) according to radiocarbon dates, how long can charcoal persist within old growth coast redwood soils? and 3) does pyrogenic carbon in redwood soils persist long enough to act as a record of fire history predating tree ring or historical records? To address those questions, we used radiocarbon dating and elemental analysis to evaluate the ages and distribution of soil charcoal and PyC in an old growth coast redwood forest in Northern California.

**Methods**

***Study Area***

We conducted this research 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). 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 coast redwood stands, 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 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 tree ring 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. That data also suggests 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 and Jennings, unpublished).

**Fig. 1. Map of study sites within Put back in!!**

***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 or road construction. We established 20 sampling sites, primarily and ideally on ridgetops (n =16), excluding for the most part, steep slopes or valley bottoms (Fig 1). This exclusion was made in order to sample specifically for spatially constrained charcoal with minimal depositional movement via erosion, runoff or debris flows, intentionally providing a more conservative estimate of charcoal presence and abundance. One valley-bottom site (EELS\_01) was sampled opportunistically for comparison. In total, 16 ridgetops were sampled, along with 7 hillslopes and 1 valley for context.

Soil pits were dug at each site in order to sample charcoal fragments at exact depths from a clean soil profile between 0 and 45 cm deep. At two sites (GOV\_01 and WORM\_03), debris-flow deposits were exposed by stream or road cuts, allowing for deeper sampling. Soil cores at debris-flow sites were obtained vertically from the face of the soil profile at 10 cm increments. Samples from these sites are displayed separately, to account for the distinct depositional nature of charcoal found within debris flows.

To analyze the PyC and overall carbon content of redwood mineral soils, multiple volumetric soil cores were obtained contiguously at each site in correspondence with radiocarbon sampling using a 5-cm split core sampler (volume 98.2 cm3) driven into the soil up to 30 cm deep. Coarse litter was removed prior to sampling, but there was no effort to distinguish between O, A, and B horizons as there were often no distinct boundaries.

***Radiocarbon Dating***

To identify the range of dates discoverable in charcoal in redwood soils and to establish whether charcoal in redwood mineral soils is stratified, charcoal samples (minimum size = XX) with known depths at each sample site were selected for accelerator mass spectrometry (AMS) radiocarbon dating based on depth and quality of sample. 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 S1).

Radiocarbon dates were calibrated using the CALIB 5.0.1 program based on the INTCAL13 calibration curve (Reimer et al. 2013), and modern dates were estimated with Oxcal. To provide an estimate of fire activity across all sites throughout the reserve, we applied a Bayesian Gaussian mixture model to the probability distributions of calibrated ages (Bchron R package, cite).

***Quantifying PyC levels in soil***

To quantify the proportion of carbon within redwood soils that is pyrogenic, we relied on two known methods of soil PyC and charcoal quantification methods: physical charcoal quantification and acid-peroxide digestion. Physical quantification is more traditional, but requires much more time and labor, while acid-peroxide digestion, established by Kurth et al. 2006 and others (Pingree et al. 2012), requires no physical counting of particles, thus potentially avoiding direct human sources of error. We used both methods in order to compare and report any difference in results between the two. [add in idea of maximum/minimum estimares]

*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. Material from both size classes 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 by dividing mass of charcoal by the dry weight of the sample.

*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 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 before being left 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. [maybe not that useful as written]

***Elemental Analysis***

Percent carbon of original and digested materials was determined on a 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:

)\* 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:

\* 10,000

where BD = bulk density (total dry weight of sample divided by the volume of the sampler as g/cm3).

Include some discussion of inbuilt age?

**Results**

*Radiocarbon Dates*

Charcoal deposited within mineral soils on ridgetops, hillslopes and valleys had a different range (modern to 3,805 calibrated median years BP) of calibrated radiocarbon ages than charcoal found within debris flows (931 to 6,839 years BP). Due to the distinct difference in age between the two, results from the two site types 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.

**Fig. 2. Radiocarbon dates of charcoal samples according to depth of sample**. 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.

*Charcoal stratigraphy*

All adjacent dates were compared pairwise for a total of 21 comparisons. Comparisons of the difference in depth and age reveal that 13 out of the 22 comparisons display an age reversal, indicating a lack of stratigraphy (Fig 3). [analysis not in methods]

**Fig. 3. Age-depth relationships of paired soil-charcoal radiocarbon dates**. [ error bars]

Stratigraphic relationship between calibrated radiocarbon age and depth in soil across soil-charcoal radiocarbon dates from 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.

*Estimates of Fire History across Reserve based on Radiocarbon dates*

Results from the Bayesian Gaussian mixture model [more introduction] show a sharp increase in fire activity around 1,500 years BP, and pulses of activity around 2,250 years BP and between 4,000-5500 years BP. These results are highly dependent on the specific fragments both found and dated but indicate a higher cumulative distribution of probability [quantification of uncertainty?] in the last 1,000 years (Fig 4).

**Fig. 4. Cumulative fire activity simulated by Bayesian Gaussian mixture model of calibrated ages.** Black bolded line represents cumulative estimate of fire activity through age based on the proxy of probability distributions of calibrated ages. Grey curves represent individual probability distributions of calibrated ages.

*Physical Charcoal Quantification*

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. Charcoal concentrations determined by physical charcoal quantification decreases significantly [needs quantification] with depth (Fig 5).

**Fig. 5. Macroscopic charcoal concentration**. Physical analysis of volumetric soil samples expressed by depth category. 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.

*Acid-Digestion Pyrogenic Carbon Quantification*

Twenty-six duplicates were run during elemental analysis, showing machine accuracy [precision? Not sure what you want to say here?] 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. [maybe convert?]

Total C of undigested bulk soil samples decreases with depth (Fig 6A). The ratio of PyC to total C slightly increases with depth, indicating the effect of preservation ability (Figure 6B). 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 across all depths, with an average of 928 g/m2 across all sites (Fig. 7).

**Fig. 6. Total soil carbon (mg) and the ratio of soil carbon to pyrogenic 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 PyC to total C across depth (0-35 cm).

**Discussion**

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

The soil charcoal record in coast redwood mineral soils contains evidence of fire history that precede tree-ring records of fire. Radiocarbon dates show charcoal 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 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 S1).

The age reversals of radiocarbon dated soil profiles indicate there is not a stratigraphy within mineral soils within coast redwood forests, signaling 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, either human or natural (tree tip-ups or down-slope soil movement). 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.

The ages of charcoal fragments from the alluvial fan would indicate that the material in the alluvial fan sampled was likely transported by a depositional event (Fig 2). While the 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 in depositional events.

There is overlap between the fire scars dated by the 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. 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. [figure comparing the 2?]

***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). 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 PyC soil content, as charcoal standards lost 34% of PyC during digestion. However, standards were recently created and likely have components that would have been lost by normal soil-respiration activity had the material been in a soil environment for decades. Decomposition rates for younger, artificially made charcoal are often 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, and more work is needed to clarify the effect of charcoal age on digestion estimates.

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, all systems that undergo regular fire at different temporal intervals (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 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.

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 that found on ridgetops is a strong indication of PyC transportation through erosion (Abney and Berhe 2018).

**Conclusions**

Soil charcoal in old growth redwood forests provide a record of fire activity extending far beyond that accessible 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 PyC are comparable to other fire-prone ecosystems, suggesting fire is a feature of coast redwood forests over thousand-year time scales.

**Acknowledgements**

This research was supported by funding provided by the Bureau of Land Management ( id number). Fieldwork was supported by the BLM Arcata field office. We thank Alexia Gee for assistance in the field and Kergis Hiebert for assistance in the laboratory. We thank Lukas Silva and Toby Maxwell for valuable support and advice. Finally, we thank Rosemary Sheriff for providing friendly review which significantly contributed to the quality of the paper.

**References**

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).

Bird, Michael I., et al. "The pyrogenic carbon cycle." *Annual Review of Earth and Planetary Sciences* 43 (2015): 273-298.

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.

Brown, Peter M., and Thomas W. Swetnam. "A cross-dated fire history from coast redwood near Redwood National Park, California." *Canadian Journal of Forest Research* 24.1 (1994): 21-31.

Brown, P.M.; Kaye, M.W.; Buckley, D. 1999. Fire history in Douglas-fir and coast redwood forests at Point Reyes National Seashore, California. Northwest Science 73: 205-216.

Brown, Peter M. "What Was the Role of Fire in Coast Redwood Forests?." *Proceedings of the redwood region forest science symposium: what does the future hold*. 2007.

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.

Fritz, Emanuel. "Problems in dating rings of California coast redwood." *Tree-Ring Bulletin* (1940).

Gavin, Daniel G., et al. "Forest fire and climate change in western North America: insights from sediment charcoal records." *Frontiers in Ecology and the Environment* 5.9 (2007): 499-506.

Hostetler, S. W., P. J. Bartlein, and J. R. Alder. "Atmospheric and surface climate associated with 1986‐2013 wildfires in North America." *Journal of Geophysical Research: Biogeosciences* (2018).

Knicker, H. 2011. Pyrogenic organic matter in soil: Its origin and occurrence, its chemistry and survival in soil environments. Quaternary International 243:251–263.

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.

Lorimer, Craig G., et al. "Presettlement and modern disturbance regimes in coast redwood forests: implications for the conservation of old-growth stands." *Forest Ecology and Management* 258.7 (2009): 1038-1054.

MacKenzie, M. Derek, et al. "Charcoal Distribution Affects Carbon and Nitrogen Contents in Forest Soils of California." *Soil Science Society of America Journal* 72.6 (2008): 1774-1785.

Norman, Steven P. "A 500-year record of fire from a humid coast redwood forest." *Save the Redwoods League* (2007).

Norman, Steven P. and Jennings, Greg. Insights into the vegetational development of Headwaters Forest Reserve.

Norman, Steven P., J. Morgan Varner, Leonel Arguello, Stephen Underwood, Bradley Graham, Greg Jennings, Yana Valachovic and Christopher Lee. "Fire and fuels management in coast redwood forests." (2009).

Noss, Reed F. *The redwood forest: history, ecology, and conservation of the coast redwoods*. Island Press, 1999.

Pingree, Melissa RA, et al. "Long and short-term effects of fire on soil charcoal of a conifer forest in southwest Oregon." *Forests* 3.2 (2012): 353-369.

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.

Reimer, P. J., E. Bard, A. Bayliss, J. W. Beck, P. G. Blackwell, C. B. Ramsey, C. E. Buck, H. Cheng, R. L. Edwards, M. Friedrich, P. M. Grootes, T. P. Guilderson, H. Haflidason, I. Hajdas, C. Hatte, T. J. Heaton, D. L. Hoffmann, A. G. Hogg, K. A. Hughen, K. F. Kaiser, B. Kromer, S. W. Manning, M. Niu, R. W. Reimer, D. A. Richards, E. M. Scott, J. R. Southon, R. A. Staff, C. S. M. Turney, and J. van der Plicht. 2013. INTCAL13 and MARINE13 radiocarbon age calibration curves 0-50,000 years cal BP. Radiocarbon 55:1869–1887.

Sawyer, John O., et al. "Characteristics of redwood forests." *The redwood forest: History, ecology, and conservation of the coast redwoods* (2000): 39-79.

Schmidt, Michael WI, and Angela G. Noack. "Black carbon in soils and sediments: analysis, distribution, implications, and current challenges." *Global biogeochemical cycles* 14.3 (2000): 777-793.

Stephens, Scott L., and Danny L. Fry. "Fire history in coast redwood stands in the northeastern Santa Cruz Mountains, California." *Fire Ecology* 1.1 (2005): 2-19.

Stuart, John D. "Fire history of an old-growth forest of Sequoia sempervirens (Taxodiaceae) forest in Humboldt Redwoods State Park, California." *Madrono* (1987): 128-141.

Stuart, John D., and L. Stephens Scott. "North coast bioregion." (2006).

Thevenon, Florian, et al. "Combining charcoal and elemental black carbon analysis in sedimentary archives: Implications for past fire regimes, the pyrogenic carbon cycle, and the human–climate interactions." *Global and Planetary Change* 72.4 (2010): 381-389.

Whitlock, Cathy, Sarah L. Shafer, and Jennifer Marlon. "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 (2003): 5-21.

**Supplement:**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table S1. Radiocarbon dates of individual pieces of soil charcoal from Headwaters Forest Reserve, California. MS = Forest mineral soil. | | | | | | | | |
| Site | Site Type | CAMS # | Sample ID | Depth (cm) | C14 Age | | Error | Cal yr BP |
| 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 |
| Alluv. 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) | Hill. MS | 177586  177587 | WOLF-01  WOLF-01 | 5  16 | 580  Modern | 30 | | 533-649 |
| Hill. 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) | Hill. 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 |