CARBON SEQUESTRATION AND AVOIDED EMISSIONS DURING ON-SITE BIOCHAR PRODUCTION IN FLAME CAP KILNS

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ABSTRACT

Waste woody biomass produced from forestry, orchard, and landscape management activity is typically disposed of by piling and burning. This generates substantial emissions, damages soil, and sequesters minimal pyrolysis-stabilized carbon. This study investigates the carbon sequestration capacity and avoided emissions of flame cap biochar kilns compared to open pile burning. It also presents data on the effects of fuel moisture on carbon sequestration and emissions from flame cap kilns.

We conducted 11 flame cap kiln burns and 4 open pile burns at a test site on Martha's Vineyard, MA using mostly mixed conifer feedstocks with moisture contents ranging from 17.7% to 51.6%. Three pollutants were measured: methane (CH_4), volatile organic compounds (VOCs), and fine particulate matter ($PM_{2.5}$). We used a portable dilution sampling system designed for field measurements of ambient (non-stack) combustion emissions. Laboratory analyses of biochar quantified yield, carbon content, and stability metrics.

Our results show that flame cap kilns sequestered nearly three times more feedstock carbon than our open pile burns, while producing less than half the emissions of all three pollutants. When data from other studies of open woody biomass burning are included in the analysis, the carbon sequestered by flame cap biochar kilns is calculated to be least 5 times that of open pile burns.

Linear regression models of our kiln emissions reveal feedstock moisture as the primary driver of emission levels. Modified Combustion Efficiency (MCE) went up significantly with decreasing feedstock moisture, as did ratios of carbon to ash. Emissions of CH_4, VOCs, and $PM_{2.5}$ are strongly correlated with feedstock moisture, decreasing with drier fuels and approaching zero at moisture contents below ~15%.

Long-term soil carbon storage potential was determined by calculating $H:C_{org}$ molar ratios to assess the efficiency of pyrolytic carbonization of lignocellulose to stable, low-$H:C_{org}$ aromatic carbon polymers. Those ratios remained beneath the widely accepted standard of 0.7 across all feedstock moistures. For fuel moistures <25%, these ratios dropped below the 0.4 benchmark for premium carbon value.

Our regression models can be useful for developing accurate carbon Life Cycle Assessments (LCA), and for Monitoring, Reporting, and Verification (MRV) metrics for on-site biochar projects with varying feedstock moistures. Our results provide clear evidence that flame cap kilns are a superior alternative to open pile burning for woody residue management, with implications for carbon marketing, air quality regulations, and wildfire risk mitigation.

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INTRODUCTION

Environmental challenges, including climate change, widespread soil degradation, increasing air and water pollution, and the accumulation of waste biomass, have rapidly escalated in recent decades. These problems require innovative, sustainable solutions that address multiple environmental issues concurrently. The conversion of waste wood to biochar is emerging as one such promising solution.

Biochar has been gaining interest among scientists and environmental policymakers for its potential to address numerous environmental challenges (Khan et al. 2024; Yadav & Ramakrishna, 2023), including carbon sequestration (Shrestha et al. 2023), improving plant growth (Premalatha et al., 2023), arresting soil degradation (Shyam et al., 2025), and removing contaminants from soil (Meng et al., 2025; Rizwan, 2023) and water (Jha et al., 2023). Once in the soil, biochar is highly resistant to decay, sequestering carbon for centuries to millennia (Woolf et al., 2021; Sanai et al. 2024; Budai et al., 2013). But even while sequestered, it continues to function as "working carbon", holding water and nutrients in the root zone, and providing critical habitat for plant growth-promoting microbes (Yan et al., 2022), thereby supporting more carbon capture through increased photosynthesis. Biochar also limits the microbial production of methane and nitrous oxide (N_2O), two particularly potent greenhouse gases (Harris et al., 2023).

Biochar is a carbon-rich, porous material produced by heating biomass in a low-oxygen environment -- a process known as **pyrolysis**. Charcoal has been made this way for millennia for cooking and early metalworking. But unlike typical charcoal, biochar is made at higher temperatures, typically 450 - 550^{o}C. When used as a soil amendment, it becomes a biochemically active substance known as **biochar** (USBI, n.d.). It is produced on scales from a traditional hole in the ground to multimillion dollar pyrolysis plants (Amonette et al. 2021).

This study focuses on biochar produced on-site in portable **flame cap kilns** (Wilson et al. 2024a), developed over the last two decades in the western U.S. for woody biomass feedstocks. These small (typically 1-10 m^3 capacity), highly mobile kilns are gaining favor for treating logging "slash" -- the unmerchantable limbs, tops and saplings left from forestry operations. If left on-site, this woody biomass becomes a serious wildfire hazard.

To reduce this risk, slash treatment typically involves hand or machine piling followed by pile burning. Open burn piles produce emissions that can harm human health and increase heat-trapping greenhouse gases (Aurell et al., 2017). Heat from these piles damages the soil below leading to "dead spots" that limit tree reestablishment (Rhoades et al., 2021) and are often recolonized by noxious weeds (Fornwalt and Rhodes 2011). Machine piling results in soil compaction, erosion, and further depletion of soil resources (Cambi, et al., 2015; Nazari, et al., 2023). In addition, escaped fires from open biomass burning are a leading source of human-caused wildfires (Western Fire Chiefs Assoc., 2024).

Enormous amounts of waste biomass are generated in timber-producing regions throughout the world, and open burning of this material is a significant source of air pollution (Pierobon et al.,2022; Ter-

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Mikaelian et al., 2016). The use of flame cap kilns to treat hazardous fuels has the potential to offer a safer, less polluting, and lower-impact conversion of this waste biomass into biochar that can be returned directly to the soil. But because this technology relies substantially on experienced forest workers rather than heavy machinery, it costs more than typical pile and burn contracts.

Given the well-established benefits of converting hazardous fuels to biochar on site, the central question driving our inquiry is: *How can the extra cost of this important ecological service be offset to enable its adoption as a mainstream land management practice?*

While biochar produced as a *product* has well-established markets, funding for on-site biochar production as an *ecological service* is much more tenuous. Currently, on-site biochar production is largely funded by grants from public agencies (e.g. NRCS, 2019) or by "niche managers" in the private sector for whom near-term return on investment is not the principal motivation for management decisions.

A promising solution to this problem is to quantify carbon sequestration and avoided emissions from biochar production in flame cap kilns to calculate the CO_2 equivalents that can be sold to established carbon markets (USBI, 2022). Several organizations worldwide have established certification standards for Monitoring, Reporting and Verification (MRV) of offset projects to ensure their quality and legitimacy, such as Verra, The Gold Standard, Climate Action Reserve, European Biochar Certificate, and others. To meet these standards, rigorous measurements of carbon inputs and outputs from flame cap kilns must be completed and compared to alternate fates of that biomass (Wilson, et al. 2022b). Measuring emissions may also facilitate permitting of flame cap kilns by regulatory agencies in air quality-challenged regions.

Studies of emissions from flame cap kilns by Cornellisen et al. (2023) show that high feedstock moisture levels are correlated with higher outputs of methane and other pollutants. In forestry applications, this has implications for wildfire risk and labor efficiency. Leaving slash on the ground during the dry season lowers feedstock moisture content, thus avoiding some emissions. But this practice also increases the length of time hazardous fuels remain on site, typically reaching their lowest moisture levels at the height of fire season. From a labor management standpoint, a "stump to kiln" process that integrates falling, bucking, limbing, and hauling straight to the kiln coordinates all of these activities, thereby increasing efficiency and reducing labor costs. It is therefore important to quantify the consequences of extra emissions from green feedstock against the increased risk of wildfire and the added cost of on-site biochar production.

The following research questions provide the framework for this study:

Research Questions

Q1: How do flame cap kilns compare to traditional open pile burns in 1) the percentage of feedstock carbon sequestered in the biochar they produce, and 2) the types and amounts of the emissions they produce?

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Q2: How does feedstock moisture content affect 1) the quantity and quality of biochar produced in flame cap kilns, and 2) the types and amounts of emissions produced?

Hypotheses

Flame Cap Kilns vs Open Burn Piles

H1: Flame cap kiln burns sequester a greater percentage of feedstock carbon than open pile burns in the biochar they produce.
H2: Flame cap kiln burns produce fewer emissions of methane (CH_4), particulate matter ($PM_{2.5}$) and volatile organic carbon (VOC) than open pile burns.

Kiln Feedstock Moisture vs Quantity and Quality of Biochar

H3A: Carbon content of biochar is negatively correlated with percent feedstock moisture.
H3B: Ash content of biochar is positively correlated with percent feedstock moisture.
H3C: Carbon stability as measured by the molar ratio of hydrogen to organic carbon ($H:C_{org}$) is negatively correlated with percent feedstock moisture.

Kiln Feedstock Moisture vs Emissions

H4: High percentages of feedstock moisture are positively correlated with greater emissions of CH_4, $PM_{2.5}$, and VOCs.

METHODS

Test Site and Kiln Design

We selected an open site at John Keene Excavation on Martha's Vineyard off the coast of southeastern Massachusetts, USA, for kiln testing because of its proximity to abundant feedstock, water availability, and space to operate large equipment for delivering and weighing feedstock. Scaffolding was used to elevate and shield emissions monitoring equipment supplied and operated by Ryan Thompson of Mountain Air Engineering based in Cottage Grove, Oregon.

The small-scale kilns used for this study (*Fig. 2* and **Appendix A**) are referred to as **flame cap kilns** and are typically used in areas where large machinery cannot or should not be used (e.g., rough terrain, biologically or culturally sensitive areas, or on easily compacted soils). They are low-impact but labor-intensive devices designed at a human-powered scale.

Test kilns were designed and fabricated by one of the authors (Carloni), in Roseburg, Oregon and shipped to Martha's Vineyard. This flame cap kiln was designed to be:

- Light weight and compact: Each panel weighs ~21kg, and fits on a standard pallet or small pickup truck bed.
- Efficient: Panels are double walled for heat insulation and guided air flow.

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- Modular and scalable: Panels can be assembled without tools in any number or shape to fit terrain, feedstock type, and available labor.
- Safety: Double walls protect workers from heat and keep the fire well contained.
- Water conservation: Panels can be opened and removed during quenching to minimize water consumption.

Because of windy conditions typical of our testing location, separate baffles were built as wind shields for the 2023 burns. However, those baffles proved to be ineffective at controlling unpredictable and shifting winds around the kiln, and instead, often created downdrafts over the kilns as wind curled over the top. This disrupted the flame cap and caused more smoke than it prevented. Their use was abandoned after Burn 4.

Feedstock Composition, Preparation, Weighing, Moisture Measurements, and Fuel Characterization

We had hoped to have access to a relatively uniform feedstock, but that proved to be impossible because of the changing types of brush constantly coming into the yard at the test site. Therefore, we took pains to sort mostly conifer material, estimate the percentages of different species, and characterize their proportions of needles, twigs, and woody branches. Typical branches of all conifer species were separated into groups of twigs and needles and groups of larger woody material and weighed separately. This allowed us to precisely calculate feedstock dry weight of for each burn with varying species and proportions of plant organs. In descending order of proportions, our feedstocks included pitch pine (*Pinus rigida*), eastern redcedar (Juniperus *virginiana*), Leyland cypress (*Cupressus × leylandii*), spruce (*Picea sp.*), oak (*Quercus sp.*), and mixed hardwood brush. Our feedstock samples averaged 50.94% carbon (see **Appendix C**) -- typical for most timber species (Van Shaik, et al., 2024).



***Figure 1*: Weighing a Fuel Load. In 2023, we weighed all of our feedstock by loading the fuel onto a tarp, connecting it to a load cell, lifting it with a truck crane, and recording the weight. In 2024, we gained access to a trailer that we could load with much larger batches of fuel and run over an industrial truck scale.**

Before each burn, branches of feedstocks available on that day were cut to fit the kiln, and weighed. In 2023, this consisted of placing brush on a heavy fabric sling, lifted with a truck crane, and weighed suspended from a digital load cell (*Fig. 1*). In 2004, we had access to a dump trailer and were able to use the truck scale at our testing site to weigh our feedstock.

On the day of each burn, representative samples of all species and sizes of feedstock were cut into disks about 2cm wide and weighed to the nearest 0.5g in 2023 and 0.1g in 2024. They were then oven-dried at 100^{o}C until their weight stopped changing and reweighed to calculate the dry mass of feedstock for each burn.

Samples of each feedstock type were then sent to an International Biochar Initiative-certified lab -- Control Laboratories in Watsonville, CA -- for Proximate Analysis (**Appendix C**). This analysis measures the percentages of carbon (C), hydrogen (H), nitrogen (N), oxygen (O), ash, volatile matter, organic carbon (C_{org}), and carbonates (as $CaCO_3$). (see example lab report in **Appendix B** – this "Proximate Analysis" test series was also used for char samples). Mixture-averaged values of fuel moisture content and fuel carbon fraction were then calculated based on the species carbon proportions and moisture content for each burn.

Flame Cap Kiln Operation and Char Yield Measurements

Over the course of both years, a total of 16 burn trials were completed -- 12 kiln burns and 4 open burns (Burns 5, 8, 11-12). We chose to overrepresent kiln burns because a number of measurements of open burns were available in the literature. Because of the wind/baffle issues noted above, Burn 4 data were omitted from our analyses, leaving 11 kiln burns included in our data set.

Kilns were assembled from modular panels into one of three footprint shapes: hexagon (Burns 1-3), rectangle (Burns 6, 9-11, 14-16) and square (Burn 7), depending on the type and amount of fuel available. Preliminary analysis of 2023 data showed that the three hexagonal burns sequestered only 24.7% of the feedstock carbon compared to 45.6% in the square (Burn 7) and rectangular (Burn 6) burns, and produced char with an average of 63.4% carbon content compared to 76.2% for rectilinear kilns. Hexagonal burns also averaged twice the ash.

We concluded that the smaller char yields of the hexagonal configuration were due to not having the labor to keep up with the larger kiln volume, resulting in a higher proportion of combustion compared to pyrolysis. Based on our experience in 2023, all of the kiln burns in 2024 (Burns 9-11, 14-16) used the rectangular configuration, and we hired an additional crew member.

Steps in the process included:

- **Loading**
- **Firing**
- **Feeding**
- **Quenching**
- **Yield Measurement**

Loading: After weighing, feedstock was cut into appropriate lengths and loaded into the kiln with medium diameter fuel (1-2 in./2-5cm) toward the bottom, larger diameter wood (3-5 in./7-13cm) at mid-height, and the most flammable fuels (dry leaves, needles, twigs) on top. This puts the largest wood closest to the flame cap.

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Firing: The kiln was then lit with a propane torch from the top. Care was taken to get a continuous flaming combustion (the "flame cap") established over the whole surface of the kiln to consume pyrolysis gases and particulates emitted from the heated fuel below.

Feeding: Once a strong flame cap was established, additional fuel was continuously added for the next 2 to 4 hours to maintain the flame cap. After flaming combustion died down, coals were then left to burn down for approximately 0.5 to 1.5 hours. Time between feeding and quenching was determined by visually judging completeness of pyrolysis.

Quenching: This step is necessary to stop the combustion process after a significant portion of the feedstock has been pyrolyzed and the flames had died down to coals. Water was sprayed onto the hot char to cool it and stop further combustion. As the char cooled, panels were removed one by one to allow us to rake the char out to find any remaining hotspots that still needed quenching.

Biochar Yield Measurement: Determining the mass of the resulting char was calculated differently in 2023 vs 2024. During our first round of burns, the volume of the char and ash remaining in each kiln was measured by using a ruler to determine the distance from the kiln top to the char at each of the 6 panels just prior to quenching. We then opened the kiln and quickly shoveled hot char into a 20-gallon (.076 m^3) steel can, suspended it with the truck crane, and weighed it to calculate the bulk density (weight per volume) of the char sample. The total mass of the char was then calculated by extrapolating the known bulk density of the char in the can to the total volume of the kiln output.

When bulk densities were measured during lab analysis using quenched char, we discovered that bulk densities calculated using the dry weight method were significantly lower. Bulk densities were determined by Control Laboratories by taking our wet samples as received, adding them to a beaker and gently tapping it to settle the char. Volume was recorded and the samples were dried at 100°C and reweighed to determine dry weight. Settling of the char during quenching was found to decrease volume by ~40%

As a result of this experience, in 2024 we used a field protocol for determining total char volume that more closely matched lab procedures. After each burn had been quenched, we shoveled all of the char into a 30-gallon (.114 m^3) steel container, tapped it on the ground to settle it, and tallied the number of containers to get the total volume of all of the char produced during each burn.

Weighing fresh and oven-dried feedstock samples allowed us to calculate the total dry weight of fuel used for each burn. Measuring the bulk density of the char using the methods described above allowed us to calculate the percentage of dry feedstock mass that was converted to dry biochar mass. Analyses of the percentages of carbon and other elements in feedstock samples for each burn, and the percentages measured in the resulting char (**Appendix C**), allowed us to determine the percentage of these feedstock elements ultimately captured in the biochar. Partially charred wood left after each burn was weighed, and the percentage of char was estimated (typically 10-15%). Moisture was determined using a pin type moisture meter (Extech MO220). The dry mass of unburned wood was then subtracted from the final mass of the feedstock.

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Open Burn Piles

Burns 5, 8, 12 and 13 were open burn piles used as experimental controls. These burns were managed to mimic a typical forestry slash disposal or yard debris open burn where all material is piled and lit from the bottom (*Fig. 2*). Unburned fuel around the outside edge was occasionally raked into the active flame in the center of the pile. This allows a realistic evaluation of the fate of feedstock carbon when burned in a typical burn pile compared to a flame cap kiln.



***Figure 2*: Open Burn Pile. These were built to simulate a typical forest slash pile**

Laboratory Analysis

Five samples of mixed char and ash were collected in different heights and areas from each burn for lab analysis. Test results are compiled in a spreadsheet in **Appendix D**. Biochar produced in all burns was analyzed at Control Laboratories (see **Appendix B**) for % organic carbon, % hydrogen, % oxygen, the molar ratio of hydrogen to organic carbon ($H:C_{org}$), % ash, and % nitrogen.

Biochar Stability

Cellulose and lignin polymers are composed of roughly 50% carbon with the remainder being made up of oxygen and hydrogen (see **Appendix C** for exact composition of our major feedstocks). Pyrolysis condenses the carbon in those polymers to amorphous sheets of highly stable polycyclic aromatic carbon structures composed of nearly pure carbon. The more condensed the biomass, the less O and H atoms remain.

Carbon stability is typically measured by the molar ratio of hydrogen to organic carbon ($H:C_{org}$). Any $H:C_{org}$ ratio below 0.7 is considered to be stable in the soil for centuries. The European Biochar Certificate Guidelines (2022) state that "The molar H/C_{org} ratio is an indicator of the degree of carbonisation and therefore of the biochar stability. The ratio is one of the most important characterising features of biochar and is indispensable for the determination of the C-sink value… Values exceeding 0.7 are an indication of non-pyrolytic chars or pyrolysis deficiencies." See **Appendix B** for these values.

The $O:C_{org}$ molar ratio has also been discussed as a measure of biochar permanence. Spokas (2010) determined that when the O:C molar ratio of biochar is below 0.2, the half-life of the biochar is expected to exceed 1000 years. O:C molar ratios were calculated for all biochar samples produced during this study.

Emission Measurement Methods

Emissions were measured using the Possum1 portable dilution sampling system (**Figs. 3&4**). A continuous sample was drawn from a multi-point sampling probe suspended in the plume. Gas concentrations were measured continuously and integrated filter samples were collected for gravimetric analysis and OC/EC thermal optical analysis. Emission factors were calculated using the carbon balance method, which requires measurements of the mass, moisture content, and carbon fraction of both fuel loaded and char remaining. A cavity ring-down spectrometer (Los Gatos Research Greenhouse Gas

Analyzer) was added to the sample train for the measurements in 2024 (Burns 9 – 16) to measure methane.

The probe is 3 meters long. The multi-point sampling nozzle has 12 holes, spaced over a sampling area of diameter 0.8 meters. A sampling platform was constructed with scaffolding. The probe was mounted off the sampling platform at a height of ~3 meters from the ground. The emissions technician on the sampling platform can move the probe to keep the sampling head in the plume. The plume diluted naturally before reaching the probe. Further dilution was added in the probe at a dilution ratio of 1:1 with clean, dry air in order to reduce sample humidity, condition the sample for representative partitioning of semi-volatile species, and ensure concentrations were in appropriate range for the sensors.

Emission Species Measured

CO_2 (carbon dioxide): Three non-dispersive infrared sensors: one in the undiluted sample train, one in the diluted sample train, and one in the dilution air train.

CO (carbon monoxide): Three electrochemical cells: one in the undiluted sample train, one in the diluted sample train, and one in the dilution air train.

NO (nitric oxide): Electrochemical cell in diluted sample train.

NO_2 (nitrogen dioxide): Electrochemical cell in diluted sample train.

VOC (volatile organic compounds): Photoionization detector (10^6 eV lamp) in diluted sample train, calibrated to ppm isobutylene.

CH_4 (methane): Cavity ring-down spectrometer in the diluted sample train.

$PM_{2.5}$ (particulate matter): The diluted sample train contains a cyclone with 2.5 micrometer cut point, 47 mm filter holders for gravimetric analysis, and an optical PM sensor. Filter flows were measured continuously with mass flow sensors. The optical (light-scattering) PM sensor shows real-time PM emissions.

PM composition: PM was collected on 47 mm quartz filter for thermal-optical analysis by Sunset OC/EC analyzer to determine the mass fractions of elemental carbon (EC) and organic carbon (OC) following method NIOSH 5040. Particle light absorption was measured in real-time using the TAP (Tri-color Absorption Photometer).

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***Figure 3*: Emissions Equipment Setup.**

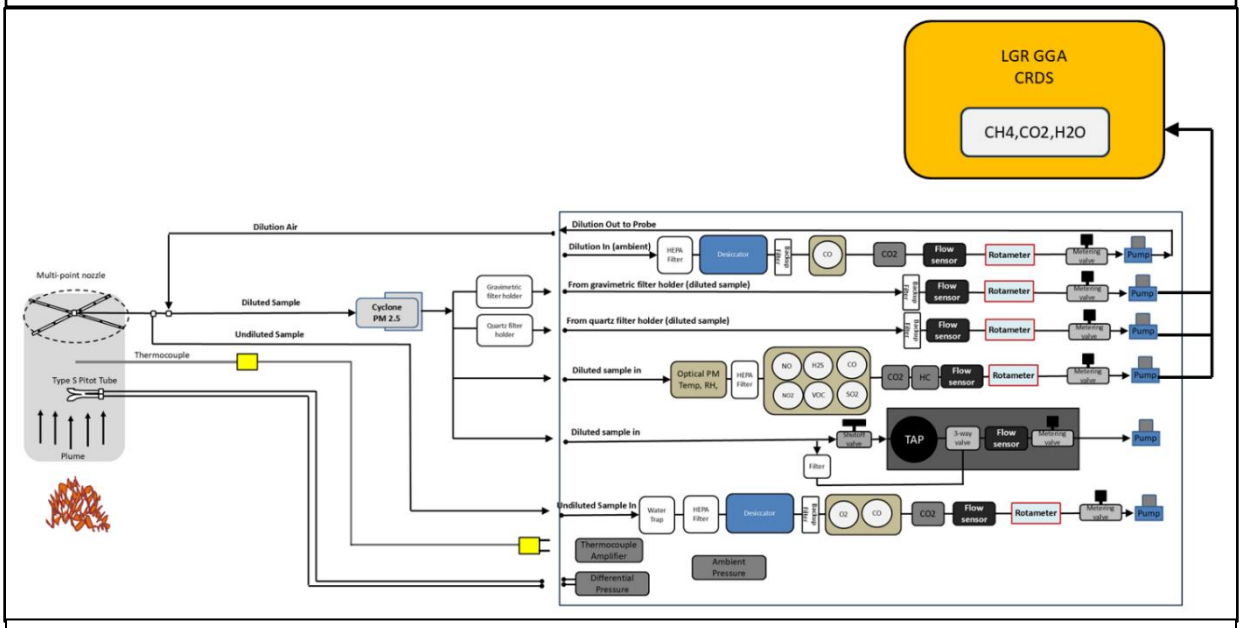


***Figure 4*: Possum1 portable sampling system flow schematic. The LGR cavity ring-down spectrometer was added during the 2024 measurements to measure methane.**

This investigation focuses on CH_4 because of its significant climate forcing potential (Etminan, et al., 2023), and on $PM_{2.5}$ and VOCs because of their effects on human health (Burnett et al., 2018; Feng, et al., 2023). NO_x can also have important health (Chen, et al., 2023) and environmental (van der Plas, et al, 2024) effects, but regression analysis of NO and NO_2 released from our burns showed no correlation with fuel moisture. This is consistent with analyses of wood stove fuels by Price-Allison et al. (2019) that "The NO_X emissions… were only dependent on the fuel-nitrogen content and not on the moisture content."

Methane Measurements

During the 2023 measurements (Burn 1 – 8), CH_4 measurements were made with a Non-Dispersive Infrared (NDIR) hydrocarbon sensor. These CH_4 measurements were low quality due to temperature drift and interference from other hydrocarbons besides CH_4. During the 2024 measurements (Burn 9 – 16), high quality CH_4 measurements were made with a cavity ring-down spectrometer (CRDS), as well as the

NDIR sensor for comparison. CH_4 derived from the NDIR sensor showed poor agreement with the actual CH_4 measured by the cavity ring-down spectrometer. However, 2024 data showed that grams of CH_4 per kilogram of dry fuel had a near-perfect correlation with CO emissions ($R^2 = 0.978$, $p = 6.67^{-5}$), so CH_4 emissions can be reliably predicted as a function of CO emissions. Therefore, the CH_4 emissions in the 2023 data were recalculated using the CH_4:CO correlation from the 2024 data.

Reporting Metrics

MCE (Modified Combustion Efficiency): The mole fraction of emitted carbon as CO_2. A value of 1 indicates complete combustion, and lower values indicate lower combustion efficiency.

$EF_{fuel,db}$: Dry fuel-based emission factor for each emission species (CO, CO_2, NO, NO_2, CH_4, VOC, $PM_{2.5}$, EC, OC) as mass of pollutant per dry mass of fuel loaded (corrected for fuel moisture content). We chose grams of emission species per kilogram of dry fuel (g/kg) as the metric to use for reporting our results because we believe this to be the most useful for field managers who can accurately calculate the dry mass of their fuel and effectively predict the grams of emission species expected per kilogram of fuel. We also report emissions in grams per kilogram of raw fuel (EF_{fuel}) and grams per kilogram of char (EF_{char}) so other researchers can more easily compare their results to ours (see below and **Appendix F**).

The following 3 metrics (EC/TC, TC/PM and AAE_{RB}) were also measured and are reported in **Appendix F**, and will be included in a future analysis.

EC/TC: Particulate matter composition. Fraction of elemental black carbon to total carbon. TC = OC + EC. Higher EC fraction indicates darker particulate matter that causes higher atmospheric radiative forcing.

TC/PM: Particulate matter composition. Fraction of total carbon mass measured by OC/EC analysis to total PM mass measured by gravimetric analysis. The remaining fraction of PM that is not carbon is typically other elements that bond with carbon in the organic matter, and ash or minerals. Values greater than 1 indicate measurement artifacts in the analysis methods.

AAE_{RB} (Absorption Angstrom Exponent): Wavelength dependence of particle light absorption, measured between red and blue wavelengths. AAE of 1 means the light absorption is equal for different wavelengths, indicative of black carbon. Higher values indicate the presence more organic carbon and/or minerals that have enhanced absorption of the short (blue) wavelength.

Measurement Uncertainty and Quality Control

All gas sensors were calibrated on site with zero and span calibration gases periodically throughout the measurement campaign. The sample train was leak-tested before and after each test run. Measurement uncertainty was estimated for each measured input and propagated to reporting metrics using first-order error propagation. Measurement uncertainty was determined from calibration checks, equipment specifications, and variability measured from repeated measurements. The dominant sources of uncertainty in the reported emission factors are from the fuel and char inputs.

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Comparison with EPA Reference Methods

EPA reference methods for regulatory compliance of stationary sources are written specifically for sources with exhaust stacks. Therefore, none of the EPA reference methods are entirely applicable for measuring open plumes from these kilns and open piles. However, some aspects of EPA reference methods can be used to measure open plumes. The advantage of EPA reference methods is that they provide a traceable standard of quality that meets the requirements of regulatory compliance. The disadvantages of EPA reference methods are high costs, lack of portability, and lack of appropriateness for climate-relevant emission characterization.

For these emission tests, the CO measurement was compliant with EPA Method 10, and the CO_2 measurement was compliant with EPA Method 3A. The $PM_{2.5}$ measurement for these emission tests was chosen to be most relevant for climate and public health impacts. The method was similar to EPA Method 201A, except the sample was conditioned with dilution air, and the sample train was at ambient temperature.

Statistical Analyses

We used one-tailed t-tests assuming unequal variances to compare all kiln burns (n=11) to all open pile burns (n=4). For comparing fuel moistures to biochar yields and emissions from kiln burns, we generated x/y scatter plots and used linear regression analysis to generate trendlines, slopes, x-intersepts, and probability values. Raw data used for all analyses below can be found in **Appendix E** for carbon sequestration, and **Appendix F** for emissions.

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RESULTS

Kiln Burns Compared to Open Burn Piles

Figure 5 shows that kiln burns using similar fuels stabilized significantly more carbon than open burns. Fuel moistures were similar: kiln burns ranged from 17.7 to 51.6% (avg. 32.3%) while open burns ranged from 19.4 to 50.6% (avg. = 39.5%). Kiln burns sequestered approximately 3 times more feedstock carbon than open burns (38.8% and 13.4 % respectively; p = 0.00008).

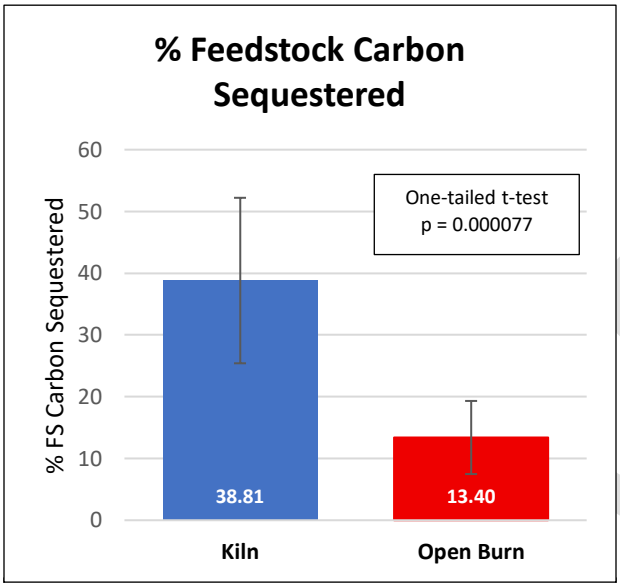


***Figure 5*: Kiln burns averaged ~3 times the carbon sequestered in biochar of open burns.**

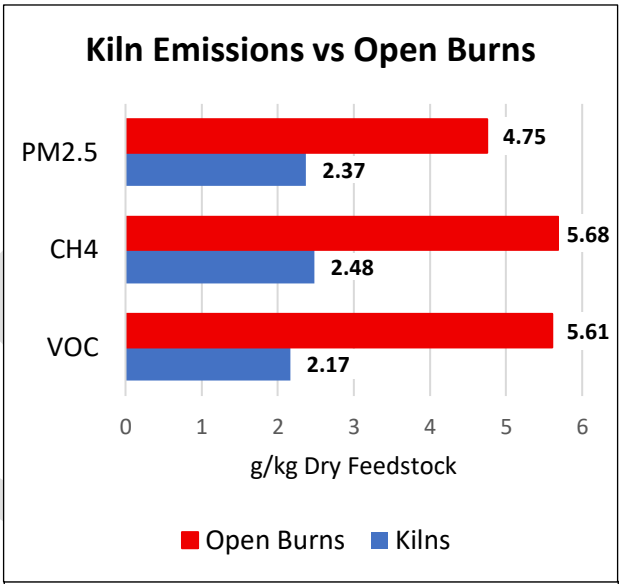


***Figure 6*: Kiln burns averaged less than half the, $PM_{2.5}$, CH_4 and VOC emissions of open burns.**

Figure 6 shows the average production of methane (CH_4), volatile organic compounds (VOCs), and particulate matter ($PM_{2.5}$) of flame cap kilns compared to open pile burns. Kilns produced significantly less methane than open burns ($p < 0.01$). Although emissions of VOCs and $PM_{2.5}$ had less than half the averages of open burns, p-values were slightly higher than the general accepted 95% confidence interval (p = 0.054 and 0.090 respectively), due to the small open burn sample size (n = 4) compared to kiln burns (n = 11).

Effects of Fuel Moisture on Biochar Yields and Emissions

We generated the following scatter plots and used linear regression modeling to analyze our data for carbon sequestration and emissions values from 11 kiln burns with feedstock moisture contents ranging from 17.7 to 51.6%. As predicted, feedstock moisture content was a significant factor in the quantity and quality of biochar from flame cap kilns as well as the amount of emissions.

Biochar Carbon Content

Our predictions that feedstock moisture content strongly influences the quantity and quality of the biochar produced in flame cap kilns is clearly supported by our data.

With this type of kiln, the heat necessary for pyrolysis is supplied by radiation from combustion of fine fuels on the surface of the kiln while also creating the flame “cap” that reduces emissions. Combustion

residues are mostly ash, so the more heat required for this process, the more ash is produced compared to char. *Figure 7* illustrates this relationship relative to fuel moisture content.

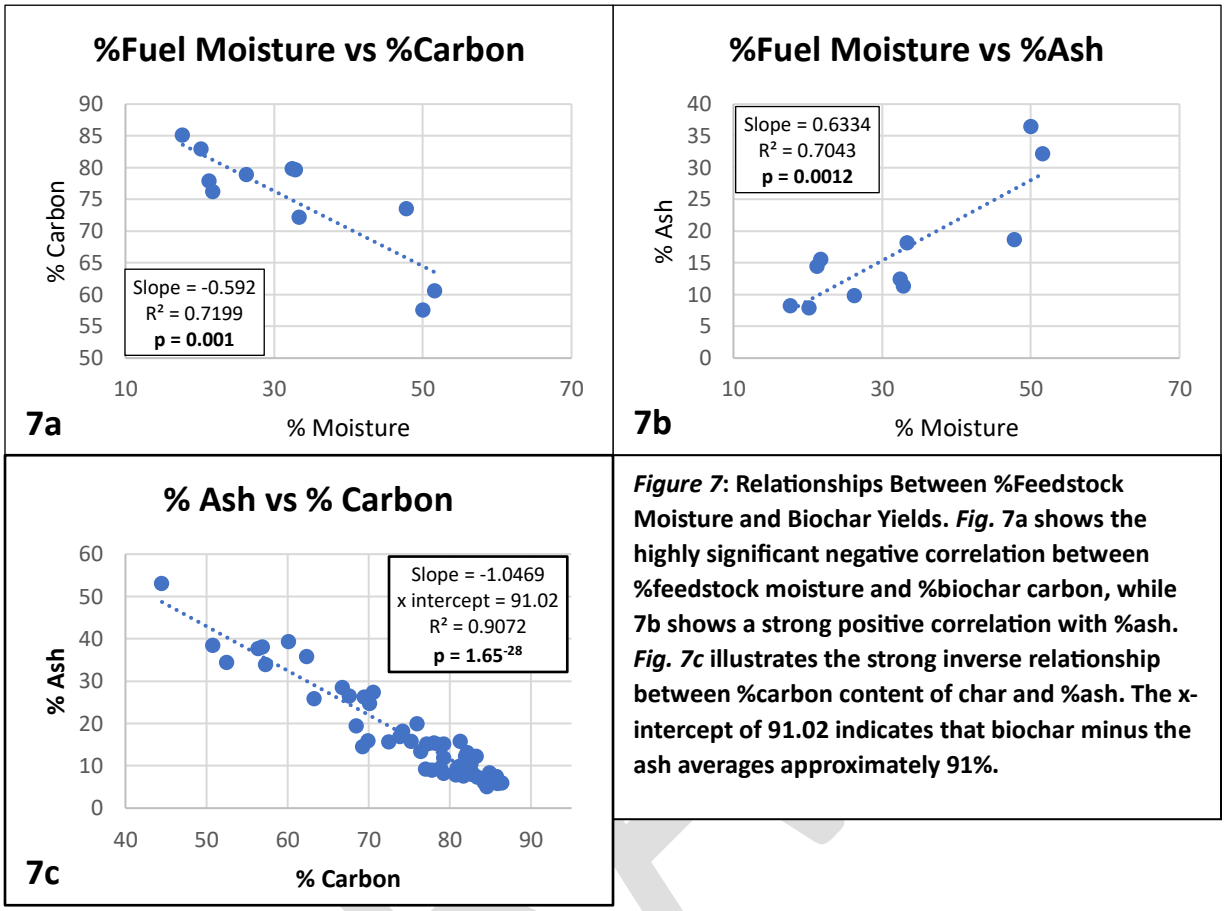


***Figure 7*: Relationships Between %Feedstock Moisture and Biochar Yields. *Fig.* 7a shows the highly significant negative correlation between %feedstock moisture and %biochar carbon, while 7b shows a strong positive correlation with %ash. *Fig. 7c* illustrates the strong inverse relationship between %carbon content of char and %ash. The x-intercept of 91.02 indicates that biochar minus the ash averages approximately 91%.**

Figure 7a and *7b* show the linear relationships between feedstock moisture and the average carbon and ash content of the resulting char. The percentage of feedstock moisture is significantly negatively correlated with carbon content (R^2 = 0.7199, p = 0.00096) and positively correlated with ash content (R^2 = 0.7043, p = 0.00124).

Figure 7c illustrates the extremely tight correlation (R^2 = 0.907, p = 1.65^{-28}) between %ash and %carbon contents of all subsamples from our 11 kiln burns (n = 54). Note that the x-intercept indicates that the carbon content of biochar minus the ash averages approximately 91%.

Biochar Stability

Figure 8 indicates that all of our burns produced biochar that with $H:C_{org}$ ratios below the 0.7, indicating a high degree of carbonization and therefore high stability (EBC, 2022). Feedstock moisture had a statistically significant impact on this parameter -- as the percentage of fuel moisture went up, so did the $H:C_{org}$ ratio, but never exceeding 0.7.

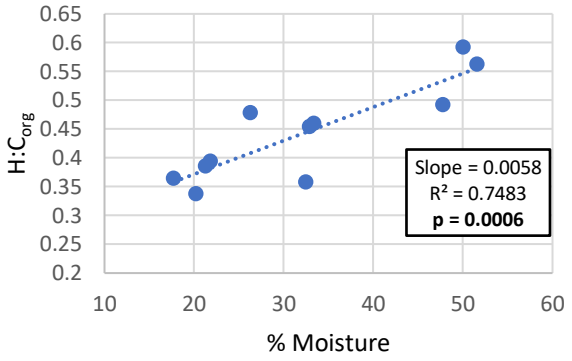


***Figure 8*: Impact of fuel moisture on H:C_{org}. Higher fuel moistures decreased the stability of biochar produced in flame cap kilns, but no burns produced char that exceeded the 0.7 threshold.**

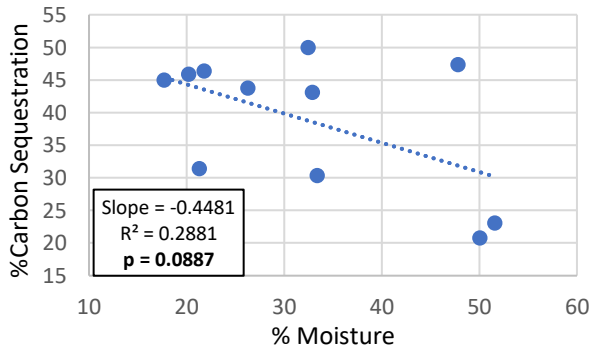


***Figure 9*: Effect of fuel moisture on the percent of feedstock carbon (dry wt. basis) ultimately sequestered in biochar. A weak but non-significant trend is evident.**

The molar ratio of O:C_{org} for all kiln burns averaged 0.050 +/- 0.019 also indicating highly carbonized char (Spokas (2010). This ratio, however, did not show any correlation with fuel moisture (R^2 = 0.0007, p >> 0.05).

Total Carbon Yields

Figure 9 shows the % of the total dry mass of feedstock carbon sequestered in the total mass of carbon produced per burn, and reveals a weak but non-significant (R^2 = 0.29, p = 0.089) negative correlation with fuel moisture.

Emissions

Figure 10 illustrates the relationship between % fuel moisture CH_4, $PM_{2.5}$, VOCs, and Modified Combustion Efficiency (MCE). These graphs indicate that high percentages of feedstock moistures are strongly positively correlated with greater emissions and negatively with combustion efficiency. These regression models show CH_4, VOC, and PM 2.5 emissions were 3 to 5 times higher for high moisture fuel (>45%) compared to dry fuel (<25%)."

X-intercepts were calculated for CH_4, $PM_{2.5}$, and VOCs (*Fig. 10*) to determine the moisture levels that would produce near-zero emissions of these pollutants. These values fall in 11-17% moisture range, suggesting that feedstock moisture levels in that range or below should produce minimal amounts of these emissions.

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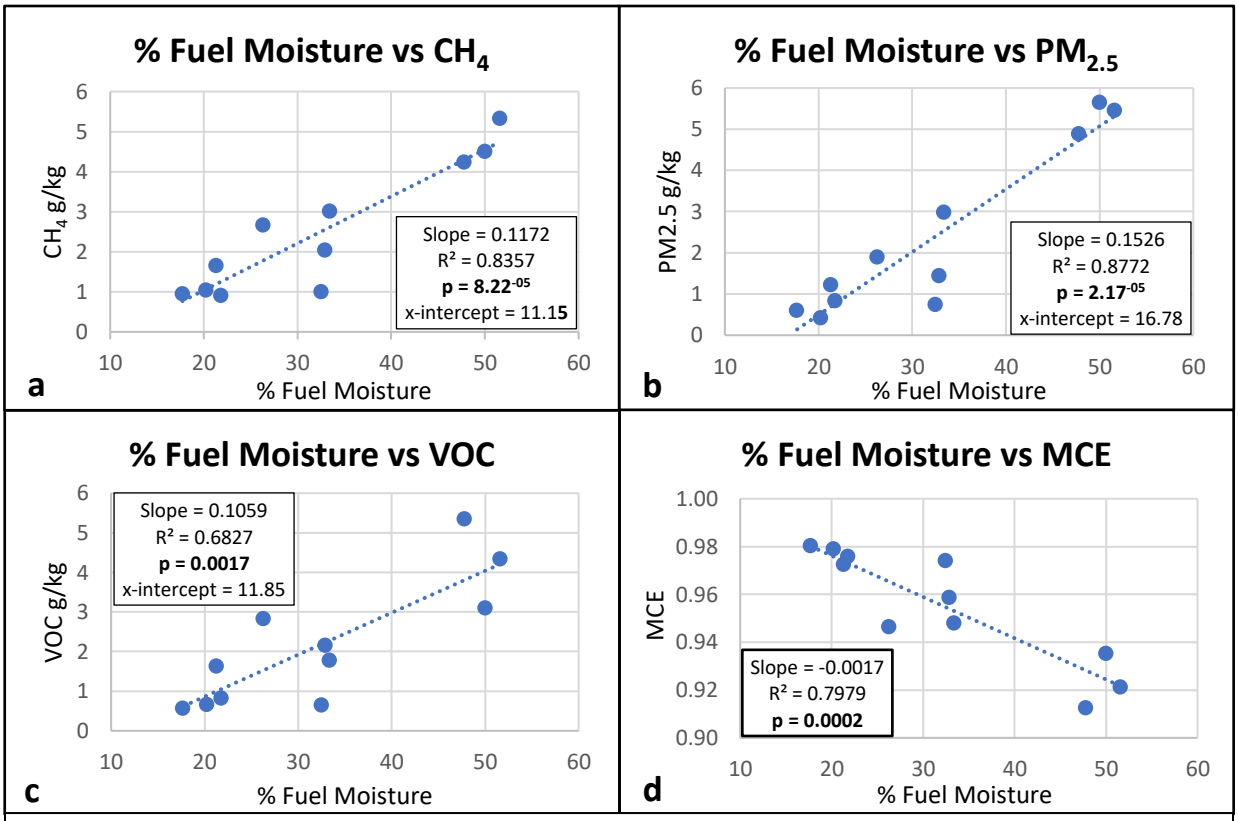


***Figure 10*: Relationship Between % Fuel Moisture and Emissions. Increasing fuel moisture has a significant influence on the production of methane (a), particulate matter (b), and volatile organic compounds (c). The increases in these emissions correspond to the decrease in Modified Combustion Efficiency (MCE) with increasing fuel moistures (d). X-intercepts for plots a-c fall in the 11-17% moisture range, suggesting that feedstock moisture levels in that range or below should produce minimal amounts of these emissions.**

DISCUSSION

Because previous researchers had already collected data on open burns of woody biomass, we chose to emphasize kiln burns to get enough replicates for robust statistical analysis. We therefore skewed our limited number of replicates to 11 kiln burns and 4 open burns as controls.

There are very few reports of flame cap kiln emissions in the literature, and that is largely limited to crop waste, e.g. rice husks, maize cobs, leaves and branches, grasses, etc. (Cornellisen, et al. 2024), although Cornellisen et al. (2016) tested “firewood” along with other feedstocks. Because we were attempting to simulate the use of flame-cap kilns in on-site land management applications, we chose to use all woody feedstock, particularly conifer species. We hypothesized that flame cap kiln burns would sequester a greater percentage of feedstock carbon and produce fewer emissions than open pile burns, and the data strongly support these predictions.

Flame Cap Kilns Sequester More Feedstock Carbon and Produce Fewer Emissions Than Open Burns

The data we present in *Fig. 5* indicate that our kiln burns sequestered approximately 3 times more feedstock carbon than our open burns. This is a conservative figure because our burn piles were not allowed to burn all the way out on their own – time constraints meant we had to quench the smoldering piles to be able to finish our work day or to move on to our next burn. This constraint was particularly evident in our 2024 burns which only averaged 2.0 hrs. per burn with a yield average of 18.4% carbon sequestration, compared to our 2023 burns which averaged 3.36 hrs. in length with an average yield of 8.4% C sequestration. Had we been better able to simulate real-world open burning, it is likely that significantly more fuel carbon would have been combusted. Finkral, et al. (2012) reported only 6-8% of feedstock carbon remained in the char after open burning of ponderosa pine slash piles. This suggests that our 2023 burns more closely mirrored typical open pile burns, and that flame cap kiln burns sequester at least *5 times more carbon* than open burns.

Figure 6 shows that flame cap kiln burns avoided more than 2 times the emissions of open pile burns across all fuel moistures. In grams of pollutant per kilogram of dry fuel, open burns released 2.12 times more CH_4, 2.00 times more $PM_{2.5}$, and 2.58 times more VOCs than our kiln burn averages. These values compare well to open burning data reported by previous studies. Andreae (2019), Akagi, et al. (2011), Baker (2014), and Levine et al. (2012) report the following ranges for these three pollutants for open burning of woody biomass: CH_4 5.16–6.04 g/kg; $PM_{2.5}$ 11.06-13.0 g/kg; and VOCs 6.48-8.2 g/kg. Our open burn averages of 5.68 g/kg CH_4, and 5.61 g/kg VOCs compare well with these reports, although our $PM_{2.5}$ value of 4.75 g/kg is considerably lower.

Compared to flaming combustion, Baker, et al. (2014) reported that smoldering emissions were significantly higher for methane (2.7X) and VOCs (3.2X), and Riesen, et al. (2018) found a 2.9X increase in $PM_{2.5}$. This again suggests that our open burn values for emissions are also conservative, particularly for $PM_{2.5}$., given that our open burn methods decreased the time spent in smoldering combustion when emissions are at their highest. Therefore, one can expect flame cap kiln burns to avoid *at least* half the emissions of these three pollutants compared to traditional open burning, especially for low-moisture fuels as discussed below.

Fuel Moisture Affects Feedstock Carbon Sequestration in Biochar

The total percentage of feedstock carbon sequestered by flame cap biochar kilns is influenced by many factors including fuel moisture, wind and weather, fuel type and structure, and kiln design and operation. Because we wanted to demonstrate the efficiency of flame cap kilns in a real-world setting, the only parameter we could reliably control for at our test site was fuel moisture. Therefore, 11 replicates were planned to account for the "noise" in the data caused by these uncontrolled influences.

As noted above, the heat necessary for effective pyrolysis in flame cap kilns is provided by the combustion of fine fuels burning on the fuel surface. Although the product of pyrolysis is highly condensed black carbon (char), combustion produces ash, the mineral fraction of biomass. Therefore, the ratio of carbon to ash content of char made in flame cap kilns is strongly influenced by the amount of combustion necessary for pyrolysis. We hypothesized that feedstock moisture would affect the quantity and quality of biochar because the phase change that occurs when water goes from liquid to vapor is endothermic, and a burn with high-moisture fuel will theoretically require more overall heat as water evaporates. That requires more fine fuel to maintain a continuous high-temperature flame cap, producing a higher proportion of ash.

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Figure 7 plots the relationships between % feedstock moisture and biochar composition. As predicted, carbon content of biochar is negatively correlated with percent feedstock moisture (*Fig. 7a*), and ash content is positively correlated (*Fig. 7b*). *Figure 7c* illustrates a strong inverse correlation between ash content vs carbon content of char across all fuel moistures. The x-intercept indicates that the carbon content of pure char averages ~91%.

These data indicate that as fuel moisture increases, ash content of biochar increases and carbon content decreases. Although this has implications for carbon sequestration applications, from an agricultural perspective, this is not negative factor. Rolka, et al. (2023) found that after growing corn in soil amended with wood biomass ash, analysis showed "…an increase in pH and a significant improvement of soil sorption properties, without causing an excessive increase in soil salinity. In addition, a significant increase in the content of available K, P, and Mg was observed".

Figure 8 shows a significant correlation between feedstock moisture and carbon stability as measured by $H:C_{org}$ molar ratios. Lower ratios indicate a higher degree of carbonization and more condensed and decay-resistant aromatic structures within the biochar. Liu et al. (2018) report that higher pyrolysis temperatures drive off more hydrogen from cellulosic feedstock, thereby decreasing $H:C_{org}$. This supports the assumption that high moisture fuels will produce lower kiln temperatures due to heat required for vaporization.

None of our kiln or open burns exceeded a ratio of 0.7, the value considered to be stable by the International Biochar Initiative and many certifying entities including the European Biochar Certificate and the Australia New Zealand Biochar Industry Group. However, the World Biochar Certificate (www.european biochar.org) and the carbon marketplace Supercritical (gosupercritical.com) recognize a premium tier with $H:C_{org}$ ratios of 0.4 or below. *Figure 8* indicates that to meet that standard, fuel moistures should be below 25%.

Feedstock Moisture Affects Emissions from Flame Cap Kilns

Figure 10a-c illustrates the strong positive correlations between % feedstock moisture and emissions of CH_4, $PM_{2.5}$, VOCs from flame cap kilns. These data clearly support our hypothesis that high percentages of feedstock moisture are positively correlated with greater emissions. In their study of flame cap kiln emissions, Cornellisen et al. (2023) report "…almost no methane… emissions for dry (< 15 % moisture) feedstock consisting of twigs and leaves". Our results agree well with their findings: The x-intercept for the plot of feedstock moisture vs CH_4 is at 11.15 % moisture content while x-intercepts for $PM_{2.5}$ and VOCs are at 16.78 and 11.85. These values verify that woody feedstocks in the 11-17% moisture range or below should produce close to zero amounts of these three emissions.

Figure 10d shows the significant negative correlation between % fuel moisture and Modified Combustion Efficiency ($R^2 = 0.798$). An MCE of 1.0 would indicate a perfectly efficient burn emitting nothing but CO_2, while an MCE of < 0.8 is largely smoldering combustion, and a value of 0.9 is considered transitional (Stockwell, et al., 2016). The phase change from liquid to gas is endothermic, so high moisture fuels would be expected to burn cooler and thus less efficiently (i.e., with a lower MCE). Although our MCE values never dropped below 0.91, the effect of fuel moisture on emissions of CH_4, VOCs, and $PM_{2.5}$ is evident in *Figs. 10a-c*. Our data compare well with other studies on MCE and these three pollutants: Yokelson, et al. (2003) found a strong negative correlation between MCE and CH_4 emissions ($R^2 = 0.874$) during African savanna fires, Permar, et al. (2021) found a strong relationship between lower MCEs of

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western wildfires and increasing VOC emissions, and wildland fuels combusted under laboratory conditions showed a similar trend for $PM_{2.5}$. (Hosseini, et al., 2013).

Kiln Operation Best Practice

When comparing open burns to kiln burns, we chose to bias our replicates toward kiln burns (n = 11) as opposed to open burns (n = 4) because of the substantial existing literature on emissions from open burning. Because we wanted to test flame cap kilns under real-world field conditions, we knew we would be dealing with a great deal of variability from wind and weather, fuel type, and labor availability and training level. We felt that 11 kiln burns would overcome the expected noise in our data, but we were also able to adjust our testing methods based on initial experience, both in 2023 and 2024.

Although our experimental regime was extremely challenging with a limited amount of time to get all of our burns completed, we were able to analyze our data every evening between burns. This allowed us to hone best practices as we progressed, based on our immediate experience. As a result, our burn efficiencies improved over time -- *Figure 11* illustrates this "learning curve".

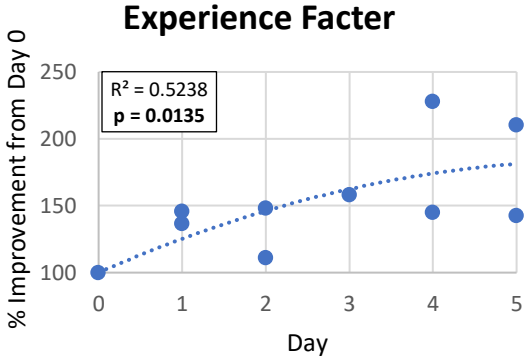


***Figure 11*. Experience Factor. This x-y plot illustrates the improvement in the amount of total carbon sequestered in successive burns compared to our first burns. Our Day 0 burns in 2023 and 2024 are both plotted as 100%, and successive burns are plotted as the percent improvement over those initial burns.**

For example, our first three burns in 2023 were conducted in kilns configured as hexagons. We found that our yields we low compared to experience from our own and other practitioners' previous burns, and our ash to char ratios were noticeably high. We realized that we hadn't accounted for the amount of labor necessary for continuous feeding, especially with the more laborious weighing methods we used that year. This meant we were not keeping up with the fuel loading necessary to minimize combustion and maximize pyrolysis. Switching to a rectangular configuration dropped the kiln volume by roughly a quarter, allowing us to better keep pace with the fuel loading required to keep a flame cap in balance. In 2024, our first burn was our lowest yield burn as we worked out our process with new crew members.

Also, during our first three burns in 2023, we built baffles in an attempt to mitigate the effect of variable and gusting winds. During previous projects in the field, we noticed that gusts from the windward side of the kiln would blow the flame cap toward the center, allowing smoke and pyrolysis gases to escape unburned through that gap. We hoped that the baffles would help to control that problem, but unfortunately, they made the problem worse as wind coming over the baffles created downdrafts that disrupted the flame cap. We discontinued their use after Burn# 4 was so badly affected.

CONCLUSIONS

Expected Carbon Sequestration Yields

Figure 12 is a plot of total feedstock carbon retained in the biochar produced for all 11 kiln burns. A weak, nonsignificant correlation was observed between feedstock moisture and the total percent of feedstock carbon sequestered in the resulting char (*Fig. 9*, $R^2 = 0.287$, $p = 0.089$). Total feedstock carbon sequestered in the biochar produced from all burns averaged 38.7%. In 2023, that average was 33.1% and in 2024 the average was 43.5.

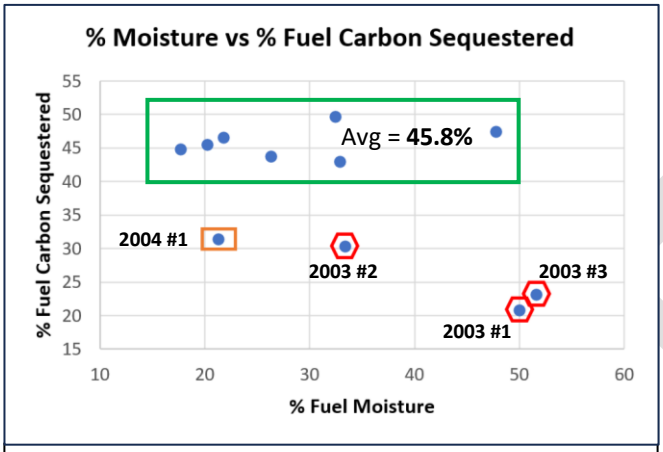


***Figure 12*: % Fuel Moisture vs Total % Feedstock Carbon Sequestered in Biochar. There is a minimal, non-significant correlation ($R^2 = 0.287$, $p = 0.089$) between feedstock moisture and the amount of total feedstock carbon ultimately sequestered from all 11 kiln burns. Removing the first three 2023 hexagonal kiln burns and the first 2024 burn leaves 7 burns ranging from 42.2 to 49.6% and averaging 45.8%.**

We believe these are conservative averages. As noted above, the first three burns in 2023 (red hexagons) were problematic because of kiln configuration and failed wind baffles, and our first burn in 2024 (orange rectangle) involved training a new crew, and produced our lowest carbon yield of that year.

If the first three burns in 2023 and the first low-yield burn of 2024 are omitted, the average amount of feedstock carbon sequestered rises to 45.8% (*Fig. 12,* green rectangle). Our results suggest that with a kiln configuration optimized for labor and feedstock type, and a well-trained crew, a contractor can consistently expect *40-50% of feedstock carbon to be sequestered regardless of the fuel moisture*.

Although the *quantity* of feedstock carbon sequestered shows little to no effect of fuel moisture, *Fig. 8* shows a significant effect on char *quality* as indicated by the $H:C_{org}$ ratios. While none of our burns ever exceeded the 0.7 ratio considered to be highly stable by most certification standards, the more stringent 0.4 ratio required by the World Biochar Certificate (WBC, 2023) to qualify for premium carbon offsets would require fuel moistures below 25%.

As noted in our introduction, significant logistical and labor savings can be achieved by combining all of the steps in biochar production including falling, bucking, limbing, yarding and charring into one integrated operation. Moving green feedstock directly from stump to kiln not only lowers costs but also decreases the risk of wildfire caused by leaving hazardous fuels on the ground to dry during fire season. While *Fig. 10* shows that emissions increase with increasing moisture content, a Life Cycle Assessment must weigh this against the carbon footprint of extra crew and equipment transportation costs, especially to remote sites, and the possibility of exacerbating the spread and intensity of a potential wildfire if slash is left on-site to dry.

Avoided Emissions

Our regression trendlines in *Fig. 10a-c* can be used by managers in in air-quality-limited areas to predict the quantities of emissions from feedstocks of varying moisture contents. We also found that flame cap kilns produce less than half the emissions of CH_4, VOCs and $PM_{2.5}$ compared to open burn piles (*Fig. 6*).

Previous research on emissions from open biomass burning suggest that these are conservative values, especially for $PM_{2.5}$.

Carbon Monoxide is a Good Proxy for Methane

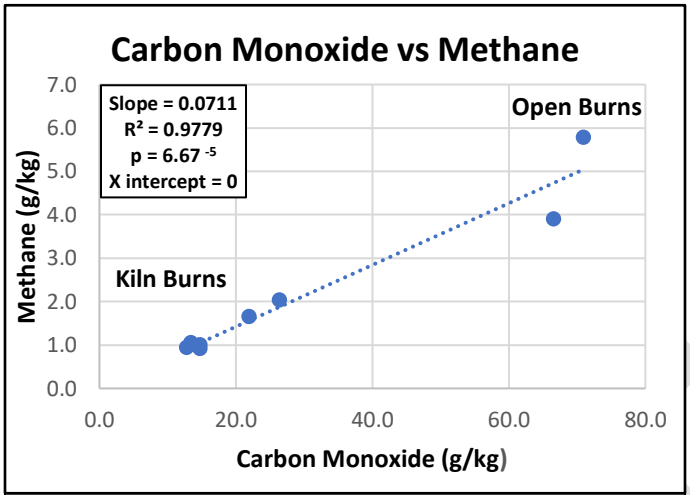


***Figure 13*: Carbon Monoxide is a Reliable Proxy for Methane. For every 1 g/kg of CO produced one can expect a 0.129 g/kg increase in CH_4.**

Accurate methane measurements can be extremely difficult to obtain without very expensive equipment. Methane data were collected during 2023 using a Non-Dispersive Infrared (NDIR) sensor to calculate methane emissions, while 2024 data were collected using a state-of-the-art Cavity Ring-Down Spectrometer (CRDS) (see METHODS). We found that the NDIR sensor did not produce consistent results, but we were able to use the 2024 data to correct the methane emissions values for the 2023 data. *Fig. 13* shows the relationship between CO and CH_4 using just the 2024 CRDS data. This opens the possibility that CO measurement alone can be used to reliably predict CH_4 production, thereby potentially lowering the overall cost of emissions monitoring.

Future Research

Appendix F includes a number of other metrics that were gathered during our burns that were not analyzed for this study. Some of the other emissions we measured, particularly black carbon and NO_x, will need to be included in a future Life Cycle Assessment. The data used in this paper were presented as averages of values collected in one-second intervals over the span of every burn, and in 2024, we integrated an anemometer to correlate wind speed and direction with emissions. Analysis of wind and emissions time series will help us assess the necessity of designing effective wind mitigation equipment for future flame cap kiln upgrades. We also plan to analyze emissions time series to help sharpen best practices, particularly focusing on the optimum interval between the end of fuel loading and quenching.

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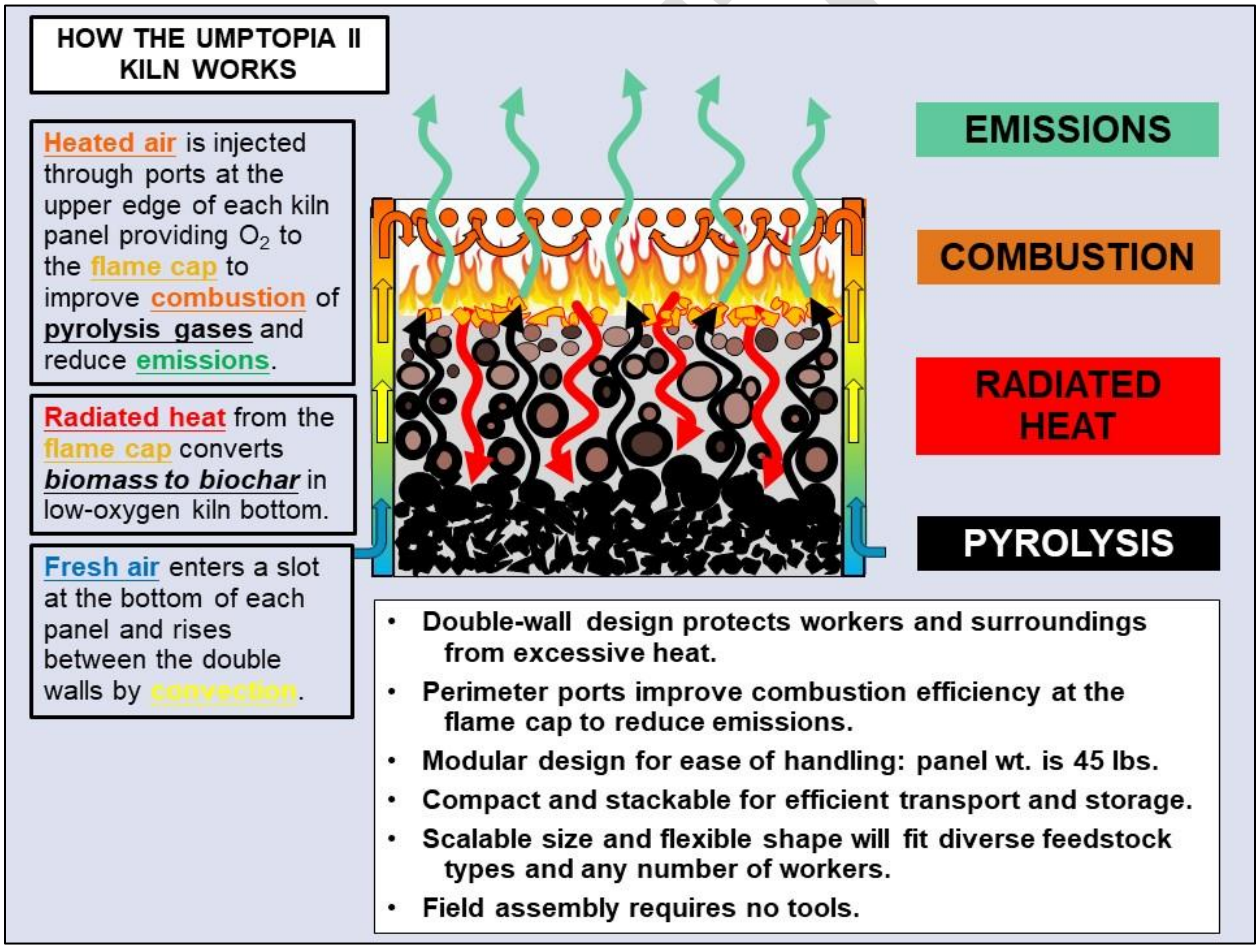
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APPENDICES

APPENDIX A: Flame Curtain Kiln Technology



Design principles of the kiln used for this analysis.

APPENDIX B: Example of Control Laboratories Data Form

Control Laboratories

42 Hangar Way
Watsonville, CA 95076
www.biocharlab.com
Tel: 831 724-5422
Fax: 831 724-3188

Account No.:
12315
Batch:
NOV 24 D
CODE:
Prox. Analysis

Maggie Craig
Martha's Vineyard Commission
9 Sheep Pen Lane
Chilmark, MA 02535

Date Received:	11/18/2024
Sample ID:	Burn #6 Sample 2
Lab ID Number:	4110230-02

Proximate Analysis

	As-Received	Dry Weight Basis	Method
Moisture	67.1 %	0.0 %	A
Bulk Density	0.48 g/cc	0.16 g/cc	
	29.9 lb/cu ft	9.8 lb/cu ft	
Carbon (C)	27.4 %	83.3 %	B
Hydrogen (H)	0.7 %	2.2 %	B
Nitrogen (N)	0.2 %	0.5 %	B
Oxygen (O -calc.)	2.0 %	6.0 %	Calc.
Ash	2.6 %	7.9 %	A
	100.0 Sum	100.0 Sum	
Phosphorus (P)		952 mg/kg	F
Volatile Matter	8.4 %	25.6 %	A
Butane Activity	1.3 g/100 g	4.0 g/100 g	C
Surface Area Correlation	85 m^2/g	259 m^2/g	E
Organic Carbon	27.2 %	82.8 %	Calc.
H/Corg.	0.32	0.32	Calc.
Carbonates (as $CaCO_3$)	1.5 %	4.6 %	D

Methods

A	ASTM D 1762-84
B	Dry Combustion
C	ASTM D 5742-95
D	ASTM 4373
E	Butane Activity Surface Area Correlation Based on McLaughlin, Shields, Jagiello, & Thiele's 2012 paper: Analytical Options for Biochar Adsorption and Surface Area
F	EPA3050B/EPA 6010

Analyst: Nik Zumberge

Red ovals highlight parameters used to characterize biochar quantity and quality.

APPENDIX C: Feedstock Composition

	FEEDSTOCK TYPE							
Species	OakWd	PineWd	JnprWd	PinN+T	JnprN+T	SprcN+T	LCN+T	FS avg
Carbon%	**48.00**	**50.30**	**48.30**	**52.60**	**53.00**	**51.40**	**53.00**	**50.94**
Nitrogen%	0.50	0.30	0.40	1.50	1.40	1.00	1.10	0.89
Oxygen%	42.40	40.60	41.20	36.80	34.60	38.10	35.30	38.43
Hydrogen%	6.60	6.70	7.10	6.60	7.20	6.30	6.80	6.76
Total Ash%	2.60	2.10	3.00	2.50	3.80	3.10	3.90	3.00

Laboratory Analysis of Feedstock. Typical branches of each species were separated into wood and needles and twigs, and weighed separately. They were then oven dried to determine the average dry weight proportion of each component.

OakWd = Oak Wood; PineWd = Pine Wood; JnprWd = Juniper Cedar Wood; PinN+T = Pine Needles and Twigs; JnprN+T = Juniper Cedar Needles and Twigs; SprcN+T = Spruce Needles and Twigs; LCN+T = Leyland Cypress Needles and Twigs.

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APPENDIX D: Composition of Biochar from Kiln Burns

		COMPOSITION OF BIOCHAR FROM KILN BURNS					
BURN #		Organic Carbon %	Hydrogen %	Oxygen %	$H:C_{org}$ Ratio Molar Ratio	Total Ash %	Total N %
1	**AVG**	**57.54**	**2.85**	**1.85**	**0.59**	**36.48**	**0.57**
	STD	9.98	0.33	3.70	0.12	13.31	0.12
2	**AVG**	**72.16**	**2.50**	**8.18**	**0.46**	**18.10**	**0.72**
	STD	7.78	0.08	4.16	0.06	7.86	0.04
3	**AVG**	**60.60**	**2.75**	**4.73**	**0.56**	**32.16**	**0.50**
	STD	7.21	0.10	3.98	0.04	4.78	0.06
6	**AVG**	**73.54**	**3.00**	**4.08**	**0.49**	**18.64**	**0.79**
	STD	6.49	0.42	4.03	0.02	8.66	0.06
7	**AVG**	**78.90**	**3.15**	**7.85**	**0.48**	**9.84**	**0.79**
	STD	4.03	0.31	0.45	0.04	3.34	0.06
9	**AVG**	**77.86**	**2.46**	**4.26**	**0.39**	**14.48**	**0.44**
	STD	12.15	0.25	1.68	0.04	13.21	0.11
10	**AVG**	**79.68**	**3.00**	**5.06**	**0.45**	**11.30**	**0.52**
	STD	2.56	0.37	3.85	0.07	2.64	0.08
11	**AVG**	**76.24**	**2.52**	**4.52**	**0.39**	**15.51**	**0.50**
	STD	1.54	0.23	1.29	0.04	1.73	0.04
14	**AVG**	**79.81**	**2.38**	**4.20**	**0.36**	**12.45**	**0.56**
	STD	2.63	0.13	2.77	0.03	5.19	0.09
15	**AVG**	**82.94**	**2.35**	**5.75**	**0.34**	**7.87**	**0.46**
	STD	2.14	0.13	0.72	0.02	1.47	0.01
16	**AVG**	**85.09**	**2.56**	**3.26**	**0.36**	**8.22**	**0.44**
	STD	1.18	0.17	1.21	0.02	2.40	0.02

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APPENDIX E: Table for Calculating %Feedstock Carbon Sequestered in Biochar

KILN & OPEN BURN DATA TABLE	Kiln Burns											Open Burns			
Burn Number & Year	**1-23**	**2-23**	**3-23**	**6-23**	**7-23**	**1-24**	**2-24**	**3-24**	**6-24**	**7-24**	**8-24**	**5-23**	**8-23**	**4-24**	**5-24**
Seq. Numbering	**1**	**2**	**3**	**6**	**7**	**9**	**10**	**11**	**14**	**15**	**16**	**5**	**8**	**12**	**13**
Kiln Configuration	Hexagon	Hexagon	Hexagon	Rectangle	Square	Rectangle	Rectangle	Rectangle	Rectangle	Rectangle	Rectangle	Burn Pile	Burn Pile	Burn Pile	Burn Pile
Feedstock Weight (lb)	3049.8	2465.2	2667.0	2315.4	1088.4	2004.9	2912.0	1940.0	2000.0	2060.0	1995.0	934.0	588.1	560.0	540.0
Feedstock Weight (kg)	1383.4	1118.2	1209.7	1050.2	493.7	909.4	1320.9	880.0	907.2	934.4	904.9	423.7	266.8	254.0	244.9
Feedstock Moisture %	50.0	33.4	51.6	47.8	26.3	21.3	32.9	21.8	32.5	20.2	17.7	50.6	46.8	39.0	19.4
Feedstock Dry Weight (lb)	1523.7	1642.4	1290.8	1208.6	802.2	1577.9	1954.0	1517.1	1350.2	1643.1	1641.8	461.4	312.9	341.7	435.3
Feedstock Dry Weight (kg)	691.1	745.0	585.5	548.2	363.8	715.7	886.3	688.1	612.4	745.3	744.7	209.3	141.9	155.0	197.5
Unburned Fuel Wt. (lb)	56.1	47.9	33.2	109.5	51.2	59.0	491.1	109.3	96.2	28.4	121.2	4.1	2.6	29.6	3.0
Unburned Fuel Wt. (kg)	25.4	21.7	15.1	49.7	23.2	26.8	222.8	49.6	43.6	12.9	55.0	1.8	1.2	13.4	1.4
Unburned Fuel Moisture %	14.7	24.8	19.5	24.9	10.6	10.8	21.2	18.2	9.7	1.2	5.6	10.0	13.8	15.5	1.0
Unburned Fuel Dry Weight (lb)	47.9	36.0	26.7	82.2	45.8	52.6	387.0	109.3	86.9	28.0	114.4	3.6	2.2	25.0	3.0
Unburned Fuel Dry Weight (kg)	21.7	16.3	12.1	37.3	20.8	23.9	175.5	49.6	39.4	12.7	51.9	1.7	1.0	11.3	1.3
FS - Unburned Dry Weight (lb)	1475.8	1606.4	1264.1	1126.4	756.4	1525.2	1567.0	1407.8	1263.3	1615.0	1527.4	457.8	310.6	316.7	432.4
FS - Unburned Dry Weight (kg)	669.4	728.6	573.4	510.9	343.1	691.8	710.8	638.6	573.0	732.6	692.8	207.6	140.9	143.6	196.1
% Feedstock DW to Unburned DW	3.1	2.2	2.1	6.8	5.7	3.3	19.8	7.2	6.4	1.7	7.0	0.8	0.7	7.3	0.7
Char Volume (gal)						227.0	284.0	282.0	265.0	340	302.0			30.0	30.0
Char Volume (ft^3)	38.1	32.9	23.9	49.7	27.7	30.3	38.0	37.7	35.4	45.5	40.4			4.0	4.0
Char Volume (m^3)	1.1	0.9	0.7	1.4	0.8	0.9	1.1	1.1	1.0	1.3	1.1			0.1	0.1
Dry Char Bulk Density (lb/ft^3)	7.2	9.9	10.3	7.5	7.6	10.2	10.9	11.2	10.9	9.7	9.9	6.9	13.9	10.2	17.4
Dry Char Bulk Density (kg/m^3)	10.7	14.7	15.3	11.1	11.2	15.2	16.3	16.7	16.3	14.4	14.7	10.2	20.7	15.1	25.8
Char Dry Weight (lb)	274.0	323.9	246.1	370.1	208.9	309.5	415.5	421.8	387.2	439.3	397.8	33.4	41.8	40.8	69.6
Char Dry Weight (kg)	124.3	146.9	111.6	167.9	94.8	140.4	188.5	191.3	175.6	199.3	180.4	15.1	18.9	18.5	31.6
Char % of Feedstock Weight	18.6	20.2	19.5	32.9	27.6	20.3	26.5	30.0	30.6	27.2	26.0	7.3	13.4	12.9	16.1
Feedstock Carbon % [1]	51.4	48.0	51.1	51.0	49.8	50.0	49.2	49.1	49.3	49.6	49.5	50.5	51.9	49.2	49.2
Feedstock Carbon Weight (lb)	758.0	771.1	646.0	574.5	377.0	762.6	770.9	691.2	622.8	801.0	756.0	231.2	161.2	155.8	212.7
Feedstock Carbon Weight (kg)	343.8	349.7	293.0	260.6	171.0	345.9	349.7	313.5	282.5	363.3	342.9	104.9	73.1	70.7	96.5
Char Carbon % [2]	57.54	72.16	60.60	73.54	78.90	77.3	79.7	76.2	79.8	82.9	85.1	55.3	34.0	76.2	50.2
Char Carbon Weight (kg)	157.6	233.7	149.2	272.2	164.8	239.3	331.0	321.6	309.0	364.4	338.5	18.5	14.2	31.1	34.9
Char Carbon Weight (lb)	71.5	106.0	67.7	123.5	74.8	108.5	150.2	145.9	140.2	165.3	153.6	8.4	6.4	14.1	15.8
% Feedstock C to Char C [3]	**20.8**	**30.3**	**23.1**	**47.4**	**43.7**	**31.4**	**42.9**	**46.5**	**49.6**	**45.5**	**44.8**	**8.0**	**8.8**	**20.0**	**16.4**
% Feedstock C to Char C by Year	**33.1**					**43.5**						**8.4**		**18.2**	
% Feedstock C to Char C Both Years	**38.7**											**13.3**			

1. Feedstock Carbon % was calculated as admixtures of fuels using data from Appendix C.

2. Average of 5 samples per burn determined by laboratory analysis.

3. Char Carbon as a percent of Feedstock Carbon, dry weight basis.

Missing values in 2023 char volume rows reflects different methods from 2003 to 2004 (see METHODS).

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APPENDIX F: Emissions Measurements

Test ID			Burn 1	Burn 2	Burn 3	Burn 4 [Not Used]	Burn 5	Burn 6	Burn 7	Burn 8
Burn-Year ID			1-23	2-23	3-23	4-23	5-23	6-23	7-23	8-23
Date			16 Oct 2023	17 Oct 2023	18 Oct 2023	19 Oct 2023	23 Oct 2023	24 Oct 2023	26 Oct 2023	27 Oct 2023
kiln			hexagon kiln	hexagon kiln	hexagon kiln	hexagon kiln	open pile	4X8 rectangle kiln	4X4 square kiln	open pile
fuel type			green branches	green branches	green branches	green branches	seasoned branches	green branches	branches, brush	green branches
fuel species			pine, juniper	oak	pine, juniper	pine, juniper	pine	spruce, pine, juniper	hardwoods	pine, juniper
variable name	units	metric description	value ± unc	value ± unc	value ± unc	value ± unc	value ± unc	value ± unc	value ± unc	value ± unc
burn time	hrs	burn time	5.17 ± 0.00	5.13 ± 0.00	5.26 ± 0.00	4.75 ± 0.00	3.43 ± 0.00	3.69 ± 0.00	3.32 ± 0.00	2.95 ± 0.00
$M_{fuel,wb}$	kg	mass of raw fuel loaded	1342 ± 67	1094 ± 55	1186 ± 59	978 ± 49	421 ± 21	976 ± 49	466 ± 23	265 ± 13
$M_{fuel,db}$	kg	mass of fuel loaded, dry basis	671 ± 75	729 ± 66	574 ± 66	493 ± 55	208 ± 23	509 ± 55	343 ± 29	135 ± 15
$MC_{fuel,wb}$	%	fuel moisture content, wet basis	50.0 ± 5.0	33.4 ± 5.0	51.6 ± 5.0	49.6 ± 5.0	50.6 ± 5.0	47.8 ± 5.0	26.3 ± 5.0	49.0 ± 5.0
$CFrac_{dryfuel}$	g/g	fuel carbon fraction, dry basis	0.51 ± 0.03	0.48 ± 0.03	0.51 ± 0.03	0.50 ± 0.03	0.50 ± 0.03	0.51 ± 0.03	0.50 ± 0.03	0.51 ± 0.03
$M_{char,db}$	kg	mass of char produced, dry basis	119.0 ± 17.0	143.0 ± 21.0	107.0 ± 15.5	37.3 ± 5.3	10.2 ± 1.5	156.0 ± 23.0	91.3 ± 13.2	16.3 ± 2.3
$CFrac_{dryfuel}$	g/g	carbon fraction of char produced	0.58 ± 0.06	0.72 ± 0.07	0.61 ± 0.06	0.64 ± 0.06	0.55 ± 0.06	0.74 ± 0.07	0.79 ± 0.08	0.34 ± 0.03
char yield	g/g	char producion per fuel mass	0.18 ± 0.03	0.20 ± 0.03	0.19 ± 0.03	0.08 ± 0.01	0.05 ± 0.01	0.31 ± 0.06	0.27 ± 0.04	0.12 ± 0.02
MCE	mol/mol	modified combustion efficiency	0.94 ± 0.00	0.95 ± 0.00	0.92 ± 0.00	0.91 ± 0.00	0.93 ± 0.00	0.91 ± 0.00	0.95 ± 0.00	0.90 ± 0.01
$EF_{CO,dryfuel}$	$g/kg_{dryfuel}$	emission factor, dry fuel mass : grams pollutant per kg fuel loaded, dry basis	61.0 ± 12.3	40.8 ± 7.7	72.0 ± 14.9	95.3 ± 17.6	71.7 ± 13.6	57.3 ± 14.5	36.1 ± 7.7	105.3 ± 19.7
$EF_{CO2,dryfuel}$	$g/kg_{dryfuel}$		1384 ± 270	1169 ± 211	1325 ± 267	1486 ± 264	1607 ± 283	938 ± 234	1000 ± 206	1534 ± 275
$EF_{NO,dryfuel}$	$g/kg_{dryfuel}$		1.03 ± 0.49	1.20 ± 0.50	0.95 ± 0.44	1.03 ± 0.84	0.70 ± 1.50	1.13 ± 0.49	1.19 ± 0.46	1.84 ± 0.94
$EF_{NO2,dryfuel}$	$g/kg_{dryfuel}$		2.68 ± 0.89	2.11 ± 0.80	1.64 ± 0.70	2.25 ± 1.34	1.32 ± 2.31	0.47 ± 0.58	1.06 ± 0.62	0.51 ± 1.28
$EF_{VOC,dryfuel}$	$g/kg_{dryfuel}$		3.09 ± 1.74	1.77 ± 1.63	4.34 ± 1.75	8.31 ± 3.55	3.40 ± 5.64	5.34 ± 2.03	2.82 ± 1.54	10.33 ± 3.87
$EF_{HC,dryfuel}$	$g/kg_{dryfuel}$		14.3 ± 5.6	8.2 ± 4.9	24.3 ± 6.8	11.6 ± 9.0	25.2 ± 17.1	23.9 ± 7.6	7.9 ± 4.4	34.4 ± 11.7
$EF_{CH4,dryfuel}$	$g/kg_{dryfuel}$		4.50 ± 1.43	3.01 ± 0.93	5.32 ± 1.71	7.04 ± 2.16	5.30 ± 1.63	4.23 ± 1.49	2.67 ± 0.87	7.78 ± 2.39
$EF_{PM,dryfuel}$	$g/kg_{dryfuel}$		5.64 ± 1.12	2.98 ± 0.55	5.45 ± 1.12	11.13 ± 2.03	5.58 ± 1.02	4.88 ± 1.23	1.90 ± 0.40	8.14 ± 1.49
$EF_{OC,dryfuel}$	$g/kg_{dryfuel}$		3.77 ± 0.79	2.14 ± 0.42	3.97 ± 0.85	8.47 ± 1.63	5.78 ± 1.13	3.67 ± 0.95	1.92 ± 0.42	6.51 ± 1.27
$EF_{EC,dryfuel}$	$g/kg_{dryfuel}$		0.23 ± 0.05	0.06 ± 0.02	0.19 ± 0.04	0.18 ± 0.04	0.15 ± 0.05	0.15 ± 0.04	0.17 ± 0.04	0.27 ± 0.06
$EF_{CO,fuel}$	g/kg_{fuel}	emission factor, fuel mass: grams pollutant per kg raw fuel loaded, wet basis	30.5 ± 5.3	27.1 ± 4.8	34.9 ± 6.3	48.0 ± 7.6	35.4 ± 5.7	29.9 ± 7.7	26.6 ± 5.7	53.8 ± 8.2
$EF_{CO2,fuel}$	g/kg_{fuel}		692 ± 116	779 ± 133	641 ± 112	749 ± 111	794 ± 114	490 ± 123	737 ± 152	783 ± 113
$EF_{NO,fuel}$	g/kg_{fuel}		0.51 ± 0.24	0.80 ± 0.33	0.46 ± 0.21	0.52 ± 0.42	0.34 ± 0.74	0.59 ± 0.26	0.88 ± 0.34	0.94 ± 0.47
$EF_{NO2,fuel}$	g/kg_{fuel}		1.34 ± 0.42	1.41 ± 0.52	0.79 ± 0.33	1.14 ± 0.67	0.65 ± 1.14	0.24 ± 0.31	0.78 ± 0.46	0.26 ± 0.65
$EF_{VOC,fuel}$	g/kg_{fuel}		1.55 ± 0.86	1.18 ± 1.08	2.10 ± 0.82	4.19 ± 1.74	1.68 ± 2.78	2.79 ± 1.06	2.08 ± 1.13	5.27 ± 1.89
$EF_{HC,fuel}$	g/kg_{fuel}		7.14 ± 2.70	5.45 ± 3.25	11.78 ± 3.08	5.82 ± 4.53	12.47 ± 8.36	12.50 ± 3.98	5.82 ± 3.22	17.57 ± 5.65
$EF_{CH4,fuel}$	g/kg_{fuel}		2.25 ± 0.68	2.01 ± 0.61	2.58 ± 0.79	3.55 ± 1.03	2.62 ± 0.76	2.21 ± 0.78	1.96 ± 0.64	3.97 ± 1.15
$EF_{PM,fuel}$	g/kg_{fuel}		2.82 ± 0.48	1.99 ± 0.35	2.64 ± 0.47	5.61 ± 0.86	2.76 ± 0.42	2.55 ± 0.65	1.40 ± 0.29	4.15 ± 0.62
$EF_{OC,fuel}$	g/kg_{fuel}		1.89 ± 0.34	1.43 ± 0.27	1.92 ± 0.36	4.27 ± 0.71	2.86 ± 0.48	1.91 ± 0.50	1.41 ± 0.31	3.32 ± 0.54
$EF_{EC,fuel}$	g/kg_{fuel}		0.11 ± 0.02	0.04 ± 0.01	0.09 ± 0.02	0.09 ± 0.02	0.07 ± 0.02	0.08 ± 0.02	0.12 ± 0.03	0.14 ± 0.03
$EF_{CO,char}$	g/kg_{char}	emission factor, char: grams pollutant per kg char produced	61.0 ± 12.3	40.8 ± 7.7	72.0 ± 14.9	95.3 ± 17.6	71.7 ± 13.6	57.3 ± 14.5	36.1 ± 7.7	105.3 ± 19.7
$EF_{CO2,char}$	g/kg_{char}		7808 ± 1673	5961 ± 1278	7112 ± 1567	19653 ± 3898	32774 ± 6541	3064 ± 823	3764 ± 892	12742 ± 2549
$EF_{NO,char}$	g/kg_{char}		5.79 ± 2.79	6.13 ± 2.65	5.12 ± 2.41	13.64 ± 11.21	14.18 ± 30.57	3.69 ± 1.64	4.48 ± 1.83	15.30 ± 7.91
$EF_{NO2,char}$	g/kg_{char}		15.10 ± 5.18	10.76 ± 4.25	8.81 ± 3.83	29.79 ± 17.97	27.00 ± 47.14	1.53 ± 1.91	3.98 ± 2.38	4.22 ± 10.60
$EF_{VOC,char}$	g/kg_{char}		17.4 ± 9.9	9.0 ± 8.4	23.3 ± 9.6	109.9 ± 47.9	69.4 ± 115.2	17.5 ± 6.9	10.6 ± 5.9	85.8 ± 33.1
$EF_{HC,char}$	g/kg_{char}		80.5 ± 32.3	41.7 ± 25.4	130.6 ± 38.4	152.8 ± 120.4	514.7 ± 352.6	78.3 ± 26.0	29.7 ± 16.8	285.9 ± 100.1
$EF_{CH4,char}$	g/kg_{char}		25.4 ± 8.4	15.3 ± 5.1	28.6 ± 9.5	93.0 ± 29.7	108.0 ± 34.9	13.8 ± 5.1	10.0 ± 3.5	64.6 ± 20.7
$EF_{PM,char}$	g/kg_{char}		31.8 ± 6.9	15.2 ± 3.3	29.2 ± 6.5	147.1 ± 29.8	113.9 ± 23.5	15.9 ± 4.3	7.1 ± 1.7	67.6 ± 13.8
$EF_{OC,char}$	g/kg_{char}		21.3 ± 4.8	10.9 ± 2.5	21.3 ± 4.9	112.0 ± 23.8	118.0 ± 25.6	12.0 ± 3.3	7.2 ± 1.8	54.0 ± 11.6
$EF_{EC,char}$	g/kg_{char}		1.30 ± 0.30	0.33 ± 0.09	1.02 ± 0.24	2.43 ± 0.58	3.03 ± 1.04	0.47 ± 0.14	0.63 ± 0.17	2.25 ± 0.55
OC/TC	g/g	particulate EC to TC ratio	0.94 ± 0.08	0.97 ± 0.09	0.95 ± 0.08	0.98 ± 0.09	0.97 ± 0.09	0.96 ± 0.09	0.92 ± 0.08	0.96 ± 0.09
TC/PM	g/g	particulate TC to PM ratio	0.71 ± 0.04	0.74 ± 0.05	0.76 ± 0.05	0.78 ± 0.05	1.06 ± 0.07	0.78 ± 0.05	1.10 ± 0.07	0.83 ± 0.05
AAE_RB	-	absorption angstrom exponent	1.56 ± 0.00	1.68 ± 0.00	1.67 ± 0.00		1.62 ± 0.00	1.58 ± 0.00	1.21 ± 0.00	1.61 ± 0.00

Test ID			Burn 9	Burn 10	Burn 11	Burn 12	Burn 13	Burn 14	Burn 15	Burn 16
Burn-Year ID			1-24	2-24	3-24	4-24	5-24	6-24	7-24	8-24
Date			16 Oct 2024	17 Oct 2024	21 Oct 2024	22 Oct 2024	22 Oct 2024	23 Oct 2024	25 Oct 2024	26 Oct 2024
kiln			4X8 rectangle kiln	4X8 rectangle kiln	4X8 rectangle kiln	open pile	open pile	4X8 rectangle kiln	4X8 rectangle kiln	4X8 rectangle kiln
fuel type			mixed branches	mixed branches	mixed branches	mixed branches	mixed branches	mixed branches	mixed branches	mixed branches
fuel species			mixed conifer	mixed conifer	mixed conifer	mixed conifer	mixed conifer	mixed conifer	mixed conifer	mixed conifer
variable name	units	metric description	value ± unc	value ± unc	value ± unc	value ± unc	value ± unc	value ± unc	value ± unc	value ± unc
burn time	hrs	burn time	2.52 ± 0.00	2.74 ± 0.00	2.45 ± 0.00	2.00 ± 0.00	2.00 ± 0.00	2.18 ± 0.00	2.42 ± 0.00	1.87 ± 0.00
$M_{fuel,wb}$	kg	mass of raw fuel loaded	881 ± 44	1049 ± 52	828 ± 41	235 ± 12	244 ± 12	850 ± 43	920 ± 46	843 ± 42
$M_{fuel,db}$	kg	mass of fuel loaded, dry basis	693 ± 56	704 ± 63	647 ± 52	143 ± 14	197 ± 16	574 ± 51	734 ± 59	694 ± 55
$MC_{fuel,wb}$	%	fuel moisture content, wet basis	21.3 ± 5.0	32.9 ± 5.0	21.8 ± 5.0	39.0 ± 5.0	19.4 ± 5.0	32.5 ± 5.0	20.2 ± 5.0	17.7 ± 5.0
$CFrac_{dryfuel}$	g/g	fuel carbon fraction, dry basis	0.50 ± 0.03	0.49 ± 0.03	0.49 ± 0.03	0.49 ± 0.03	0.49 ± 0.03	0.49 ± 0.03	0.50 ± 0.03	0.50 ± 0.03
$M_{char,db}$	kg	mass of char produced, dry basis	140.7 ± 19.9	189.0 ± 26.7	192.0 ± 27.0	18.6 ± 2.6	31.6 ± 4.5	176.0 ± 24.9	200.0 ± 28.2	180.8 ± 25.6
$CFrac_{dryfuel}$	g/g	carbon fraction of char produced	0.77 ± 0.02	0.80 ± 0.02	0.76 ± 0.02	0.76 ± 0.02	0.50 ± 0.01	0.80 ± 0.02	0.83 ± 0.03	0.85 ± 0.03
char yield	g/g	char producion per fuel mass	0.20 ± 0.03	0.27 ± 0.04	0.30 ± 0.05	0.13 ± 0.02	0.16 ± 0.03	0.31 ± 0.05	0.27 ± 0.04	0.26 ± 0.04
MCE	mol/mol	modified combustion efficiency	0.97 ± 0.00	0.96 ± 0.00	0.98 ± 0.00	0.93 ± 0.00	0.92 ± 0.00	0.97 ± 0.00	0.98 ± 0.00	0.98 ± 0.00
$EF_{CO,dryfuel}$	$g/kg_{dryfuel}$	emission factor, dry fuel mass : grams pollutant per kg fuel loaded, dry basis	21.9 ± 3.8	26.4 ± 5.6	14.8 ± 3.1	66.6 ± 11.7	71.0 ± 10.9	14.8 ± 3.5	13.4 ± 2.7	12.8 ± 2.6
$EF_{CO2,dryfuel}$	$g/kg_{dryfuel}$		1221 ± 200	962 ± 199	944 ± 193	1319 ± 222	1374 ± 201	871 ± 201	979 ± 194	998 ± 193
$EF_{NO,dryfuel}$	$g/kg_{dryfuel}$		1.44 ± 0.35	0.86 ± 0.25	1.08 ± 0.28	1.41 ± 0.55	1.19 ± 0.41	0.94 ± 0.32	1.03 ± 0.27	0.93 ± 0.28
$EF_{NO2,dryfuel}$	$g/kg_{dryfuel}$		0.60 ± 0.36	0.70 ± 0.29	0.44 ± 0.25	0.91 ± 0.74	0.08 ± 0.51	0.33 ± 0.33	0.43 ± 0.24	0.71 ± 0.34
$EF_{VOC,dryfuel}$	$g/kg_{dryfuel}$		1.63 ± 0.89	2.15 ± 0.78	0.83 ± 0.58	4.08 ± 1.95	4.61 ± 1.55	0.65 ± 0.78	0.65 ± 0.55	0.56 ± 0.73
$EF_{HC,dryfuel}$	$g/kg_{dryfuel}$		14.6 ± 3.7	17.6 ± 4.3	6.6 ± 2.2	13.8 ± 5.8	14.1 ± 4.5	8.2 ± 3.1	14.1 ± 3.4	9.4 ± 2.9
$EF_{CH4,dryfuel}$	$g/kg_{dryfuel}$		1.65 ± 0.28	2.03 ± 0.43	0.91 ± 0.19	3.89 ± 0.69	5.77 ± 0.89	0.99 ± 0.24	1.04 ± 0.21	0.94 ± 0.19
$EF_{PM,dryfuel}$	$g/kg_{dryfuel}$		1.22 ± 0.20	1.44 ± 0.30	0.84 ± 0.17	2.31 ± 0.40	2.98 ± 0.45	0.74 ± 0.17	0.42 ± 0.08	0.60 ± 0.12
$EF_{OC,dryfuel}$	$g/kg_{dryfuel}$		0.63 ± 0.11	0.99 ± 0.22	0.34 ± 0.07	2.02 ± 0.37	2.29 ± 0.37	0.39 ± 0.09	0.28 ± 0.06	0.29 ± 0.06
$EF_{EC,dryfuel}$	$g/kg_{dryfuel}$		0.38 ± 0.07	0.18 ± 0.04	0.41 ± 0.09	0.23 ± 0.05	0.36 ± 0.06	0.31 ± 0.08	0.45 ± 0.09	0.31 ± 0.06
$EF_{CO,fuel}$	g/kg_{fuel}	emission factor, fuel mass: grams pollutant per kg raw fuel loaded, wet basis	17.2 ± 2.8	17.7 ± 3.8	11.6 ± 2.5	40.6 ± 6.5	57.2 ± 7.9	10.0 ± 2.5	10.7 ± 2.2	10.5 ± 2.1
$EF_{CO2,fuel}$	g/kg_{fuel}		961 ± 151	645 ± 136	738 ± 152	805 ± 122	1108 ± 144	588 ± 142	781 ± 157	821 ± 160
$EF_{NO,fuel}$	g/kg_{fuel}		1.13 ± 0.27	0.58 ± 0.17	0.84 ± 0.22	0.86 ± 0.33	0.96 ± 0.32	0.63 ± 0.22	0.82 ± 0.21	0.76 ± 0.23
$EF_{NO2,fuel}$	g/kg_{fuel}		0.47 ± 0.28	0.47 ± 0.20	0.34 ± 0.20	0.56 ± 0.45	0.07 ± 0.41	0.22 ± 0.22	0.34 ± 0.19	0.58 ± 0.28
$EF_{VOC,fuel}$	g/kg_{fuel}		1.28 ± 0.70	1.44 ± 0.52	0.65 ± 0.46	2.49 ± 1.18	3.72 ± 1.22	0.44 ± 0.53	0.52 ± 0.44	0.46 ± 0.60
$EF_{HC,fuel}$	g/kg_{fuel}		11.48 ± 2.82	11.81 ± 2.90	5.14 ± 1.73	8.42 ± 3.47	11.40 ± 3.56	5.55 ± 2.10	11.21 ± 2.74	7.72 ± 2.43
$EF_{CH4,fuel}$	g/kg_{fuel}		1.30 ± 0.21	1.36 ± 0.29	0.71 ± 0.15	2.37 ± 0.38	4.65 ± 0.65	0.67 ± 0.17	0.83 ± 0.17	0.77 ± 0.16
$EF_{PM,fuel}$	g/kg_{fuel}		0.96 ± 0.15	0.97 ± 0.21	0.65 ± 0.14	1.41 ± 0.22	2.40 ± 0.32	0.50 ± 0.12	0.33 ± 0.07	0.49 ± 0.10
$EF_{OC,fuel}$	g/kg_{fuel}		0.50 ± 0.09	0.67 ± 0.15	0.27 ± 0.06	1.23 ± 0.21	1.85 ± 0.28	0.26 ± 0.07	0.22 ± 0.05	0.24 ± 0.05
$EF_{EC,fuel}$	g/kg_{fuel}		0.30 ± 0.05	0.12 ± 0.03	0.32 ± 0.07	0.14 ± 0.03	0.29 ± 0.04	0.21 ± 0.05	0.36 ± 0.08	0.26 ± 0.05
$EF_{CO,char}$	g/kg_{char}	emission factor, char: grams pollutant per kg char produced	21.9 ± 3.8	26.4 ± 5.6	14.8 ± 3.1	66.6 ± 11.7	71.0 ± 10.9	14.8 ± 3.5	13.4 ± 2.7	12.8 ± 2.6
$EF_{CO2,char}$	g/kg_{char}		6016 ± 1210	3581 ± 839	3184 ± 746	10172 ± 1997	8555 ± 1601	2839 ± 726	3594 ± 826	3830 ± 866
$EF_{NO,char}$	g/kg_{char}		7.11 ± 1.92	3.20 ± 1.00	3.64 ± 1.04	10.90 ± 4.41	7.40 ± 2.69	3.05 ± 1.08	3.78 ± 1.07	3.56 ± 1.16
$EF_{NO2,char}$	g/kg_{char}		2.96 ± 1.80	2.61 ± 1.13	1.47 ± 0.86	7.05 ± 5.76	0.50 ± 3.20	1.06 ± 1.07	1.57 ± 0.90	2.71 ± 1.34
$EF_{VOC,char}$	g/kg_{char}		8.0 ± 4.5	8.0 ± 3.0	2.8 ± 2.0	31.5 ± 15.4	28.7 ± 10.2	2.1 ± 2.6	2.4 ± 2.0	2.1 ± 2.8
$EF_{HC,char}$	g/kg_{char}		71.9 ± 19.8	65.6 ± 17.4	22.2 ± 7.8	106.4 ± 45.9	88.0 ± 29.9	26.8 ± 10.4	51.6 ± 13.8	36.0 ± 12.0
$EF_{CH4,char}$	g/kg_{char}		8.1 ± 1.7	7.6 ± 1.8	3.1 ± 0.7	30.0 ± 6.1	35.9 ± 7.0	3.2 ± 0.8	3.8 ± 0.9	3.6 ± 0.8
$EF_{PM,char}$	g/kg_{char}		6.0 ± 1.2	5.4 ± 1.3	2.8 ± 0.7	17.8 ± 3.6	18.5 ± 3.5	2.4 ± 0.6	1.5 ± 0.4	2.3 ± 0.5
$EF_{OC,char}$	g/kg_{char}		3.1 ± 0.7	3.7 ± 0.9	1.2 ± 0.3	15.6 ± 3.3	14.3 ± 2.9	1.3 ± 0.3	1.0 ± 0.2	1.1 ± 0.3
$EF_{EC,char}$	g/kg_{char}		1.85 ± 0.40	0.69 ± 0.17	1.39 ± 0.34	1.80 ± 0.39	2.23 ± 0.46	1.00 ± 0.27	1.64 ± 0.39	1.19 ± 0.29
OC/TC	g/g	particulate EC to TC ratio	0.63 ± 0.05	0.84 ± 0.07	0.45 ± 0.04	0.90 ± 0.08	0.86 ± 0.08	0.56 ± 0.05	0.38 ± 0.03	0.48 ± 0.04
TC/PM	g/g	particulate TC to PM ratio	0.83 ± 0.05	0.81 ± 0.05	0.91 ± 0.05	0.97 ± 0.06	0.89 ± 0.05	0.95 ± 0.05	1.74 ± 0.09	1.00 ± 0.06
AAE_RB	-	absorption angstrom exponent		1.30 ± 0.00	1.00 ± 0.00	1.32 ± 0.00	1.20 ± 0.00	1.03 ± 0.00	0.97 ± 0.00	1.03 ± 0.00