Producing, Characterizing and Quantifying Biochar in the Woods Using Portable Flame Cap Kilns

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Citation

Wilson, K.J., Bekker, W., Feher, S.I. Producing, Characterizing and Quantifying Biochar in the Woods Using Portable Flame Cap Kilns. *J. Vis. Exp.* (203), e65543, doi:10.3791/65543 (2024).

Date Published

January 5, 2024

DOI

10.3791/65543

URL

jove.com/video/65543

Abstract

One of the biggest challenges in utilizing non-commercial forest biomass is its widely distributed nature. The best solution to the biomass problem, to avoid expensive and carbon-intensive processing (chipping) and transportation costs, is to process it onsite. However, conventional burn piles have destructive impacts on forest soil and provide no benefits other than fuel reduction. Converting forest slash to biochar onsite has many ecological advantages over the current practice of slash disposal by incineration in burn piles, including reduced soil heating and particulate emissions, along with multiple benefits of the biochar to forest soil health and water holding capacity when left in place. Making biochar onsite in the woods is a way to return a pyrogenic carbon component to forest soils that has been missing due to the recent history of fire suppression. Biochar is also a leading method of carbon removal and sequestration for climate change mitigation. In this study, we document a method for making biochar using a portable biochar kiln. This low-cost method utilizes hand crews equipped with water for quenching kilns before the biochar burns to ash. Simple techniques for quantifying and characterizing the biochar produced are incorporated into the method for the purpose of measuring impact and qualifying for carbon removal certificates to help pay for the cost of the work. We describe the CM002 Component Methodology that provides standardized procedures for the quantification of GHG benefits during three stages of the process: waste biomass sourcing, biochar production, and biochar soil application. The CM002 Methodology is based on international best practices, including the most recent VCS methodology VM0044 Standards and EBC C-Sink Artisan Standards. Reliable quantification methods utilizing appropriate safety factors are the first essential step toward eligibility for carbon removal finance.

Introduction

In many world regions, including the western US, climate change, drought, and alien invasive species have created a wildfire crisis that threatens ecosystems and communities. As forests and woodlands burn uncontrollably, large amounts of particulates and greenhouse gasses are emitted into the atmosphere, with devastating consequences for human health and the climate. For instance, wildfires in California in 2020 are estimated to have released around 127 million megatons of greenhouse gas emissions, approximately two times the amount of California's total GHG emission reductions from 2003 to 2019[1]. Increasingly, scientists and land managers are investigating human actions that can help restore these forests and woodlands and their ecosystem services. The manual thinning and removal of excess biomass is one of the most important actions that must be taken[2]. Removal of biomass includes its disposal, and where the biomass is situated in remote and difficult-to-access locations, there are few options other than incineration onsite in unmanaged slash piles. Unmanaged burn piles do the job of removing fuels from the landscape, but they damage forest soils as the concentrated heat under the piles incinerates the soil's organic horizon, leaving behind bare soil that is vulnerable to erosion and colonization by invasive species. It can take decades to regenerate the organic soil horizon in a burn pile scar[3]. Unmanaged burn piles are also a source of particulate and greenhouse gas emissions. Smoke from slash pile burning also restricts the burning window in air-quality-limited watersheds, making it more difficult to accomplish the work.

Researchers for the USDA Forest Service have examined the alternative of producing biochar from slash materials, and have identified several promising techniques, including the option of using small, mobile biochar kilns in the forest[4]. Converting forest slash to biochar onsite has many ecological advantages over the current practice of slash disposal by incineration in burn piles, including reduced soil heating and particulate emissions. Biochar produced onsite can be removed and utilized in agriculture, or it can be left in place where it serves several functions in restoring forest health and improving adaptation to climate change and drought. Because up to 50% of the total carbon in many forest soils is charcoal from historic, natural fires[5], leaving biochar on the site where it is made can restore forest soil charcoal that is often missing from recent soil horizons due to fire suppression, with unknown impacts on ecosystem processes[6]. Biochar left in place on forest soils can mimic the effects of charcoal produced by natural fire and produce similar effects on soil carbon content and soil physical, chemical and biological properties[7].

In recent years, an international network of forestry workers, woodland owners, researchers, and biochar consultants has developed a suite of carbonization methods for converting forest slash into biochar onsite as an alternative to slash pile incineration. These methods are based on the principle of flame carbonization, first developed and commercialized in Japan as the "smokeless carbonizing kiln" offered by the Moki company[8]. This steel ring kiln makes well-carbonized biochar with reported biomass-to-biochar conversion efficiency of 13% to 20%, depending on the feedstock used[9].

The process of producing biochar or charcoal is often referred to as pyrolysis, the separation of biomass components by heat in the absence of oxygen. This is usually conceived of as retort pyrolysis, where biomass is physically isolated from air in an externally heated vessel. However, pyrolysis can also take place in the presence of limited air, as in gasification and flame carbonization, because solid fuels like wood burn in stages. When heat is applied to biomass, the first stage of combustion is dehydration, as water is evaporated from the material. This is followed by devolatilization and simultaneous char formation, also known as pyrolysis. Volatile gas containing hydrogen and oxygen is released and burned in a flame, continually adding heat to the process. As the gas is released, the remaining carbon is converted to aromatic carbon, or char. The final stage of combustion is the oxidation of the char to mineral ash[10].

Because these are discrete phases that occur in an open combustion process, we have the opportunity to stop the process after char formation by removing air or heat. This is accomplished during the biochar production process by continually adding new material to the burn pile so that the hot char is buried by new material that cuts off the flow of oxygen. Hot charcoal accumulates in the bottom of the pile and is prevented from burning to ash as long as flame is present, because the flame consumes most of the available oxygen. When all of the fuel has been added to the pile, the flame begins to die down. At that point, the hot charcoal can be preserved by removing oxygen and heat, usually by spraying the coals with water and raking them thin to cool[11].

The basic principle of operation is that of counter-flow combustion. Counter-flow combustion air keeps the flame low and prevents the emission of embers or sparks. The flame also burns most of the smoke, reducing emissions. In summary, the following principles explain the operation of counter-flow combustion in a flame cap kiln: (1) Gas flows upward while combustion air flows downward, (2) Counter-current flow is established as burning fuel draws air downward, (3) Flames stay low and close to fuel, minimizing ember escape, (4) Smoke burns in the hot zone, (5) Because all the combustion air comes from above, it is consumed by the flames (6) Very little air is able to reach the unburned coals that fall to the bottom of the kiln, (7) The coals are preserved until the end of the process when they are quenched or snuffed.

In addition to its benefits to soil, biochar is also a leading method of carbon removal for climate change mitigation. Up to half the carbon in woody biomass can be converted to stable, aromatic carbon in the form of biochar[12]. However, not all pyrolysis technologies produce the same amount of recalcitrant carbon that remains stable in soils for 100 years or more (the key metric for determining carbon removal value). Biochar stability is closely correlated with the temperature of production. The adiabatic flame temperature of burning wood is estimated to be close to that of propane, 1,977 °C[13]. Biochar production in a flame cap kiln is closely coupled with the flame, with no heat transfer losses by conduction through a metal wall, as in retort pyrolysis. Therefore, we would expect that the temperature of production would be high as long as a flame is maintained during the process. A survey of chars using Raman spectroscopy[14] reported that a biochar sample from a flame cap kiln (provided by lead author Kelpie Wilson) was among the three samples with the highest apparent temperature of char formation, in the range of 900 °C.

Thermocouples are required to access the interior of the burn and accurately measure the production temperature of biochar in a flame cap kiln or burn pile, and these are expensive and not available to low-tech producers. Therefore, we have used a method described by researchers working in the Brazilian Amazon that uses heat crayons (used by welders to check the temperature of metal parts) that melt at a calibrated temperature[15]. Bricks are marked with crayons, wrapped in aluminum foil, and placed in various places in the kiln during production. We used this method several times and determined that the kiln temperatures exceeded 650° C, as the crayon marks were completely melted. This will be a useful method to confirm production temperatures where needed; however, the main verification point will be documenting the presence of flame throughout.

There is not much published data on the characteristics of biochar made by low-tech flame carbonizing methods. However, biochar samples made by flame carbonizing methods in several kiln types were analyzed by Cornellissen et al. and found to meet European Biochar Certificate (EBC) standards for biochar, including low PAH content and high biochar stability. Furthermore, the biochar produced from both woody and herbaceous feedstocks had an average carbon content of 76 percent[11]. The US Forest Service Rocky Mountain Research Station[16] analyzed five biochar samples from flame cap kilns and burn piles made at a field day in California in 2022. The average carbon content of the samples was 85 percent. Given these results, we can conclude that it is likely that biochar made from woody residues in flame cap kilns will meet the basic requirements for verified carbon removal: high carbon content and high biochar stability.

Two carbon removal protocols for low-tech, place-based biochar production have now been released by Verra[17] and the European Biochar Consortium Global Artisan C-Sink protocol[18]. These newly developed protocols are promising; however, they have some limitations when applied to forests, woodland, and other landscapes under threat from drought and wildfire. Accordingly, this paper will describe a new methodology, the Methodology CM002 V1.0, from AD Tech[19], that is being developed specifically for flame carbonization of woody debris as part of vegetation management and fuel load reduction activities. Life cycle analysis confirms that biochar carbon sequestration using onsite biochar production from woody biomass in flame cap kilns produces a net carbon removal benefit[20]. Successful implementation of carbon removal protocols can help support financially the vital fuels reduction work that needs to take place to protect communities and ecosystems from wildfires and ecosystem degradation. In order to access carbon removal payments, field measurements and digital monitoring, reporting and verification (D-MRV) methods are incorporated as routine practices into the biochar production methodology described here. Details of the platform are discussed in the Supplemental Information (**Supplementary File 1**).

While several open-source designs of flame cap kilns are being manufactured by individuals for their own use[21], to our knowledge, at this time, there is only one flame cap kiln with a capacity of greater than one cubic meter that is being mass produced for sale in North America, the Ring of Fire Kiln[22], a lightweight, portable flame cap kiln that is designed for easy mobility using hand crews. The kiln consists of an inner ring comprising six sheets of mild steel secured together. An outer ring composed of lighter gauge steel bolts onto the brackets that hold the inner ring together. The outer ring serves as a heat shield that holds in heat for better efficiency. The top of the kiln is open to the air, and this is where the flame cap forms. Air flowing up through the annular gap between the main kiln body and the heat shield provides pre-heated combustion air to the kiln, further increasing combustion efficiency (**Figure 1**)

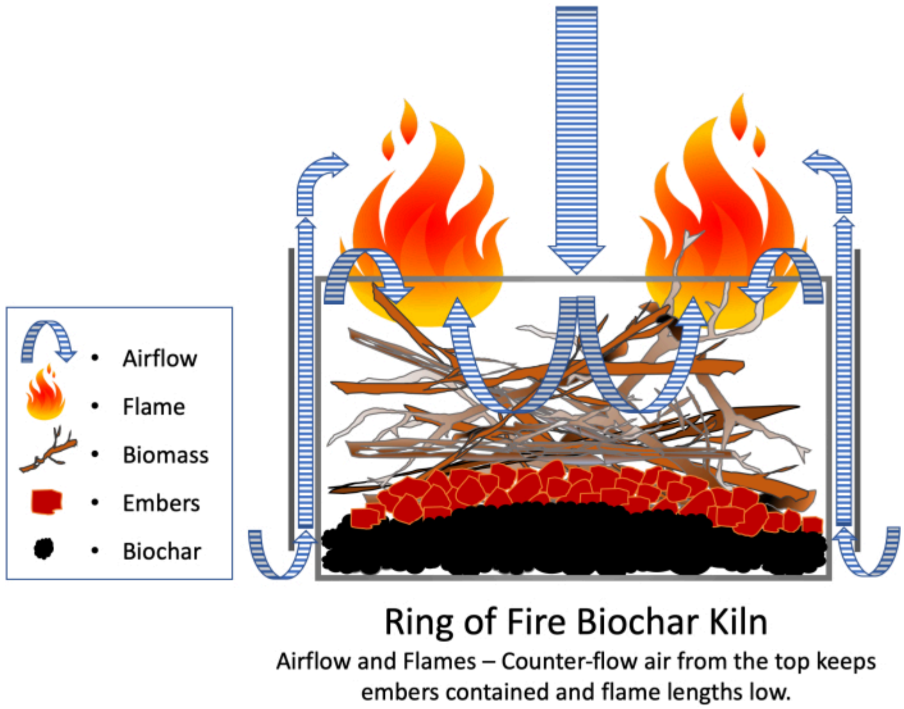

Figure 1: Schematic showing air flow, flame characteristics, and char accumulation in the Ring of Fire Kiln. Counter-flow combustion air pulls the smoke into the hot zone, where it burns up. Air flowing up through the annular gap between the main kiln body and the heat shield provides pre-heated combustion air to the kiln, further increasing combustion efficiency. Please click here to view a larger version of this figure.

The kiln diameter is 2.35 m, forming a cylinder that is one meter tall for a total volume of 4.3 m^3. In practice, the kiln is never filled completely to the top, so a typical production batch will fill the kiln from between ½ to ¾ full for a volume of biochar that is between 2 and 3 cubic meters.

Because the Ring of Fire Kiln is a standardized design, it is being adopted as the first certified technology for use in the CM002 Component Methodology that provides standardized procedures for the quantification of greenhouse gas (GHG) benefits. Measurement and data collection steps meeting the requirements of the CM002 are incorporated into the method. Reporting is done through a smartphone application by answering short questionnaires throughout the process and uploading photos and video clips to the mobile app.

Protocol

NOTE: This methodology uses Ikhala smart phone application (henceforth referred as D-MRV application; **Table of Materials**) to access carbon removal payments, field measurements and digital monitoring, reporting and verification.

1. Gathering feedstock and confirming the suitability

1. Select and report the feedstock size.
2. Select woody material less than 15 cm in diameter. Ensure that all materials are branchy or non-uniform in shape so that it does not pack tightly and inhibit airflow in the kiln.
3. On the D-MRV application, click on the **Take a Photo** button in the **Feedstock** section to open the camera. With the camera open, aim at the subject (dry feedstock piles with a measuring stick), and capture the image by pressing the **Shutter** button on the screen.
4. Report feedstock species: Open the D-MRV application and answer the short digital questionnaire reporting the amounts of each species type. Reporting is based on visual estimations.
5. Determine and report feedstock moisture.
    1. Using a standard firewood moisture meter, take a reading by inserting the pins in the middle of the largest piece of each type of feedstock.
    2. On the D-MRV application, take a photo of each moisture meter reading. Click on the **Take a Photo** button in the moisture meter section, and type in the value displayed on the moisture meter in the text field. Submit one photo and text entry for each moisture meter reading.

2. Assembling, loading, and lighting the kiln

1. On level ground, clear flammable organic material from a circle approximately 3 m in diameter. Assemble the 6 inner kiln panels into a cylinder using the connector brackets,
2. Using a shovel or similar tool, seal the bottom edge of the cylinder with a small berm of mineral dirt or clay so that air cannot enter the kiln from the bottom.
3. Attach the 6 heat shield panels to the connector brackets, ensuring that an air gap is left at the bottom of the heat shield so that air can flow through the annular gap between the inner and outer cylinders. Attach the kiln ID tag to the heat shield using the heat shield hardware.
4. Identify the kilns used in the batch. In the **Burn Preparation** section, click the **Take a Photo** button to take pictures of the assembled kiln and the ID tag and submit them for each kiln on site.
5. Load the kiln: Use smaller (2-6 cm thick is ideal), drier material for the initial loading of the kiln. Pack the material up to the kiln rim, arranging any non-branchy material, such as poles, so that it does not pack too tightly and restrict airflow.

    NOTE: The goal is to make sure the material is packed tightly enough to sustain a flame but also allow combustion air to reach to the bottom of the pile.
6. Light the kiln: Add small, dry kindling material on top of the loaded kiln. Use an accelerant if needed and light with a match, or use a propane torch. Light the kiln in several places on the top so that a cap of flame quickly develops over the entire kiln.
7. Using the D-MRV app, take a 30 s video clip as soon as the flame cap is established. In the **Burn Start** section, click on the **Take Video** button and then click on the **Submit Video** button.

3. Feeding and tending the kiln

1. During the first phase of operation, air is drawn from the top down to the bottom of the kiln, while the initial load

mostly burns down to a layer of coals. Ensure that the first load produces a good bed of coals before adding more material. Add a new layer of feedstock when the previous layer begins to show a film of white ash.

2. Transition to continuous loading: Load new material in the kiln at a steady rate. Try to keep each layer of wood the same diameter so the charring is even.
    1. Use the flame as an indicator of loading rate: Let the flame be the guide for adding new material. Ensure that a good strong flame is maintained on top because that is the heat source for making char.
    2. If the operator loads too much, too fast, the flame will be smothered. If that happens, pause and wait for the flame to come back up. If the operator does not load enough material, the flame will die down, and the char will start to burn to ash. If that starts to happen, add more material to keep the flame going.
3. Verify the flame presence during the burn as an indicator of clean, hot combustion that will minimize methane emissions and maximize stable char formation.
    1. Using the D-MRV application, take a 30-s video of the flame approximately 1 h after the kiln is lit. Navigate to the **Burn Quality Proof** section and click on the **Proof of Burn at First Hour** button.
    2. Click on the **Take Video** button, press **Record** for a minimum of 30 s, and click the **Submit Video** button.
4. Add the biggest material in the middle stages of the burn so it has time to char completely. The kiln will fill with biochar at different rates, depending on feedstock type, size, and moisture.
5. Using the D-MRV application, take a 30-s video of the flame at the end of the second hour of the burn. Click the **Proof of Burn at Second Hour** button and then the **Take Video** button. Press **Record** for a minimum of 30 s and click the **Submit Video** button.
6. Using the D-MRV application, take a 30-s video of the flame at the end of the third hour of the burn. Click the **Proof of Burn at Third Hour** button and then the **Take Video** button. Press **Record** for a minimum of 30 s and click the **Submit Video** button.
7. As the kiln fills with red hot glowing coals, make the last few layers of medium-sized material to allow any larger pieces to finish charring.

4. Finishing, quenching, and measuring the biochar

1. End the burn when the accumulated biochar is within 10-20 cm of the top rim of the kiln, when the feedstock is all used, or when the work day ends.
2. The charring is complete when there are no longer any flames. Wait for 10-15 min after adding the last piece of feedstock for the flames to die down. There will always be a few bigger pieces that do not char completely, which is not a concern.
3. Before quenching, use a steel rake to level the hot, glowing coals in the kiln.
    1. Place a measuring stick vertically in the kiln, against the kiln wall, so that one end touches the level char. On the D-MRV application, take a picture of the measuring stick that shows the depth of the char in the kiln by navigating to the **Measuring the Biochar** section and click on the **Take a Photo** button.
    2. In the text input field for the question **What is the reading from the top of the biochar to the top of kiln**, enter the value on the measuring stick.

3. Repeat this measurement and photo recording two more times at different locations within the kiln by clicking on the **Submit and Add Another Photo** button.

4. Immediately after reporting the char depth measurements, take a photo of the kiln identification tag for verification purposes.

5. Measure char bulk density.

1. When the biochar batch is complete, but before quenching, fill a metal bucket with hot glowing coals shoveled from the kiln. Weigh the bucket to get the tare weight using a hanging scale. Take a picture to record the weight.

2. Fill the bucket with hot coals and weigh it, taking a picture to record the weight.

3. Repeat the sampling procedure (4.5.1-4.5.2) two more times, taking samples from different parts of the kiln and recording the value with a photo.

6. Quench with water.

1. Begin to spray water at low pressure into the kiln until the heat shield is cool enough to touch. Remove all the heat shield panels and stack them out of the way.

2. While spraying water, remove several kiln panels and rake the char out into a thin layer to cool. Continue to spray and rake until the char is completely cool. The biochar should be cool enough to put a hand in it.

7. Remove and record unburned pieces. Remove any partially charred pieces and arrange them on one of the kiln panels in a single layer, with the measuring stick laid alongside. Using the D-MRV application, take a picture of the incompletely charred pieces.

Representative Results

A well-organized and implemented biochar batch using the Ring of Fire kiln will produce 2-3 m^3 of biochar in 4-5 h of burn time. Using the CM002 Component Methodology and recording burn parameters in the D-MRV application is intended to allow a certified verifier to confirm the batch biochar production volume and biochar quality. More information on the methodology is provided in the Supplemental Information (**Supplementary File 1**).

The process verification points for a typical batch of biochar made in the Ring of Fire kiln are listed here (**Figure 2**). **Table 1** gives typical values as measured in the field or determined by verification.

1. Report feedstock type.
2. Feedstock size: picture of feedstock pile with a ruler in place.
3. Feedstock moisture: one picture showing moisture meter reading from the largest piece of each feedstock species.
4. Ignition: One 30-s video showing the start of the kiln burn and recording time of start. Video shows a strong flame cap has developed.
5. Production temperature verification based on flame presence: three 30-s videos show strong flame presence during the burn.
6. Biochar volume: three pictures of measuring stick in the kiln to show the height of level char in the kiln at three locations. Measured distances from the top of the kiln to the char are averaged to one value for calculations.
7. Bulk density: One picture of the scale showing the empty weight of the bucket. Three pictures of scale showing the weight of the char and bucket. Char taken from 3 locations

in the kiln. The three weight measurements are averaged to one value for calculations

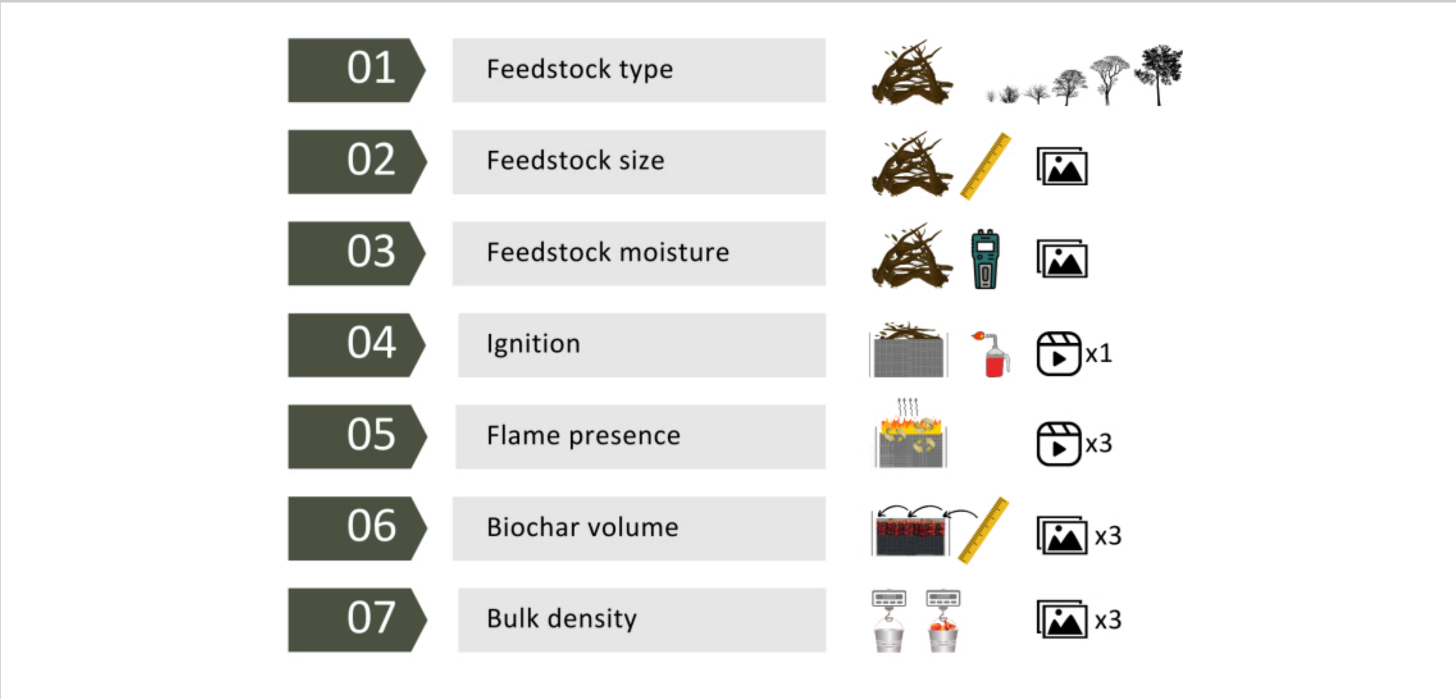

Figure 2: Infographic showing the process verification points. The process verification points for a typical batch of biochar made in the Ring of Fire kiln. Please click here to view a larger version of this figure.

	Data point #1	Data point #2	Data point #3
Feedstock species	pine 50%	fir 50%	
Moisture meter reading	19%	23%	
Volume of empty kiln cylinder	4.3 m^3		
Height of kiln cylinder	1 m		
Height of char level in kiln	60 cm	61 cm	59 cm
Tare weight of 7 liter bucket	0.6 kg		
Weight of bucket with char	1.8 kg	1.9 kg	2.0 kg
Database value of char carbon content	86.8%		
Carbon stability factor	0.74		

Table 1: Representative values used to verify production results and processing parameters for a typical batch of biochar produced in a Ring of Fire biochar kiln.

Using these points of control, the verifier determines that the biochar has been made with appropriate feedstocks and at a temperature above 600 °C to meet the requirements of the CM002 Component methodology for long-term stability. This allows the carbon stability factor of 0.74 for 100-year permanence to be applied to the biochar batch. To determine the volume of the biochar batch, the verifier uses the volume of the empty kiln as verified by the kiln ID tag (4.3 m^3) and the height of the char level in the kiln (1 m - 0.4 m = 0.6 m). Since the kiln is 60% full, the volume of char is 0.6 x 4.3 m^3 = 2.6 m^3. The verifier then calculates the bulk density of the biochar based on bucket measurements. Subtracting the 0.6 kg bucket weight from each measurement gives values of 1.2 kg, 1.3 kg, and 1.4 kg that are averaged to 1.3 kg/7 L. This is equivalent to 185.7 kg/m^3. Therefore, the dry weight of the biochar produced is (185.7 kg/m^3) x (2.6 m^3) = 483 kg.

The verifier can take the carbon content of the biochar from a database, or in this case, from a simple lab test that confirmed a carbon content of 86.8% from a batch of mixed softwoods produced in a Ring of Fire Kiln in Sonoma County, California in 2021. The test was performed by Control Laboratories of Watsonville, CA[23]. The carbon stability factor of 0.74 is applied. Therefore, the stable organic carbon content on a dry weight basis for biochar is derived from the mass of biochar, its organic carbon content, and the 100-year stability factor for a final value of (483) x (0.868) x (0.74) = 310.2 kg of stable carbon. To arrive at the final value of carbon removal, project leakage is subtracted, and the appropriate security margins are applied along with the conversion factor from solid carbon to carbon dioxide, as described in **Supplementary File 1**. The certified biochar removal value of the biochar depends on final verification that the biochar has been applied to soil or compost and is not burned or otherwise oxidized.

Supplementary File 1: Detailed information regarding the methodology and calculations. Please click here to download this File.

Discussion

Different biomass species will produce biochar with differing fractions of carbon and ash, regardless of production temperature, due to the elemental composition of the biomass[24]. Because the existing databases of biochar characteristics for different feedstocks are not complete, projects may need to submit samples for lab analysis to verify the organic carbon content of the biochar. To keep project costs down, we recommend a simple lab procedure that can be done at low cost by students in school laboratories at the high school or community college level[25]. Over time, as more projects are implemented on the ground, the database of biochar carbon content values for different feedstock types will grow and become more usable.

Many of the D-MRV measurements are intended to verify that the production conditions are optimal for producing biochar with characteristics that closely match database values. These key measurements are the feedstock moisture and the video series documenting the quality of flaming combustion, which determines the temperature of production and the resulting stability of the carbon in the biochar.

While measuring the volume of biochar produced in the kiln is straightforward, determining the dry mass of the biochar produced is not easy. Working with biochar is challenging because the complex particle density of the material makes bulk density measurements difficult to determine[26]. Once biochar has been quenched, it is not possible to get a dry weight of a certain volume of biochar in the field. However, the dry bulk density of biochar can be measured in the field by filling a metal bucket of known volume with hot coals and weighing it. This procedure can give us a good approximation of the dry mass of the biochar.

A key drawback to this methodology is the inherent variability of the field operations, including feedstock variability and the skill level of the operator. The operator must determine the feedstock loading rate and work to maintain a strong flame in the kiln. Failure to maintain the flame by over-loading will affect the temperature of char formation and hence, the char stability. This is best addressed by an effective training program for operators. Worker training and safety protocols are crucial to the success of onsite biochar production. Given the labor requirements, training programs will need to be well-organized and made widely available[27].

Another limitation of the methodology is the variability in implementing the D-MRV measurements. Feedstock moisture can be quite variable within a given batch, even if all of the feedstock is otherwise uniform. The method of taking three snapshot videos of the flame during the process to verify that proper temperatures are reached is limited by the dynamic nature of the burn. Three snapshot videos may not be representative of the whole process. A viable cross-check to this measurement is simply knowing how long the burn took and how much biochar was produced because non-optimal temperature conditions will result in lower production volumes. The field D-MRV measurements of bulk density and volume are limited in their precision; however, this is compensated for by using security margins to ensure that the final values are conservative and do not overestimate the carbon removal.

Operational logistics also contribute to the variability of biochar production parameters and the success of projects. Operational logistics must consider factors such as weather, terrain, access, worker safety, training, tools and equipment, and water availability. Most of the tools and supplies needed to make biochar are standard equipment provided to firefighters and forestry crews. Specific tools needed for implementing D-MRV with the Ring of Fire biochar kiln are listed in the **Table of Materials** file.

Making biochar in the field from waste biomass must compete with the alternative of open burning or incineration, which has the advantage of very low cost. The marginal cost of making biochar versus open burning has mostly to do with increased labor requirements, as the capital cost of the simple flame cap kilns is low[27]. To date, there are not enough large-scale projects with robust data collection to pinpoint the actual marginal cost of biochar production over incineration. However, one example can show the potential for carbon finance to fill the gap.

Watershed Consulting in Missoula, MT, treated slash thinned from 21 acres of mixed conifer forest in Western Montana in 2021 using Ring of Fire biochar kilns[28]. The total project cost was $42,302.00, and the total biochar yield was 112.5 cubic yards. Using our own standard assumptions about biochar characteristics made in flame cap kilns, we estimate that the project sequestered 31.75 metric tonnes of CO_2 at $1,332.35 per tonne. The cost of piling and incinerating the material would have been $15,750.00, leaving a marginal cost of $26,552.00 to make biochar instead of incineration, or $836.28 per tonne of biochar produced. That marginal cost could be at least partially compensated by carbon removal payments of $100 to $200 per tonne of CO_2, validating the importance of the D-MRV process. To complete the economic picture of the project, it is important for financing authorities to acknowledge the ecosystem benefits of avoiding soil damage from burn pile scars, reduced greenhouse gas emissions, and particulate air pollution, as well as returning char to forest soils for moisture retention, nutrient cycling, and soil health.

The detailed methods described in this paper will help individuals and groups working in ecosystems impacted by alien invasive species, drought, and wildfire to implement economically feasible biomass-to-biochar projects that can improve and restore soils and native ecosystems while avoiding greenhouse gas emissions and sequestering carbon for climate mitigation. Despite the variability and lack of precision in the measurements and verification points in this practical field methodology, we conclude that it is still a valuable approach to sequestering carbon in field situations where other approaches, like the transport of biomass to an industrial pyrolysis facility, are not practical.

Disclosures

Author Kelpie Wilson is the inventor and manufacturer of the Ring of Fire Biochar Kiln. Author Wihan Bekker is part-owner of African Data Technologies (Pty) Ltd., developer of the CM002 Component Methodology and Ikhala D-MRV reporting platform.

Acknowledgments

Many thanks to the US Biochar Initiative and the USDA Forest Service for sponsoring and supporting the Biochar in the Woods network for sharing information amongst a variety of practitioners who are inventing and refining methods to make and use biochar for environmental management and climate mitigation.

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