# GHG life cycle assessment of CharBoss® biochar production and potential use for CDR certificate generation

Report prepared for USDA Forest Service and US Biochar Initiative


Lead Author and LCA Practitioner:
Gudmundur Johannesson

Lead GHG Analyst:
Stephen Boles

Editor:
Link Shumaker

Biosystems Engineering, PLLC
101 Westview Dr
Carrboro, NC 27510-1501

Rocky Mountain Research Station
1221 South Main Street
Moscow, ID 83843

US Biochar Initiative
5474 SW Arrow Wood Lane
Portland, OR 97225



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## Abstract

An ISO-compliant life cycle assessment (LCA) study was performed of the Air Burner Inc. CharBoss® pyrolyzing air curtain burner (Charboss). The LCA was set in the context of the Charboss processing forest fire reduction waste biomass into biochar. The purpose of the LCA is to quantify the carbon dioxide removal (CDR) certificate generation potential of the CharBoss use in this context.

The goal of the study was to carry out an attributional LCA study to calculate net emissions from biochar used as a carbon sink. This study is proof-of-concept focused and is compatible with LCA and greenhouse gas (GHG) accounting standards. The scope of this study is to calculate the net climate change impact of GHG emissions, in units of metric tons of carbon dioxide equivalent (MT $CO_2$eq), associated with the feedstock processing and burning, and final use of the biochar produced.

All activity or foreground data is project-specific and originates from the CharBoss operations for United States Forest Service (FS) research projects on forest fire protection initiatives, covering all biochar production-related operations from biomass feedstock source to biochar utilization.

Through applying the puro.earth methodology to the activity data of the study, a carbon dioxide removal certificate CORC potential of -2.70 MT $CO_2$eq per MT biochar produced was calculated. Similarly, it has been determined that this project has the potential to generate 2,403.81 MT $CO_2$eq of CORC certificates of biochar during a 12-month period, through use of the CharBoss machine and subsequent application of the biochar to forest soils.

The study demonstrated that use of the CharBoss machine to process forest fire reduction harvest biomass into biochar has the potential to create marketable CDR certificates, while improving the sustainability of the National Forests under FS care.

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## List of abbreviations

| Abbreviation | Definition |
|---|---|
| °C | Degrees Centigrade (Celsius) |
| °F | Degrees Fahrenheit |
| AZ | Arizona, CharBoss burn site in the state of Arizona |
| BDT | Bone Dry Ton |
| BE | Biosystems Engineering, PLLC |
| BLM | Bureau of Land Management, CharBoss burn site in the state of Oregon |
| CAR | Climate Action Reserve |
| CDR | Carbon Dioxide Removal |
| CFP | Carbon Footprint of a Product |
| $CH_4$ | Methane |
| $CO_2$ | Carbon Dioxide |
| $CO_2eq$ | Carbon Dioxide Equivalents |
| CORC | Carbon Dioxide Removal Certificate (Puro.earth issued) |
| $C_{org}$ | Organic Carbon |
| CRADA | Cooperative Research and Development Agreement |
| DMB | Dry Matter Basis |
| EBC | European Biochar Certificate |
| EF | Emission Factor |
| EP | Environmental Professional, ECO Canada |
| EPA | (US) Environmental Protection Agency |
| EU | European Union |
| FL | Florida, State of |
| FS | (USDA) Forest Service |
| FU | Functional Unit |
| GHG | Greenhouse Gas |
| GPS | Global Positioning System |
| GREET | Greenhouse Gases, Regulated Emissions and Energy in Transportation |
| GT | Global Warming Potential |
| GWP | Global Warming Potential over a 100-year Horizon |
| H | Hydrogen, Chemical Element |
| ID | Idaho, State of |
| IPCC | Intergovernmental Panel on Climate Change |
| ISCC | International Sustainability & Carbon Certification |
| ISO | International Standards Organization |
| LCA | Life Cycle Assessment |

| | |
|---|---|
| LCFS | Low Carbon Fuel Standard |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| LLC | Limited Liability Company |
| MESH | Manager of Environmental Safety and Health |
| MT | Metric Tonne |
| NC | North Carolina, State of |
| $NO_2$ | Nitrous Oxide |
| OAR | (USEPA) Office of Air and Radiation |
| OECD | Organisation for Economic Co-operation and Development |
| OR | Oregon, State of |
| ODEQ | Oregon department of Environmental Quality |
| PCR | Product Category Rules |
| PE | Professional Engineer |
| PLLC | Professional Limited Liability Company |
| SC | South Carolina, State of |
| TH | Tima Horizon |
| UIEF | University of Idaho Experimental Forest, CharBoss Burn Site in Idaho |
| USBI | United States Biochar Initiative |
| USDA | United States Department of Agriculture |
| WBC | World Biochar Certificate |

# 1. Introduction

A life cycle assessment (LCA) study was performed of the Air Burner Inc. CharBoss® pyrolyzing air curtain burner (Charboss) The study was prepared from May 2023 to January 2024 through an iterative process of data collection and analysis by Biosystems Engineering, PLLC (BE) personnel and ongoing correspondence with United States Department of Agriculture (USDA) Forest Service (FS) and US Biochar Initiative (USBI) contacts. Calculations were performed using the methodology developed by (Woolf et al. 2021), as applied by the puro.earth CDR biochar protocol (puro.earth 2022). The study and this report meet the ISO standard requirements for LCA and carbon footprint of a product (CFP) (ISO 2006a; 2006b; 2018). Additionally, industry standard greenhouse gas (GHG) accounting practices have been followed, as specified in the relevant ISO 14064-2:2019 standard (ISO 2019).

An overview of the team involved in the project and their roles is provided in Table 1. The biochar project primary contacts are Drs. Deborah S. Page-Dumroese and Nathaniel Anderson of the USDA FS, who provided data to the BE team and hold a relationship with Air Burners Inc. through a Cooperative Research and Development Agreement (CRADA), along with Tom Miles of the USBI.

*Table 1. CharBoss lifecycle GHG and CDR potential project personnel responsibilities and roles.*

| Person | Organization | Role | Contact |
|---|---|---|---|
| Dr. Deborah S. Page-Dumroese[1] | FS | Senior Scientist & Research Soil Scientist | debbie.dumroese@usda.gov |
| Tom Miles[2] | USBI | Executive Director | tmiles@trmiles.com |
| Dr. Nathaniel Anderson | FS | Research Forester and Acting Program Manager | nathaniel.m.anderson@usda.gov |
| Joanne M. Tirocke[3] | FS | Biological Science Technician (Plant) | joanne.m.tirocke@usda.gov |
| Gudmundur Johannesson | BE | Lead author and LCA Practitioner | gudmundur@gobiosystems.com |
| Stephen Boles | BE | Lead GHG Analyst | steve@gobiosystems.com |
| Link Shumaker | BE | LCA Project Manager and Report Editor | link@gobiosystems.com |

The FS and Air Burners Inc. cooperate in field trials of the CharBoss machine, processing slash from forest fire protection initiatives to generate biochar. This biochar may become the basis for carbon dioxide removal (CDR) certificates created by future projects using the CharBoss. Project reporting and carbon footprint analysis was led by BE team members as described in Table 1.

[1] Dr. Deborah S. Page-Dumroese profile page (FS homepage)
[2] Tom Miles profile page (USBI homepage)
[3] Joanne M. Tirocke profile page (FS homepage)

# 2. Goal and scope definition

## 2.1. Goal of the study

The reason for this study was to estimate net GHG emissions associated with generation of biochar, resulting from processing of forest waste biomass in the CharBoss pyrolyzing air curtain burner. **The goal of the study is to carry out an attributional LCA study to calculate net emissions from biochar used as a carbon sink. This study is a proof-of-concept compatible with LCA and GHG accounting standards.** This includes all relevant processes, sources, and sinks of GHG emissions, applicable to the cradle-to-grave lifecycle of biochar feedstock sourcing, production, and use.

The study's intended audience and application are (i) the FS staff working on the CharBoss application use for improved forest management practices in the following US Department of Agriculture (USDA) Forest (FS) Regions[4]: the Northern, Southwestern, Intermountain, and Pacific Northwest Regions. (ii) other interested parties such as USBI and the CharBoss manufacturer (iii) possible use of project data and calculations as part of a project to pursue CDR certification.

The study period is one year of biochar production from application of the CharBoss machine in FS forest management projects in the western US, using actual year 2023 operational data of feedstock properties, biochar generation and application, as well as estimated operational data for the CharBoss pyrolizer for a full year of operations. This data collection period is based on the best available data from 2023, as well as previous generations of forest wood waste, and planned biochar application to soils.

## 2.2. Scope of the study

**The scope of this study is to calculate the net climate change impact of GHG emissions, in units of metric tons of carbon dioxide equivalent (MT $CO_2$eq), associated with the feedstock sourcing, production, and final use of the biochar produced, as required by the ISO 14067:2018 standard**. Note that as this is a potential carbon removal project, the climate change impact is calculated as negative emissions. This scope is consistent with the goal of the study, which is to include all relevant processes, sources, and sinks of GHG emissions, applicable to net emissions from biochar used as a carbon sink. All justifications and exclusions in this study are based on best practice GHG accounting and LCA methods and are reported where applicable.

### 2.2.1. Product-systems considered

**The project system analyses the use of the CharBoss, a pyrolyzing air curtain burner utilized by the FS throughout the US West (see Appendix A - 2 for site details used in this study), that has the function of producing biochar from fire prevention waste wood biomass. This biomass is in the baseline system burned in open slash piles or left to decompose on the forest floor.**

Risk and severity of forest fires has increased significantly in the Western US , partly due to the historical lack of harvesting and fire risk reduction management, increased severity of

[4] Forest Service Regions (FS homepage)

climate change, and expanding human development (Sarauer, Page-Dumroese, and Coleman 2019). This problem applies to both public and private land, i.e., forests kept for recreational use, that additionally provide numerous ecosystem services, as well as commercially harvested forest land.

The solution to this problem includes selected harvesting and incineration of biomass that reduces the availability of fuel for forest fires, thereby reducing the risk and severity of forest fires. However, this selected harvesting approach, particularly using typical slash pile incineration, generates GHG emissions, and has negative effects on air quality through other gases and particular matter caused by the slash pile burning. A potential solution to these problems is the use of air curtain burners, such as the CharBoss[5](Figure 1), that remediate many of the downsides of open slash burning. Beside a significantly cleaner burn of biomass slash, the CharBoss, is a pyrolyzing air curtain burner, meaning that it also generates biochar thereby returning stable carbon back to the soil. In addition, use of the CharBoss does not impact the soil under the equipment and does not leave burn scars, as the slash pile burning does.

*Figure 1. The CharBoss machine, an air curtain burner designed for efficient, low pollution biomass burning, that generates biochar (Source: AirBurners.com).*

The CharBoss is a self-contained air curtain burner, with a built-in diesel engine powering hydraulic and air curtain systems and has a ceramic refractory lined burn chamber (firebox) for improved combustion efficiency. Feedstock is loaded into the burn chamber, commonly by a small excavator machine. The biochar generated through biomass burning is removed from the firebox via a conveyor belt and deposited into a quenching pan, where it exits the CharBoss system.

#### 2.2.2. Baseline system (baseline alternative)

In a baseline system, where the CharBoss is not utilized, a typical forest fire reduction harvest (forest fire fuel treatment) is carried out, where small trees, understory growth, as well as dead and unhealthy trees are harvested, collected, and piled up for an open fire

[5] Introducing CharBoss: New mobile biochar production machine (FS webpage)

incineration (Figure 2). The slash piles usually are left to dry for 1-2 years before the burning[6] takes place. Therefore, there are emissions associated with the collection of the slash, decomposition in the pile, and burning of the slash piles (Figure 3).

*Figure 2. Forest fire fuel reduction biomass slash pile burning (Source: USDA FS[7]).*

There is a large variation in the composition and amount of harvested forest fire fuel reduction material based on local conditions, including tree species and diameter (size), amount of dead vs live vegetation etc. Additionally, the harvested biomass varies considerably in log vs. slash ratio, leading to large variations in inputs to the collection effort and efficiency.

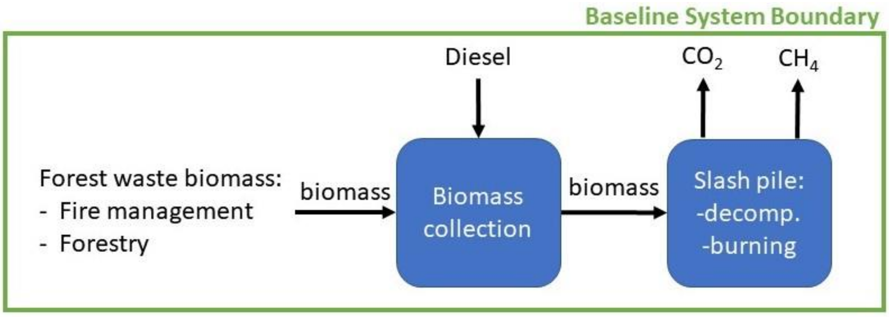


*Figure 3. Baseline system description including collection of slash using diesel-operated machinery, and emissions associated with decomposition and burning of the slash pile.*

As the forest fire fuel reduction harvest biomass will happen both in the baseline and project systems, the main difference between the two systems is burning of the biomass. Subsequently the collection of the biomass will be excluded from the data collection, i.e., is considered outside of the project boundary.

[6] 'Prescribed Fire - Pile Burning' (FS webpage)
[7] 'Pileburning' (FS information sheet)

### 2.2.3. Project system (biochar scenario)

The purpose of the project system is to describe the process leading to possible generation of certified CDR certificates from the use of the of the CharBoss. This route is being explored as a means of adding monetary and environmental value to the process of forest fire reduction harvest operations.

Since the process of collecting the forest fire fuel reduction slash into piles is identical to the baseline system, the project boundary is considered to begin at the piles, with the feeding of fuel into the CharBoss, using a diesel-powered excavator (Figure 4).

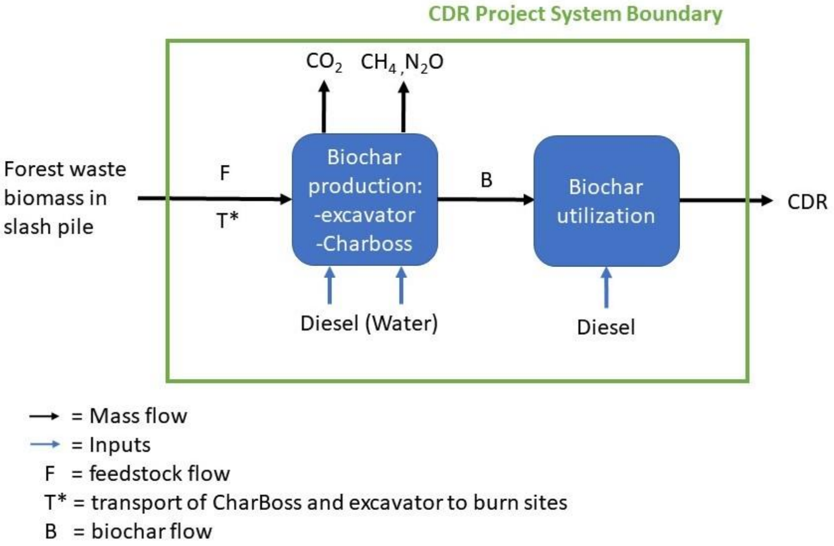


*Figure 4. Process flow chart of the CharBoss pyrolysis system. Emissions from biochar production include $CO_2$ of both biogenic (not counted) and fossil origin, as well as $CH_4$ and $N_2O$, both counted.*

The CharBoss utilizes the principles behind an air curtain burner design, where air is blown over the ceramic-lined burnbox of the machine to create a shield of air, trapping gases and particles rising from the combustion, and increasing the burn temperature to a point where particles are largely incinerated, and gas emissions are greatly reduced (Figure 5).

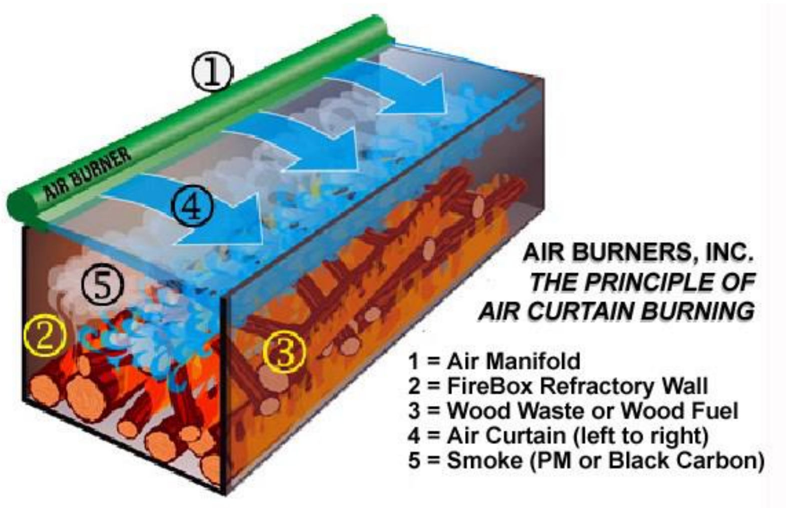


*Figure 5. Principles of air curtain burning, where flowing air from a blower traps particles from the burning biomass in a ceramic lined firebox and increases the burning temperature to over 980° C (1,800° F). Source: [AirBurners.com](AirBurners.com).*

Additionally, and unlike many other air curtain burners, the CharBoss is designed to remove the biochar from the burning process before complete combustion has taken place. The biochar is removed from the burn box by a conveyor belt and cooled down by a built-in water quenching process, before exiting the CharBoss system. The biochar can afterwards be applied to the soils at the burn site, where the slash was harvested, or transported to another location for soil application, or other final uses.

#### 2.2.4. Functional unit(s) and reference flow(s)

**For this study the functional unit (FU), as well as reference flow, is one metric ton (MT) biochar, dry matter basis (DMB), that has been applied to and incorporated into soils**. Other reference flows include the mass of waste biomass or slash resulting from forest fire reduction initiatives used as feedstock for biochar production using the CharBoss machine on project locations throughout Western US.

#### 2.2.5. Impact categories and impact assessment methods

Only one impact category, climate change, is considered for this study, assessed through the net climate change impact of GHGs from activities related to the system studied. The net climate change impact of GHGs is reported in MT $CO_2$eq., as a common unit for CDR certificate creation potential.

**The characterization factor used in this study is a 100-year global warming potential ($GWP_{100}$) of kilogram carbon dioxide equivalence (kg $CO_2$eq) calculated following Intergovernmental Panel on Climate Change (IPCC) 5th Assessment report** (IPCC 2014).

#### 2.2.6. System boundaries

System boundary in this study is defined as 'cradle-to-grave' i.e., from the source of waste wood feedstock at a forest waste slash pile, to generation of biochar through burning of the feedstock in the CharBoss machine, to transport of biochar, and final through application and incorporation of the biochar to forest soils.

A generalized process diagram of system processes and boundaries can be seen in Figure 3 and Figure 4 where biochar feedstock boundaries are outlined, along with major inputs and outputs of the production system. The figures further include the major unit processes used for the biochar feedstock generation, biochar production, and biochar uses for CDR creation. For the CharBoss biochar generation this includes transportation to and from burn sites, as well as fuel use during biomass burning and biochar applications.

Geographical and temporal (time period) boundaries of GHG emissions, used for calculations were based on primary operational data from the CharBoss applications from 2023, representing all contribution levels to produce the biochar (see Table 2 to Table 4). The permanence of the potential CDRs created through the use of the CharBoss, i.e. the amount of $CO_2$ sequestered through the land application of the biochar, is assumed to be at a minimum of a 100-year time horizon.

Decisions on data sources to use for this study were based on an evaluation of temporal, geographical, and technological relevance, following recognized procedures used in LCA and carbon accounting (e.g. Ciroth et al. 2016; Weidema and Wesnæs 1996). Appendix A - 6 includes an assessment of data quality that meets the requirements in ISO 14067:2018, sec 6.3.5, using a simplified process developed by Ciroth et al. (2016).

Data collection took place from May 2023 to January 2024, through a systematic, iterative approach using a dedicated questionnaire (available upon request), specifically designed for this purpose. Data sources are primary, using CharBoss operations-specific data, provided by the FS, while GHG emission factors are geographically and temporally relevant to this project. A list of emission factors used for the calculations in this study is provided in Appendix A - 7.

All relevant GHG sources and sinks for this project, aligned with system boundaries described above, have been considered, primarily $CO_2$, but also $CH_4$, and $N_2O$, which are reported as $CO_2$eq emissions. Only quantified GHGs are reported, if specific gases are not reported, it can be assumed that emissions of those gases are negligible.

Cut-off criteria follows best practice GHG accounting and LCA conventions on materiality, i.e., emissions are included if they are relevant and significant and quantifiable (within boundaries, related to activities for this carbon footprint quantification, and technically quantifiable). No relevant data was excluded from analysis of the CharBoss operations in the Western US in 2023, which included all processes within project boundaries (green box, Figure 4).

#### 2.2.7. Multi-functionality and allocation procedures

In this study allocation was avoided where possible, as recommended in the ISO 14044 (ISO 2006b) and the ISO 14067:2018 (ISO 2018) standards. As the biochar generated by the CharBoss is the main purpose of the system operation, and no by-products are generated, no allocation was applied to the system emissions.

#### 2.2.8. Assumptions and limitations

Where specific components of the LCA study have a greater impact on results, an estimate of sensitivity and uncertainty should be included, as has been done in this study. Discussion and qualitative estimates of sensitivity are included in section 4, with reference to the data quality estimate scheme in Appendix A - 6.

As being the only energy input in this study, all fuel data has relevant emission factors and other specific factors documented and referenced. Data sources include estimated energy use at all stages of the biochar production, based on invoices and expert estimates, extrapolated to a 12- month operating period.

Interpretation of life cycle emissions for this study (see section 4) includes identification of significant issues, based on calculation results, and an evaluation of data completeness and consistency, and sensitivity analysis of results. Study conclusions (section 5) are based on findings from collected data with limitations and recommendations based on a scientific and material basis.

In this study only primary data, including an ODEQ-compliant air emission test provided by USBI and FS, were used as input for calculations as well as scientific conventions. This primary data was used to extrapolate from a single CharBoss burn event to annual operations over a large geographic area.

A description of all project life cycle stages is included, meeting ISO 14067:2018 (and thereby ISO 14040/44 standards) for LCA study compliance. This includes sourcing of biomass feedstock, biochar production, and its end uses. Detailed process descriptions, data sources and values, calculations, and results with discussion on findings and limitations, are included throughout this report.

Neither alternative user profile, nor end-of-life scenarios were formulated for this study. As defined in the study Goal and Scope sections above (sections 2.1 and 2.2), only one use was considered for the product under study (biochar), which is to apply and incorporate the biochar into forest soils to create potential CDR certificates.

The time period used for this carbon footprint of a product (CFP) calculation is representative for the full year period of biochar production, and collected data directly reflects the biochar production output used for this project, thereby meeting the requirements in sec 6.3.6 of the ISO 14067:2018 standard.

No product category rules (PCR) were defined for this study, as this was not applicable to the project (see ISO 14067:2018, sec 3.1.1.9).

This CFP of a product is not intended for product performance tracking; therefore, a description of performance tracking is not included in the study (sec 6.4.7, ISO 2018).

# 3. Life cycle inventory analysis

This section includes a description of the LCA study, materials and methods used, and inventory data tables and descriptions. Data sources, quality and representativeness is documented and defined, applying best LCA practices, as defined by ISO 14040 and 14044 (ISO 2006a; 2006b).

## 3.1. Software, databases, and other data sources

Data collection and calculations were carried out using custom built applications in Microsoft Excel for Office 365. This includes data collection sheets, and a calculator based on puro.earth methodology, requirements, and calculation formulae.

**All activity or foreground data is project-specific and originates from the CharBoss operations for FS research projects on forest fire protection initiatives, covering all biochar production-related operations from biomass feedstock source to biochar utilization.** As the biochar production using the CharBoss machine is still in early temporal phase, some of the biochar properties specific data may need to be updated as lab analysis data matures over time. Data related to feedstock sourcing from slash piles, biochar generation, as well as its possible transport and land application, are based on limited year 2023 operations data and may therefore change somewhat.

Upstream or background data consists mostly of emission factors (EF) for fuel use. These EFs, listed in Appendix A - 7, are geographically and temporally appropriate for the project. Appendix A - 7also has a list of conversion factors used in calculations. All activity data and EFs used in this study represent the technology used for generating and processing the biochar that forms the basis of the life cycle GHG calculations.

### 3.2. Missing data disclosure

No relevant data, within boundaries (foreground) or upstream (background) of the system, was excluded from this analysis. Substantial effort was undertaken to properly define the system boundary and processes, and to collect any relevant activity data affecting possible emissions from feedstock sourcing, production, and use of the biochar. All data is based on actual production records from the CharBoss operations, collected from sites where the biochar is produced, and emission factors are geographically and temporally relevant to the project.

No data is missing from the processes and parameters defined in the project process flow diagram in Figure 4, and all parameters are based on primary, project specific, data. Only soil temperature, outside the project boundary but important for CDR permanence, is not based on direct, site specific measurements over time. However, soil temperature values used in CDR potential and permanence factor calculations are conservative, and do not overestimate the benefits or potential of CharBoss to generate CDR certificates.

### 3.3. Inventory data

The Life Cycle Inventory (LCI) data was collected based on the baseline and project flow charts (Figure 3 and Figure 4) developed in collaboration with the FS research team led by Dr. Deborah S. Page-Dumroese, as well as Tom Miles of the USBI, and is aligned with project boundaries as defined in section 2.2.3 of this report. Activity data is based on projected 12-month production period for the 2023 operations of the CharBoss, which is used as temporal boundaries for the net GHG emission calculations for the project biochar production and uses.

Operational parameters for machinery include embedded steel used for construction of the air curtain burner and the excavator, transport from place of manufacturing to place of use, and fuel use during CharBoss operations (Table 2). The project boundary is assumed to start with feeding the CharBoss from a slash pile to a final use of the generated biochar. In addition to the CharBoss operational fuel use, the initial start of the burn in the firebox requires use of fuel to start the fire, after which the burn is fuelled through the burning process.

*Table 2. Operational data and assumptions for machinery production and operation stages of the CharBoss CDR LCA calculations. Data sources are from CharBoss team, unless otherwise specified.*

| Parameter | Value | Unit | Comment |
|---|---|---|---|
| Embedded steel, CharBoss | 7.94 | MT | From: 'Operating Manual CharBoss® T26 |
| Transport, CharBoss from place of manufacture to place of use | 5,177 | km | Palm City FL to Roseburg OR |
| Embedded steel, Takeuchi excavator | 3.37 | MT | From specs on Takeuchi website<br>Assumed excavator only used for CharBoss operations |
| Transport, Takeuchi from place of manufacture to place of use | 4,450 | km | Moore SC to Roseburg OR |
| Diesel fuel use, CharBoss transportation to burn site | 11.83 | L/site | FS estimate: 1 ton towing vehicle w 16 miles/gallon of diesel. |
| Diesel fuel use, Takeuchi transportation to burn site | 11.83 | L/site | BE assumption: same as CharBoss |
| Frequency of CharBoss + Takeuchi transportation | 1.00 | Site/week | Assume once a week / every 5 days move to a new burn site, BE estimate, accepted by FS. Assuming 50 work weeks per year |
| Diesel fuel use, excavator feeding CharBoss | 6.54 | L/hr | FS estimate: 44 hours and used 76 gallons of diesel, 75% moving slash, 25% loading CharBoss |
| Diesel fuel use, CharBoss operation | 3.41 | L/hr | FS estimate: 0.9 gallons of diesel/hour. |

Generation rate of biochar is based on operational parameters for the CharBoss and burn rate of biomass, and biochar yield, as well as duration of use. These parameters are based on data provided by FS (see appendix A - 4) documenting an actual burn operation of the CharBoss that took place near Flagstaff, AZ in May 2023. Apart from the operational parameters, a third party emission test was carried out on the CharBoss in May of 2023, where the emission factor used in Table 3 is obtained (ODEQ 2023).

*Table 3. Biochar production related data for the the CharBoss operations and CDR LCA calculations.*

| Parameter | Value | Unit | Comment |
|---|---|---|---|
| Burn rate, CharBoss | 1.72 | MT/hr | FS estimate: AZ burn data, see appendix A - 3<br>- 2.1 tons (BDT) biomass burned in 1.1 hrs = burn rate of 1.9 ton/hr<br>- fully dried biomass (BDT/hr), original mc = 24.2%, 2.8 tons (wet) were processed |
| Biochar yield, Charboss | 0.17 | dimensionless | FS estimate: AZ burn data, 17.2% of feedstock mass (BDT) for 'mixed' diameter |
| Feedstock moisture content | 0.242 | dimensionless | FS estimate: AZ burn data, 24.2% mc for 'mixed' diameter class |
| Days of CharBoss annual operation | 250 | d/y | Study assumption |
| Hours of daily operation | 12 | h/d | Study assumption |
| Annual feedstock use - wet | 6,822 | MT/y | Based on BE operation assumptions, FS burn rate and moisture content data |
| Annual feedstock use - dry | 5,171 | MT/y | Based on BE operation assumptions, FS burn rate and moisture content data |
| Production rate, Biochar | 0.296 | MT/hr | Based on FS data on CharBoss burn rate and biochar yield data |
| Biochar production, year | 889 | MT/y | Based on FS data on CharBoss annual operation activity |
| $EF_{CharBoss}$ | 0.0082 | MT CO2eq / MT | CharBoss air emission test report, Table 1-4, p. 10[8] |

As the focus of this proof-of-concept study is to estimate the maximum potential of the CharBoss to generate CDR credit, a full year of operations is used, i.e. that the CharBoss is running at a 100% capacity. This includes 5 days per week during 50 weeks of the year, resulting in 250 days of operation for the CharBoss. It is further assumed that each day of operations include a 12-hour run, which is likely in the remote places of operation that the CharBoss would often be utilized. As discussed in section 5, in most likely scenarios, the CharBoss would be run for less total operating hours per year than calculated in this maximum potential study.

After the biochar has been generated at a forest location, where slash piles have been drying out for an extended period of time, the biochar will likely be used, either at the location of a burn, or at a forest location within 80 km (50 mi.) of the burn site (Table 4).

*Table 4. Data related to use of biochar generated through CharBoss operations indicating range of options, with the options used in CORC calculations in bold font. Data and calculations are based on information provided by the CharBoss team.*

| Parameter | Value | Unit | Comment |
|---|---|---|---|
| **Diesel fuel use for biochar use -scenario 1** | **13.08** | **L/hr** | **Use on-site and mixed into the log landing with an excavator, 1-2 hours of work at the end of the run (or day)** |
| Diesel fuel use for biochar use - scenario 2 | 24.91 | L/hr | Used within a watershed with a transport distance of ≤50 miles,<br>i.e. 50 mi. transportation w. a truck & trailer + 2 hrs on excavator |

The life cycle inventory for the use of the CharBoss and subsequent utilization of the biochar, is a complete set of data including all activities defined in the system boundary description. This data was used to generate estimates of the CORC potential of this project, presented in section 4.

[8] Air Curtain Incinerator Emission Testing. ODEQ website.

### 3.4. Feedstock type definition decision process

An important part of an ISO 14067:2018 compliant CFP, and any ISO compliant LCA study, is the definition of project boundaries so that a study accurately represents the resulting product of activity under investigation. In the case of the CharBoss machine operation and biochar generation, the biomass used as a feedstock for the air curtain burner consists of slash material generated through forest fire protection initiatives by the FS.

To systematically determine if the feedstock should be classified as waste product, an internationally recognized decision process (ISCC 2022), specifically developed for definition of waste/residue and product/co-product classification was applied (see Appendix A - 3).

In summary, the outcome of the decision process diagram is that the feedstock used for the CharBoss is waste, and activities related to its upstream impacts is outside this study LCA boundary. Subsequently, data collection starts at the point of this woody waste having been left in piles at the forest, as described in section 2.2.2 above.

### 3.5. Feedstock sustainability information

Demonstration of feedstock sustainability is an important part of CDR certificate creation through any of the currently available protocols. For forest-source feedstock sustainability, the fundamental assumption is that an implementation of a CDR project will not cause a net reduction in the size of the carbon sink stored in the forest biomass. These sustainability requirements usually include an approved sustainable management plan from a relevant jurisdiction's environmental management or protection agency. Other acceptable sustainability information may include third party commercial sustainability certificates, such as the Programme for the Endorsement of Forest Certification (PEFC)[9] or Forest Stewardship Council (FSC)[10]. Yet another approach approved by some CDR protocols is the renewable biomass criteria defined by the UNFCCC CDM[11] methodologies. The relevant CDR protocol normally provides a list of acceptable feedstocks; however final feedstock approval is in practical terms usually project specific and subject to a CDR protocol technical team acceptance.

As the feedstock used by the CharBoss for biochar generation originates from National Forests, the management and oversight of forest sustainability is handled by the FS. Lands managed or held by federal agencies such as the FS are unable to use FSC or other commercial certifying entities. These lands are held in public trust and are subject to very rigorous federal oversight in their use. This oversight is governed by the US National Environmental Policy Act (NEPA) and every federal agency (e.g., FS, Department of Interior Bureau of Land Management (BLM), US Army Corp of Engineers, and many others) are required to pursue a fixed and detailed process to identify and provide compensating programs for any action taken on the public lands under their control. To accomplish this, NEPA prescribes periodic creation and review of Environmental Impact Assessments (EIA) or Environmental Impact Statements (EIS). Either or both are rigorous, transparent, and open to public scrutiny in their development and in many respects can be seen to exceed the requirements of private commercial certifying entities.

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[9] PEFC homepage
[10] FSC homepage
[11] UNFCCC CMD Methodologies homepage

As subsequent to the legal obligations of the FS, all its decision-making processes are based on best available science and adaptive management practices. Therefore, a wealth of information exists on the status and utilization of any National Forest resources. This in turn guides the feedstock sourcing for the CharBoss biomass feedstock use and is primarily focused on the sustainability of the feedstock extraction rates and practices in the affected National Forests.

# 4. Life cycle impact assessment and interpretation

During this LCA study of the CharBoss operations and biochar generation, all relevant activities have been included in the LCI stage of the study, as defined by the study goal and scope definitions. The Life Cycle Impact Assessment (LCIA) calculations of the net GHG emissions from the cradle-to-grave boundaries of the biochar collection and use project system, presented in this section, similarly considered all relevant emissions, primarily carbon dioxide ($CO_2$), but also other GHGs such as methane ($CH_4$) and nitrous oxide ($N_2O$), that are presented as part of the net $CO_2$eq balance of the project.

The collected data is applicable to any sort of net GHG emission calculations, although here only the puro.earth calculations methodology (puro.earth 2022) has been applied. The Woolf et al. (2021) GHG accounting methodology for use of biochar to soils is used by the puro.earth biochar protocol. The Woolf et al. approach is dynamic in how it accounts for biochar properties and environmental conditions on quantities and permanence of $CO_2$ removals by biochar production and use.

A conservative approach has been applied in all stages of data collection and GHG calculations, as not to overestimate the benefits of the project.

The systemic estimate of data quality used in the LCA study shows that most data is of high quality, and representative of the project. Each data parameter, presented in Table 12 of Appendix A - 6, shows reliability of data all falling into the score of 1-2, based on the scoring system developed by Ciroth et al. (2016). This scoring results indicate high reliability and completeness of the collected data, as it is largely first hand, based on operational data, and/or is applicable to geographic and temporal scope of the study.

The lab results of biochar properties are similarly based on biochar generated by the CharBoss operations, for the period of study duration. Soil temperature data presented are also applicable to the relatively wide range of the geographic scope of the CharBoss operations. For both biochar properties and soil temperature average values are used for the net GHG calculations (CORC potential), however sensitivity analysis is provided, taking into account these impactful parameters for the calculations.

As the study is based on one-year operations of the CharBoss, it can be expected that the reliability of the data will improve once the CharBoss biochar production and use system has run consistently over expanded time period and geographic area.

## 4.1. Biochar properties and CORC calculations parameters

The following CDR potential calculation, in the form of CORCs, is based on projected annual 889 MT DMB biochar production and the net GHG emissions from the cradle-to-grave lifecycle of the project, as well as laboratory analysis of biochar properties (Table 5). The laboratory analysis is presented in Appendix A - 3 and is based on samples of biochar from the CharBoss air curtain burner during the 2023 operations.

*Table 5. Biochar characterization from laboratory reports, and CORC calculation parameters from the puro.earth methodology. Where averages are used in CORC calculations, the value used is in bold font. Data and calculations are based on information provided by the CharBoss team.*

| Parameter | Value | Units | Comment |
|---|---|---|---|
| Biochar amount, DMB | 889 | MT | Estimated project production, dry matter basis |
| Biochar moisture – AZ | 4.62 | % | Lab analysis results report, (app. A - 3) |
| Biochar moisture – BLM | 5.79 | % | Lab analysis results report, (app. A - 3) |
| Biochar moisture – UIEF | 4.06 | % | Lab analysis results report, (app. A - 3) |
| **Biochar moisture – average** | **4.82** | **%** | **Average of three location used in calculations** |
| Organic Carbon – AZ | 67.67 | % | Lab analysis results report, (app. A - 3) |
| Organic Carbon – BLM | 92.87 | % | Lab analysis results report, (app. A - 3) |
| Organic Carbon – UIEF | 89.29 | % | Lab analysis results report, (app. A - 3) |
| **Organic Carbon – average** | **83.3** | **%** | **Average of three locations used in calculations** |
| Mass ratio, $H:C_{org}$ – AZ | 0.18 | Unitless | Lab analysis results report, (app. A - 3) |
| Mass ratio, $H:C_{org}$ – BLM | 0.12 | Unitless | Lab analysis results report, (app. A - 3) |
| Mass ratio, $H:C_{org}$ – UIEF | 0.15 | Unitless | Lab analysis results report, (app. A - 3) |
| **Mass ratio, $H:C_{org}$ – average** | **0.15** | **Unitless** | **Average of three locations used in calculations** |
| Soil temperature – North | 12.78 | °C | North: Bitterroot National Forest[12] - 55°F |
| Soil temperature - Central | 9.44 | °C | Central: Caribou-Targhee National Forest[13] – 49°F |
| Soil temperature – South | 15.00 | °C | South: Grand Mesa-Uncompahgre-Gunnison National Forest[14] – 59°F |
| **Temperature, soil - average** | **12.41** | **°C** | **Average of South, Central, North regions used in calculations** |
| Regression coefficient "c" | 1.07 | Unitless | Soil temperature dependent* |
| Regression coefficient "m" | -0.61 | Unitless | Soil temperature dependent* |
| Permanence factor "$F_p^{TH,Ts}$ " | 0.98 | Unitless | Calculated (c + m x $H:C_{org}$)* |
| GHG emission allocation factor | 1.00 | Unitless | No co-products are generated |

*Section 4.2, puro.earth biochar methodology **(puro.earth 2022)**.

As it is not clear which of the biochar properties and soil temperature can be considered 'typical' for the operations of the CharBoss, an average of the available data is used for the base estimates of CDR potential. While the biochar moisture content data is in a relatively narrow range, both organic carbon content and soil temperatures show a larger difference between minimum and maximum, making it hard to define if the averages used sufficiently describes a normal use of the CharBoss and soil conditions where the biochar is applied.

To address this large variation in these important parameters, a sensitivity analysis is provided in section 4.3, using a range of biochar and soil temperature parameters. This is done to demonstrate the effects of variability of these parameters on the CDR potential, presented as CORC intensity (MT $CO_2$eq/ MT biochar) and permanence of this CDR project.

[12] Bitterroot National Forest
[13] Caribou-Targhee National Forest
[14] Grand Mesa, Uncompahgre and Gunnison (GMUG) National Forests

### 4.2. CORC calculation results

By using project activity data presented with the Inventory Data (section 3.3, Table 2 to Table 4) and biochar properties in Table 5, along with appropriate emission factors, listed in Appendix A - 7, the net GHG balance of the project was calculated using the puro.earth methodology for biochar, Edition 2022 V2 (puro.earth 2022).

The net CDRs (as CORCs) are calculated following section 4 of the puro.earth biochar methodology, presented in Equation 1 below. Each 'E' term describes a project life cycle stage from biomass sourcing to biochar utilization, while the 'CORCs' term represents the net $CO_2$ removal potential by the project.

*Equation 1. puro.earth formula for calculation of net carbon sequestration over a 100-year permanence horizon.*

$$CORCs = E_{stored} - E_{biomass} - E_{production} - E_{use}$$

The 'E' terms represent Level-1 emissions which are the sum of all GHGs for each LCA stage, while Level-2 emissions are itemized GHGs that contribute to each Level-1 stage sum.

**Principal Findings:**

A summary of the CORC calculations results for the CharBoss CDR potential project in Figure 6 indicates a **carbon removal intensity (in the form of CORC intensity) of -2.70 MT $CO_2$eq per MT DMB of biochar produced**. The overall GHG contribution to the net CORC intensity is the $E_{stored}$ term (-2.88 MT $CO_2$eq $MT^{-1}$), representing the long-term carbon sequestered in the biochar. Sourcing of biomass contributes zero emissions as it is outside of project boundary, while biochar production ($E_{production}$ = 0.16 MT $CO_2$eq $MT^{-1}$), and utilization of biochar ($E_{use}$ = 0.01 MT $CO_2$eq $MT^{-1}$) represent 5.57%, and 0.43%, of the $E_{stored}$ sum value, respectively.

It has been determined that this project has the potential to generate **2,403.81 MT $CO_2$eq of CDR certificates (in the form of CORCs)** from biochar during a 12-month period, through use of the CharBoss machine and subsequent application of the biochar to forest soils.

This lopsided importance of the carbon sequestration potential in the results is further depicted in Figure 6, where the contribution of the sum of $E_{biomass}$, $E_{production}$ and $E_{use}$ is 5.99% of the $E_{stored}$ sub-stage.

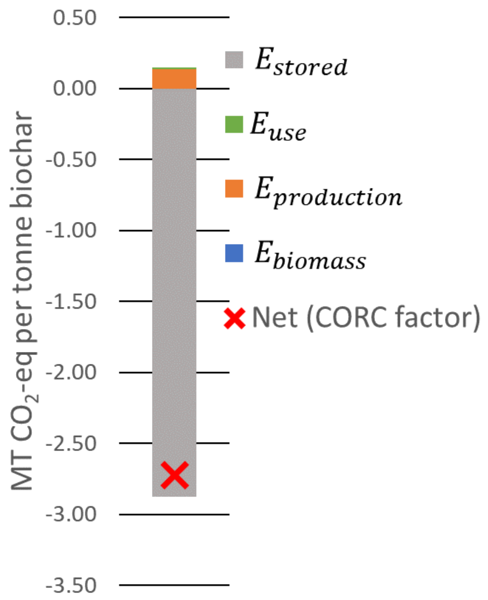


*Figure 6. Project LCIA results of biochar production and use, grouped by puro.earth methodology level-1 categories, with red 'X' indicating net CORC intensity of -2.70 MT $CO_2$eq per tonne biochar produced and incorporated into forest soils.*

The waterfall chart in Figure 7 further adds to underline the relative size of the $E_{stored}$ value and its contribution to the CORC intensity of this project. The size of the $E_{stored}$ value is largely dependent on the parameters presented in Table 5, namely the quantity of biochar generated, its organic carbon content and the permanence factor for this project. The permanence factor in turn builds on the $H:C_{org}$ content ratio of the biochar, as well as the soil temperature for the location of biochar final use.

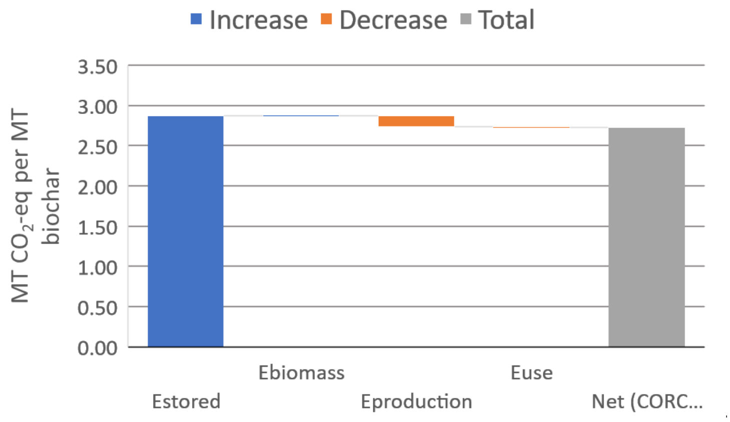


*Figure 7. Project life cycle emissions LCA results by puro.earth Level-1 contribution categories, and per functional unit in MT $CO_2$eq per MT of generated biochar used for land application.*

### 4.3. Sensitivity analysis, CDR potential and $H:C_{org}$ ratio

Considering the importance of biochar properties, especially the $H:C_{org}$ ratio, and soil temperature, on the CORC potential of this project, sensitivity calculations were carried out demonstrating how the expected range of these project parameters will impact the project CDR potential, with all other parameters held constant.

Actual analysis of the biochar generation inputs and net CDR potential of this project are presented in sections 3.3 and 4.1, based on data collected from the CharBoss team, and laboratory analysis results summarized in Table 5. The inventory data and net climate impact calculation results provide the basis for the CDR certificate or CORC potential of the project, and reflects information on the CharBoss operational parameters, as well as ecological and environmental regions where this project will operate.

The sensitivity calculation matrices are based on soil temperature range of 8°C to 18°C, in two-degree increments. This temperature range covers the large geographic range of the CharBoss operation area, reflecting the tremendous ecological range of forests under FS care in the Western US. Similarly, the impacts of the potential range of $H:C_{org}$ ratio, indicative of the physical environment of the biochar production, is presented in the range of 0.1 to 0.7 in 0.1 increments, which covers most pyrolysis technology conditions used for biochar production. Most importantly this information reflects the operating temperature and residence time of biomass feedstock in the pyrolizers.

As the CharBoss project biochar $H:C_{org}$ ratio fall between 0.1 and 0.2 with average of 0.15, and the proposed soil temperature of final use ranges 9.4°C to 15.0°C, the first two rows of Table 6 represent the potential range of carbon removal intensities for this project. This means a range of carbon removal intensities from -2.48 to -2.94 MT $CO_2$ per MT of biochar generated, with the minimum value (Soil T = 18°C and $H:C_{org}$ = 0.2) about a 15% less that the maximum potential (Soil T = 8°C and $H:C_{org}$ = 0.1).

*Table 6. Carbon removal intensities (MT $CO_2$eq / MT biochar) for this project as a function of varying $H:C_{org}$ and soil temperature values.*

| CORC intensity (MT/MT) | | Soil temperature (°C) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 8 | 10 | 12 | 14 | 16 | 18 |
| $H:C_{org}$ | 0.1 | -2.94 | -2.88 | -2.83 | -2.77 | -2.72 | -2.67 |
| | 0.2 | -2.78 | -2.71 | -2.65 | -2.59 | -2.53 | -2.48 |
| | 0.3 | -2.62 | -2.54 | -2.47 | -2.40 | -2.34 | -2.28 |
| | 0.4 | -2.47 | -2.38 | -2.29 | -2.22 | -2.15 | -2.09 |
| | 0.5 | -2.31 | -2.21 | -2.12 | -2.03 | -1.96 | -1.90 |
| | 0.6 | -2.15 | -2.04 | -1.94 | -1.85 | -1.77 | -1.70 |
| | 0.7 | -1.99 | -1.87 | -1.76 | -1.66 | -1.58 | -1.51 |

The permanence factor is included in CORC calculations, as indicated in Table 5, and in the puro.earth biochar protocol (puro.earth 2022), that is in turn based on work done by (Woolf et al. 2021). The permanence factor is an important parameter in determining the biochar carbon sequestration potential ($E_{stored}$) value of the CORC, where puro.earth methodology use the relationship shown in Equation 2.

.

*Equation 2. Calculation formula for biochar carbon sequestration according to puro.earth methodology.*

$$E_{stored} = Q_{biochar} \times C_{org} \times F_p^{TH,T_s} \times \frac{44}{12}$$

Where the equation parameters are as follows:

- $Q_{biochar}$ : quantity of biochar generated during the study period
- $C_{org}$ : organic carbon content of the biochar
- $F_p^{TH,Ts}$ : permanence factor over a time horizon TH, and soil temperature Ts

As the quantity of biochar and its organic carbon content are largely defined by the feedstock properties and the pyrolysis technology, the permanence factor is of interest in maximizing the CORC potential of a project.

The permanence factor is derived as follows in Equation 3.

*Equation 3. Permanence factor formula*

$$F_p^{TH,T_s} = c + m \times \frac{H}{C_{org}}$$

At a given time horizon (commonly 100 years or more) and soil temperature, the permanence factor is only a function of the $H:C_{org}$ ratio. The constants c and m are a result of the linear regression used in the Woolf et al. (2021) methodology to describe the permanence of biochar carbon over time and soil temperature.

Table 7 summarises the sensitivity analysis of the permanence factor (dimensionless), as a function of varying soil temperatures and $H:C_{org}$ ratio, using the same range and increments as done in the CORC sensitivity analysis in Table 6.

*Table 7. Permanence factor ($F_p^{TH,Ts}$) as a function of varying $H:C_{org}$ and soil temperature values.*

| $F_p^{TH,Ts}$ | | Soil temperature (°C) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 8 | 10 | 12 | 14 | 16 | 18 |
| $H:C_{org}$ | 0.1 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 0.96 |
| | 0.2 | 1.00 | 0.98 | 0.95 | 0.93 | 0.91 | 0.90 |
| | 0.3 | 0.95 | 0.92 | 0.89 | 0.87 | 0.85 | 0.83 |
| | 0.4 | 0.89 | 0.86 | 0.83 | 0.81 | 0.78 | 0.76 |
| | 0.5 | 0.84 | 0.80 | 0.77 | 0.74 | 0.72 | 0.70 |
| | 0.6 | 0.78 | 0.75 | 0.71 | 0.68 | 0.65 | 0.63 |
| | 0.7 | 0.73 | 0.69 | 0.65 | 0.62 | 0.59 | 0.56 |

Again, due to the narrow range of biochar $H:C_{org}$ ratios and relatively large range of soil temperatures for the CharBoss biochar land application, the expected permanence factors fall into the first two rows of Table 7. This indicates that 90% to 100% of the biochar carbon will still be present after a 100-year reference period.

The sensitivity analyses presented in Table 6 and Table 7 provide information to evaluate some of the most important factors for calculation of CORC potential of a CDR project. Further discussion of the implications of these parameters for the CharBoss project is found in section 5.

# 5. Discussion, conclusions, and recommendations

This report is presented as an ISO compliant LCA and CFP study (ISO 14040/44:2006, as well as 14067:2018) of using the CharBoss air curtain burner to burn waste wood biomass, generating in the process high quality biochar that subsequently will be used for soil application and incorporation. Prior to the implementation of the CharBoss for burning of slash forest biomass the biomass was burned in open slash piles.

Data collection and project calculations took place from May 2023 to January 2024, carried out by BE personnel, with support of Drs. Deborah S. Page-Dumroese and Nathaniel Anderson, Tom Miles, and Joanne Tirocke on behalf of the project proponents, USBI and FS**.**

This project is a proof-of-concept to demonstrate the maximum potential of using the CharBoss for processing of forest waste biomass, with the added environmental benefits of producing biochar that is eligible forCDR certificates in the form of puro.earth or other CDR protocols. These CDRs are considered additional from the baseline operation of forest fire reduction operations, as the biochar production and use for forest soil application creates a larger and more permanent carbon sink than previously did exist for the waste forest wood biomass carbon. When the forest fire reduction biomass is burned in slash piles, almost all the carbon in the biomass is emitted as $CO_2$ through the combustion. Conversely, the application of the CharBoss sequesters a portion of the biomass carbon in the forest waste biomass. The percentage of feedstock carbon retained ranges from 23.3% (AZ), to 30.7% (UIEF), and 31.9% (BLM), with an average of 28.6% of woody feedstock carbon retained in biochar generated[15]. These carbon recovery ratios are similar to common values in industrial pyrolysis systems[16]

The results of the study are consistent with the goal and scope of the study, as presented in sections 2.1 and 2.2, aiming to include all relevant sources of GHGs from feedstock sourcing to biochar use. As all the activity data, biochar properties and soil temperature data used for calculations are primary information from actual CharBoss operations, and are temporally and geographically relevant, the results have a high level of certainty associated with them. However, some of the activity data are based on limited scope of CharBoss operations. This includes the data used for modelling of the CharBoss burn rate and biochar yield, which are based on one burn in Arizona. It can be argued that, as this 'burn' was a demonstration, the biomass was not randomly collected, as would be the case in regular fire risk reduction harvest operation. Additionally, and due to the wide geographic area for the CharBoss operations, a great variability exists in wood quality, size distribution between stem and branch, and other properties of the slash biomass properties used as feedstock for the CharBoss. These factors, and a great variability in forest terrain, will further mean that variability exists in the amount of labour needed for feedstock collection and processing. Although the collection of the feedstock is outside of the boundaries for this study, these factors will affect the efficiency of the CharBoss operations, and the quantity and quality of the biochar produced. Consequently, it can be anticipated that collecting burn data from locations across the geographic scope of CharBoss operations might improve the reliability of these important parameters. These considerations depend for instance on local wood

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[15] Applying the assumptions and data used in the study, e.g. 50% carbon content of feedstock biomass, a 17.2% biochar yield, and average as well as site-specific carbon content of biochar (see Table 11 in appendix A - 5).
[16] Tom Miles, USBI, personal communication.

species used as feedstock, and climatic conditions, both of which affect burn rate, yield of biochar, and perhaps composition of the biochar.

Similarly, the CharBoss runtime assumptions, consisting of 12 hours days for 5 days a week and 50 work weeks a year, resulting in 3,000 hrs. per year, will linearly affect the output of the burner, and thereby the CORC creation potential of its use. These assumptions are likely to represent a maximum possible output from the CharBoss, and do not consider limitations due to e.g. downtime and repairs, unsuitable weather conditions or seasonality. However, it is assumed that the CharBoss stays in one location for a week (i.e. transferred between sites once weekly), and it is likely that at a remote location the most would be made of available working hours.

Given the outsized contribution of the carbon sequestered by the biochar ($E_{stored}$) to the CORC value for this project, amounting to about 95% of the gross GHG emissions of the CORC calculations, it can be expected that changes in biochar analysis findings may affect the CDR calculations results most significantly. Among the most impactful of those parameters is the H:Corg ratio, that is relatively low for this biochar, but also the soil temperature. In the initial calculations an assumed soil temperature value of 12.41°C is used. This is due to lack of knowledge on the soil temperatures at the actual location of final use of the biochar in the project.

Throughout this report, full adherence to the ISO 14040/44:2006 and 14067:2018 standards were maintained, as well as compliance with requirements to the puro.earth protocol, following the full life cycle of the CDRs, from feedstock to final use.

No significant issues have been identified that limit the findings of the report, and the findings are based on scientific and material basis and developed through a rigorous process of best industry LCA and GHG accounting practices.

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# 7. Appendices

The following Appendices contain information relevant to background and supporting information needed for the completion of this report, as well as details not included in the report main text.

## A - 1. BE team project practitioner credentials.

**Gudmundur Johannesson, MSc, PhD** is an environmental expert with 6+ year experience in ISO 14040/44 compliant Life Cycle Assessment (LCA) projects that, among others, include conventional and renewable energy, biofuels, and industrial systems. Clients include governments and private organizations in Canada, USA, and Europe. Further, Gudmundur has 20+ year experience in applied research that includes greenhouse gas emission measurements (GHG) using agrometeorological approach and emission modelling according to IPCC protocols. Other research and development work includes soil science, agronomy, organic waste, and agriculture water quality, both in the field and a laboratory setting using variety of instrumentation, protocols, and data analysis. Gudmundur's extensive work experiences include private consulting, academia, and government, while his PhD in Atmospheric Science and MSc in Soil Science are obtained from the University of Guelph, Ontario Canada.

**Stephen (Steve) Boles, MSc, EP** (sustainability) has been active in the climate change community as a scientist and consultant for over 20 years. He received his Master of Science degree from the University of Alaska Fairbanks in 1998 and spent the next eight years working as a scientist at one of the world's leading climate change research centers at the University of New Hampshire. As a consultant, Stephen has led GHG quantification, verification, or reduction projects for clients in a range of industry sectors including oil and gas, automotive manufacturing, insurance, government (federal, provincial, municipal), food processing, energy utilities, retail finance, and real estate. Stephen is active in the development of GHG policies in North America. He served as an expert stakeholder on the working groups commissioned by the Climate Action Reserve to develop waste- related and agriculture-related carbon offset protocols for Ontario's former cap and trade program. He also served as an expert stakeholder on the working group to develop a forestry carbon offset protocol in the Province of Alberta.

**Link Shumaker, MSc, PE** is a practicing engineer with 17 years of experience in industrial biofuels and bioenergy process scale-up and operations. He owns Biosystems Engineering, PLLC which is active in regenerative technology deployment for carbon-sensible 21st century systems at the nexus of food, energy, and water. Link is an accredited lead auditor under International Sustainability and Carbon Certification (ISCC), lead verifier under California's Low Carbon Fuel Standard (LCFS), certified Manager of Environmental Safety and Health (MESH) and certified Lean Six Sigma Black Belt. Link holds a Master of Science in Biosystems and Agricultural Engineering and a Bachelor of Science in Chemical Engineering from the University of Kentucky. He is licensed to practice engineering in North Carolina, Tennessee and Missouri. His passions include creating order from chaos and exploring the world with youngsters.

## A - 2. Biochar production site information

Biochar production sites used in this study represent a large range of geography, forest types and climate. Summary of those site locations and forest species properties is presented in Table 8.

*Table 8. Information on sites used for CharBoss operations in this study.*

| Site ID | Coordinates (GPS) | Nearest urban area | Site/feedstock forest species composition |
|---|---|---|---|
| **AZ** | 36.10390, -111.65883 | Flagstaff, AZ | Ponderosa pine |
| **UIEF** | 47.16112, -116.80043 | Princeton, ID | Cedar, Douglas-fir |
| **BLM** | 44.77927, -122.73304 | Springfield, OR | Douglas-fir, ponderosa pine, grand fir |

Google Earth image, see Figure 8 below (link to Google map)

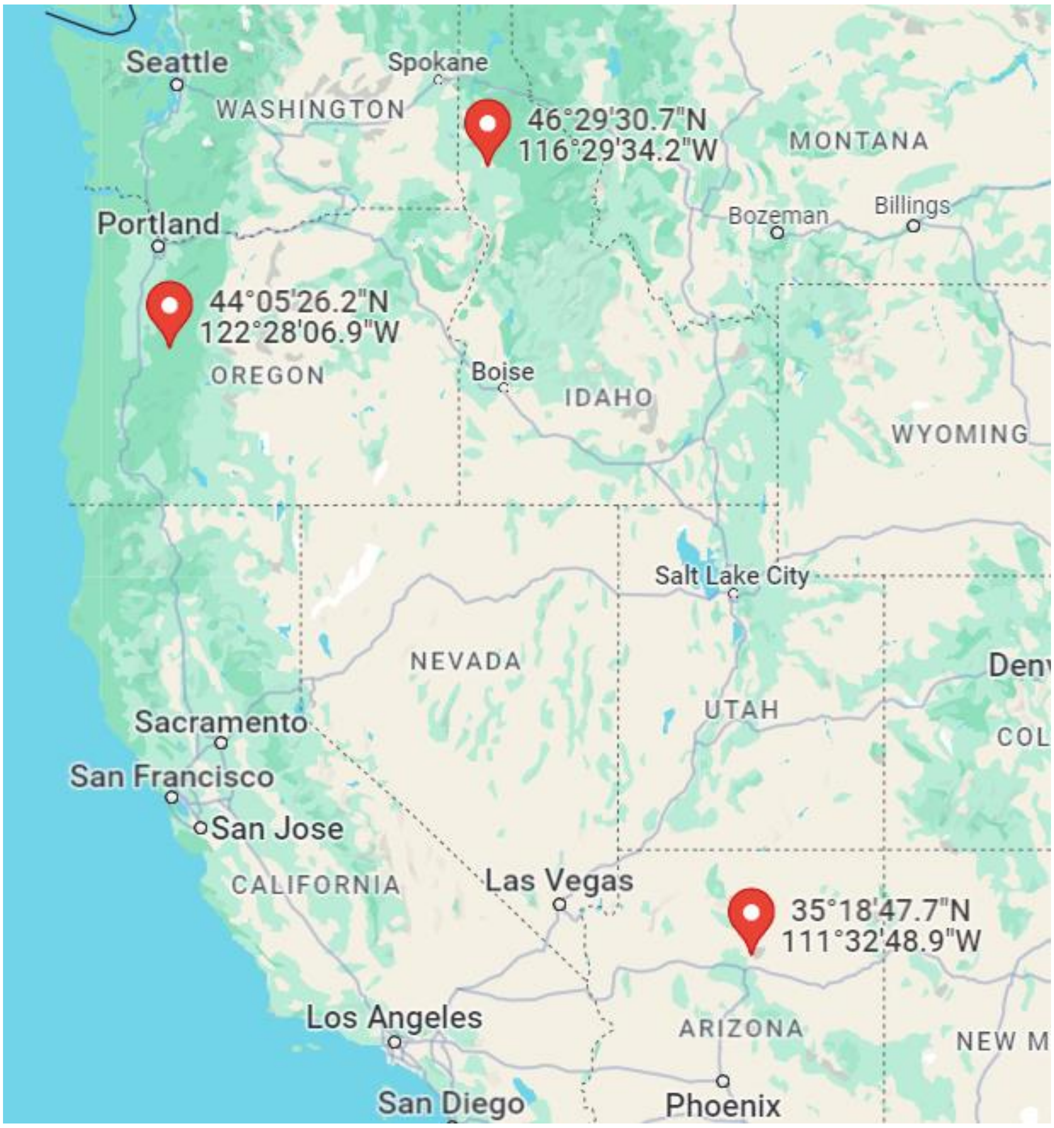


*Figure 8. Map of biomass burn sites where the CharBoss air curtain burner was utilized. Source: Google Maps, FS.*

## A - 3. Feedstock definition decision process

The following decision-making flow diagram was published by the International Sustainability & Carbon Certification (ISCC)[17], to assist in defining material origin as a waste or co-product (ISCC 2022).

Based on the analysis by BE Personnel with input from FS research scientists and operators of the CharBoss machine, the answers to the flow chart in Figure 9 for the forest slash used as feedstock for the CharBoss are **Box 1, 2, and 3: No, No, Yes**. We conclude that the FS, due to its mandate as caretaker of the National Forests, where the CharBoss operates, is obligated to dispose of the slash material (box 3), defining this material as waste by the ISCC determination process.

Therefore, we conclude that the slash piles from forest fire production initiatives is a waste material, and that the upstream activities related to this material is outside of boundaries for this LCA study.

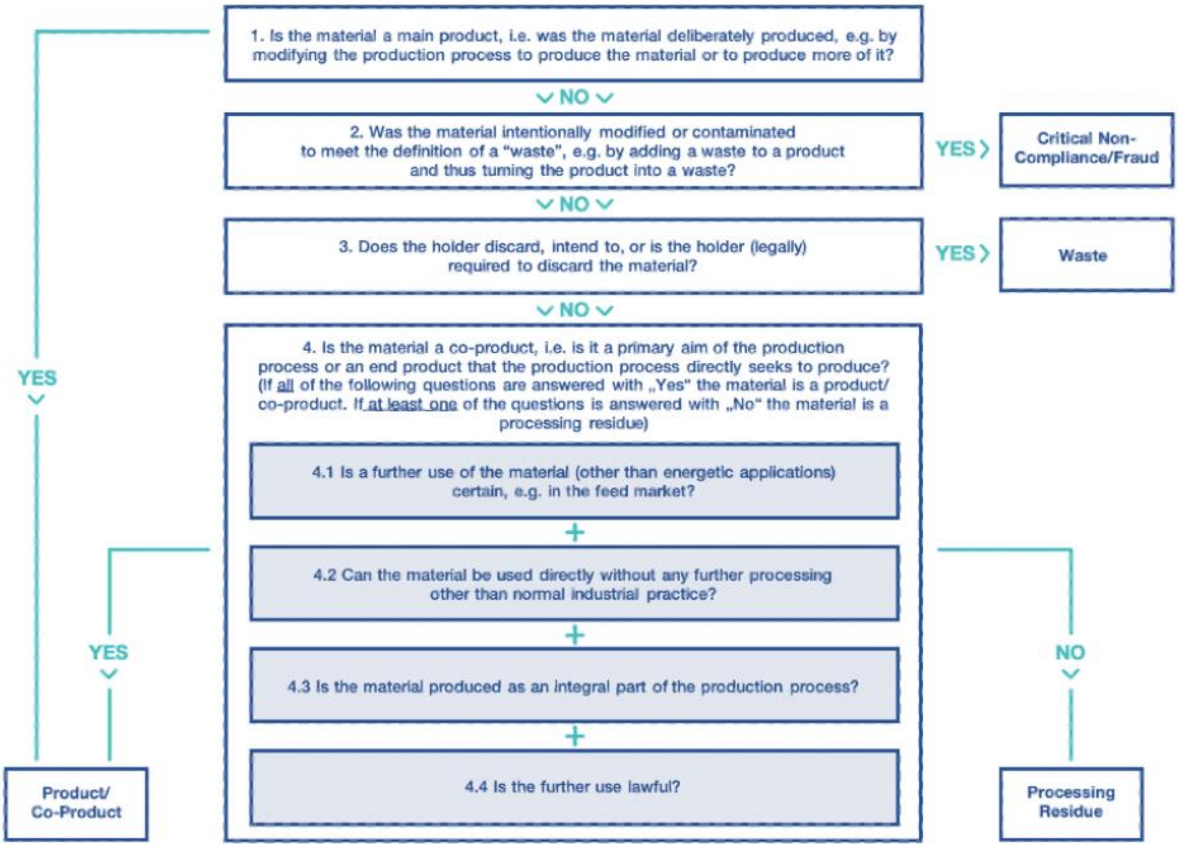


*Figure 9. Decision flowchart process to determine if a material meets the definition for waste or a co-product. Source: ISCC.*

[17] https://www.iscc-system.org/

## A - 4. Trial burn data used for biochar generation estimates

The following information were provided by Dr. Deborah S. Page-Dumroese, FS Senior Scientist, based on data collected by Northern Arizona University post-doctoral researcher Dr. Paul Oyier in Arizona (see appendix A - 2) in May 2023.

For calculations, the 'mixed' diameter class data was used, as it best represents slash biomass assumed to be fuel used for CharBoss application in forest fire fuel reduction projects.

*Table 9. Feedstock properties and CharBoss operations parameters from Arizona site demonstration in May 2023*

| Diameter Class | Description of biomass | Green weight (GT) | Average green moisture (%) | BDT of biomass | Burning time (hr) | Burning rate (BDT/hr) |
|---|---|---|---|---|---|---|
| Small (<5cm) | Biomass salvaged from pipeline fire and with no pine needles | 3.1 | 13.1 | 2.7 | 1.3 | 2.1 |
| Medium (5-10cm) | | 4.1 | 19.4 | 3.3 | 2.1 | 1.6 |
| Large (>10cm) | | 4.8 | 40.1 | 2.9 | 4.5 | 0.6 |
| **Mixed (small, medium, and large)** | | 2.8 | 24.2 | 2.1 | 1.1 | 1.9 |
| Green slash | Fresh biomass from tree trimmings toppings of up to 20cm in diameter | 12.3 | 43.8 | 6.9 | 6.5 | 1.1 |

*Table 10. Feedstock properties and CharBoss operations parameters from Arizona site demonstration in May 2023*

| Diameter Class | Weight (tons) | Average green moisture (%) | BDT of biomass | Burning time (hr) | Burning rate (BDT/hr) | Quantity of biochar | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | *Volume (ft3)* | *Wet Weight (lb)* | Wet Moisture (%) | Oven dry moisture (%) | Yield (BDT) | Yield (%BDT) |
| Small (<5cm) | 1.5 | 13.1 | 1.3 | 1.7 | 0.8 | 20.91 | 960 | 64.2 | 35.8 | 0.17 | 13.2 |
| Medium (5-10cm) | 2.6 | 19.4 | 2.1 | 4.7 | 0.4 | 38.34 | 1920 | 62.4 | 37.6 | 0.36 | 17.2 |
| Large (>10cm) | 2.6 | 40.1 | 1.6 | 5.5 | 0.3 | 13.94 | 880 | 62 | 38 | 0.17 | 10.7 |
| Mixed (small, medium, and large) | 2 | 24.2 | 1.5 | 2.6 | 0.6 | 26.14 | 1400 | 62.8 | 37.2 | 0.26 | 17.2 |
| Green slash | 4.7 | 43.8 | 2.6 | 5.2 | 0.5 | 19.52 | 1220 | 62 | 38 | 0.23 | 8.8 |

*Comments:*

Average yield as % of BDT for the mixed biomass = 17.2%

For 100 BDT of biomass, the yield = 17.2 BDT

Total burning time is the actual time recorded between the start and stop of biochar production from the biomass loaded into the CharBoss machine.

### A - 5. Biochar laboratory analysis report

The following lab report results are excerpts from a full report, that is available upon request, with information on hydrogen and carbon content of the biochar produced at three sites, used to calculate hydrogen to carbon content ratio (H:C). It is assumed that the carbon content reported is organic carbon, although not specified in the reports.

A summary of the laboratory report is presented in Table 11, where the most relevant results for the estimate of the CDR certificate potential of this project. Information on site details in found in appendix A - 2.

*Table 11. Summary of laboratory analysis of biochar generated from the CharBoss operations*

| Sample ID | Moisture | Ash | H | C | H:C |
|---|---|---|---|---|---|
| | --------------------------- % --------------------------- | | | | n/a |
| AZ | 4.62 | 27.73 | 1.03 | 67.67 | 0.18 |
| BLM | 5.79 | 1.63 | 0.91 | 92.87 | 0.12 |
| UIEF | 4.06 | 5.26 | 1.11 | 89.29 | 0.15 |
| **Average** | **4.82** | **11.54** | **1.02** | **83.28** | **0.15** |

The high ash content at the AZ site is attributed to proximity to a roll off air burner next to the CharBoss and windy conditions blowing ash and dust onto the wet biochar.

**Hazen Research, Inc.**
4601 Indiana Street
Golden, CO 80403 USA
Tel: (303) 279-4501
Fax: (303) 278-1528

Lab Control ID: 23F01619
Received: Nov 28, 2023
Reported: Dec 21, 2023
Purchase Order No.
None Received

Customer ID: 04589Z
Account ID: Z03686

ANALYTICAL REPORT

Joanne Tirocke
USDA Forest Service

**Client Sample ID –** AZ
Lab Sample ID – 23F01619-001

Air Dry Loss, % 4.06

| | As Rec'd | Dry | Air Dry |
|---|---|---|---|
| **ULTIMATE** | | | |
| Moisture, % | 4.62 | 0.00 | 0.58 |
| Ash, % | 26.45 | 27.73 | 27.57 |
| Sulfur, % | 0.016 | 0.017 | 0.017 |
| Carbon, % | 64.55 | 67.67 | 67.28 |
| Hydrogen, % | 0.98 | 1.03 | 1.03 |
| Nitrogen, % | 0.45 | 0.47 | 0.47 |
| Oxygen, %* | 2.94 | 3.08 | 3.06 |
| | 100.00 | 100.00 | 100.00 |
| **PROXIMATE** | | | |
| Moisture, % | 4.62 | 0.00 | 0.58 |
| Ash, % | 26.45 | 27.73 | 27.57 |
| Volatile Matter, % | 5.48 | 5.74 | 5.71 |
| Fixed Carbon, %* | 63.46 | 66.53 | 66.14 |
| | 100.00 | 100.00 | 100.00 |

By:

* by difference

Fuel Laboratory

File: 23F01619 R1.pdf    An Employee-Owned Company    Page 2 of 7

*Figure 10. Laboratory report of properties of biochar generated by CharBoss operations at Arizona site, AZ. Source: FS.*

HAZEN Hazen Research, Inc.
4601 Indiana Street
Golden, CO 80403 USA
Tel: (303) 279-4501
Fax: (303) 278-1528

Lab Control ID: 23F01619
Received: Nov 28, 2023
Reported: Dec 21, 2023
Purchase Order No.
None Received

Customer ID: 04589Z
Account ID: Z03686

ANALYTICAL REPORT

Joanne Tirocke
USDA Forest Service

Client Sample ID – **BLM**
Lab Sample ID – 23F01619-002

| | | | |
|---|---|---|---|
| Air Dry Loss, % | 5.33 | | |
| | **As Rec'd** | **Dry** | **Air Dry** |
| **ULTIMATE** | | | |
| Moisture, % | 5.79 | 0.00 | 0.49 |
| Ash, % | 1.53 | 1.63 | 1.62 |
| Sulfur, % | 0.020 | 0.021 | 0.021 |
| Carbon, % | 87.48 | 92.87 | 92.41 |
| Hydrogen, % | 0.86 | 0.91 | 0.91 |
| Nitrogen, % | 0.56 | 0.60 | 0.60 |
| Oxygen, %* | 3.75 | 3.98 | 3.96 |
| | 100.00 | 100.00 | 100.00 |
| **PROXIMATE** | | | |
| Moisture, % | 5.79 | 0.00 | 0.49 |
| Ash, % | 1.53 | 1.63 | 1.62 |
| Volatile Matter, % | 4.38 | 4.65 | 4.63 |
| Fixed Carbon, %* | 88.29 | 93.72 | 93.26 |
| | 100.00 | 100.00 | 100.00 |

By:

Fuel Laboratory

* by difference

File: 23F01619 R1.pdf

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Page 3 of 7

*Figure 11. Laboratory report of properties of biochar generated by CharBoss operations at Oregon site, BLM. Source: FS.*

Hazen Research, Inc.
4601 Indiana Street
Golden, CO 80403 USA
Tel: (303) 279-4501
Fax: (303) 278-1528

Lab Control ID: 23F01619
Received: Nov 28, 2023
Reported: Dec 21, 2023
Purchase Order No.
None Received

Customer ID: 04589Z
Account ID: Z03686

**ANALYTICAL REPORT**

Joanne Tirocke
USDA Forest Service

**Client Sample ID –** **UIEF**
Lab Sample ID – 23F01619-003

| Air Dry Loss, % | 3.64 |
|---|---|

| | As Rec'd | Dry | Air Dry |
|---|---|---|---|
| **ULTIMATE** | | | |
| Moisture, % | 4.06 | 0.00 | 0.44 |
| Ash, % | 5.04 | 5.26 | 5.23 |
| Sulfur, % | 0.016 | 0.017 | 0.017 |
| Carbon, % | 85.66 | 89.29 | 88.90 |
| Hydrogen, % | 1.06 | 1.11 | 1.10 |
| Nitrogen, % | 0.51 | 0.53 | 0.53 |
| Oxygen, %* | 3.64 | 3.80 | 3.78 |
| | 100.00 | 100.00 | 100.00 |
| **PROXIMATE** | | | |
| Moisture, % | 4.06 | 0.00 | 0.44 |
| Ash, % | 5.04 | 5.26 | 5.23 |
| Volatile Matter, % | 5.12 | 5.33 | 5.31 |
| Fixed Carbon, %* | 85.78 | 89.41 | 89.02 |
| | 100.00 | 100.00 | 100.00 |

By:

Fuel Laboratory

* by difference

File: 23F01619 R1.pdf An Employee-Owned Company Page 4 of 7

*Figure 12. Laboratory report of properties of biochar generated by CharBoss operations at Idaho site, UIEF. Source: FS.*

## A - 6. Project data quality Indicator scheme

A qualitative assessment matrix for all data variables used in the calculations for this study are presented in Table 12 below. The data quality scoring system is based on the approach developed by Ciroth et al. (2016) which is presented in Table 13 on the following page.

*Table 12. Qualitative data assessment matrix for all activity data used in the CharBoss biochar generation net GHG emission life cycle study.*

| DATA VARIABLE | DATA QUALITY SCORES | | | | |
|---|---|---|---|---|---|
| | Reliability | Completeness | Temporal | Geographical | Technological |
| Amount of feedstock | 1 | 1 | 1 | 2 | 1 |
| Moisture content, feedstock | 1 | 1 | 1 | 2 | 1 |
| Embedded steel, CharBoss | 2 | 1 | 1 | 1 | 1 |
| Distance, transportation CharBoss | 2 | 1 | 1 | 1 | 1 |
| Embedded steel, Takeuchi excavator | 2 | 1 | 1 | 1 | 1 |
| Distance, transportation Takeuchi excavator | 2 | 1 | 1 | 1 | 1 |
| Fuel use, CharBoss, Takeuchi, transport to site | 1 | 1 | 1 | 1 | 1 |
| Fuel use, Takeuchi feedstock moving, feeding | 1 | 1 | 1 | 1 | 1 |
| Fuel use, CharBoss | 1 | 1 | 1 | 1 | 1 |
| Operating hours, CharBoss | 2 | 1 | 1 | 1 | 1 |
| Stack methane emissions, CharBoss | 1 | 1 | 1 | 2 | 1 |
| Transportation, biochar to final use | 2 | 1 | 1 | 2 | 1 |
| Biochar produced | 2 | 1 | 1 | 1 | 1 |
| Moisture content | 1 | 1 | 1 | 2 | 1 |
| Organic carbon fraction | 1 | 1 | 1 | 2 | 1 |
| H / Corg ratio | 1 | 1 | 1 | 2 | 1 |
| Soil Temperature | 2 | 1 | 1 | 2 | 1 |
| Allocation factor | 1 | 1 | 1 | 1 | 1 |

*Table 13. Qualitative data scoring system for assessment of data used in the CORC project (based on Ciroth et al. 2016).*

| DATA QUALITY PARAMETER | SCORE | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| **Reliability** | Verified data based on measurements | Verified data partly based on assumptions or non-verified data based on measurements | Non-verified data partly based on qualified estimates | Qualified estimate (e.g., by industrial expert) | Non-qualified estimates |
| **Completeness** | Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations | Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations | Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods | Representative data from only one site relevant for the market considered or some sites but from shorter periods | Representativeness unknown or data from a small number of sites and from shorter periods |
| **Temporal correlation** | Less than 3 years of difference to the time period of the data set | Less than 6 years of difference to the time period of the data set | Less than 10 years of difference to the time period of the data set | Less than 15 years of difference to the time period of the data set | Age of data unknown or more than 15 years of difference to the time period of the data set |
| **Geographical correlation** | Data from area under study | Average data from larger area in which the area under study is included | Data from area with similar production conditions | Data from area with slightly similar production conditions | Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) |
| **Further Technological correlation** | Data from enterprises, processes, and materials under study | Data from processes and materials under study (i.e., identical technology) but from different enterprises | Data from processes and materials under study but from different technology | Data on related processes or materials | Data on related processes on laboratory scale or from different technology |

## A - 7. Emission and conversion factors used.

Emission factors used for project lifecycle emissions calculations are listed in Table 14 to Table 15 below.

*Table 14. Scope 1 emission factors, (US EPA, OAR 2015)*

| Energy Type | $CO_2$ (g / L) | $CH_4$ (g / L) | $N_2O$ (g / L) | $CO_2eq$ (g / L) | Upstream $CO_2eq$ (g / L) | Total $CO_2eq$ (g / L) |
|---|---|---|---|---|---|---|
| **Diesel** | 2697.198 | 0.108 | 0.021 | 2705.787 | 624.09 | 3329.88 |

UK DEFRA. Government conversion factors for company reporting of greenhouse gas emissions

*Table 15. Other emission and conversion factors (IPCC 2014)*

| | | | |
|---|---|---|---|
| ***GLOBAL WARMING POTENTIAL VALUES*** | | | |
| ***$CO_2$*** | ***$CH_4$*** | ***$N_2O$*** | |
| ***1*** | *28* | *265* | |
| ***LIFE CYCLE GHG EMISSION FACTORS*** | | | |
| ***Input Material*** | ***MT $CO_2eq$ / MT*** | ***Source*** | |
| ***Steel (well to use)*** | *1.9857* | *GREET 2021.Net Software: Steel Production Main Output: Steel* | |
| ***LOGISTICS FACTORS*** | | | |
| ***Transport Type*** | ***Unit*** | ***Value*** | ***Source*** |
| ***Diesel consumption truck (loaded)*** | *liters/km* | *0.49* | *International Sustainability & Carbon Certification (ISCC) EU 205: Greenhouse Gas Emissions* |

*Equation 4. Conversion factors used in data processing and calculations*

| Conversions | Factor | Unit | Comment |
|---|---|---|---|
| **US gal to L** | 3.7854 | L/gal | Volume of US gallons converted to liters |
| **Ton to MT** | 0.9071847 | Short ton/MT | Mass of short ton (2,000 lbs) converted to metric tonne |
| **miles to km** | 1.6094 | km/mi | Distance in miles converted to kilometers |
| **miles/gal to km/L** | 0.4252 | km/L | Fuel efficiency of miles per gallon converted to liters per kilometer |
| **Pound to kilogram** | 0.453592 | lb/kg | Mass of pounds converted to kilograms |

Emission factor for CharBoss operations (Table 3) is from ODEQ emission test report (ODEQ 2023).