Biomass and Bioenergy 190 (2024) 107364

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

FireBox and CharBoss: An alternative to open burning of woody biomass

Paul O. Oyier [a], Han-Sup Han [a,*], Dipita Ghosh [a], Nathaniel Anderson [b], Deborah S. Page-Dumroese [c], Daniel W. McCollum [d], Joanne M. Tirocke [c], Derek N. Pierson [c]

[a] Ecological Restoration Institute, Northern Arizona University, Flagstaff, AZ, 86001, USA
[b] Rocky Mountain Research Station, USDA Forest Service, Missoula, MT, 59801, USA
[c] Rocky Mountain Research Station, USDA Forest Service, Moscow, ID, 83843, USA
[d] Rocky Mountain Research Station, USDA Forest Service, Fort Collins, CO, 80526, USA

A R T I C L E I N F O

Keywords:
Forest biomass
Biochar
Biomass utilization
Soil amendment
Carbon storage

A B S T R A C T

Open burning is commonly used to dispose of piles of forest residues generated by forest management activities; however, this method is associated with smoke emissions and damage to forest soil. Air curtain burners (ACB), such as the Firebox (FB) and CharBoss® (CB), offer an alternative to open burning. This study evaluated the performance of FB for biomass disposal and CB for biomass disposal and biochar production with the objective of quantifying the benefits and limitations of each machine. Ponderosa pine biomass obtained from harvesting after a wildfire event and freshly cut wood from ponderosa pine trimmings were used to evaluate the performance of each machine. We measured the combustion rate for both machines and biochar produced from CB. The burning rate for large-diameter (>10 cm) biomass using FB machine was 1.1 GT/h (924 °C) while small-diameter (<5 cm) biomass burned at the rate of 2.4 GT/h (814 °C), and for biomass consisting of mixed-sized materials it was 2.5 GT/h with the highest recorded temperature of 1089 °C. The biochar yield from CB operations ranged between 8.8 % and 17 % on a bone-dry ton basis. The size of biomass material, machine type and moisture content influenced the burning rate. The FB is most appropriately used in a centralized setting where large quantities of biomass are available near harvest operations, while the CB is better used for biochar production in a mobile setting. These results are useful for understanding alternative biomass management options, the long-term financial implications, and environmental benefits.

1. Introduction

In the southwest United States (US), forest restoration generally involves cutting small-diameter trees to promote forest health and reduce the risk of catastrophic wildfire [1]. This operation leads to the production of large quantities of low-value forest biomass which, due to the lack of readily available markets in this region and the high hauling cost, leads to a biomass bottleneck [2]. Thus, it is imperative to use alternative disposal and utilization methods to reduce the risk of a high-severity wildfire [3,4]. Currently, regional bioenergy and bio-based markets are being subsidized to support forest restoration efforts by state and federal agencies [5]. Unlike traditional timber harvests, restoration thinnings are focused on sub-dominant trees and woody understory vegetation rather than valuable sawlogs, and often results in a net cost to public agencies as they seek to re-establish appropriate stand stocking levels that are resilient to fire, insects, diseases, and drought [6]. Addressing disposal of the low value/waste biomass or its conversion to bioproducts calls for innovative approaches.

Low-value woody biomass from forest thinning operations is typically burned in piles for disposal to limit fire risk, open growing space for residual trees, reduce the risk of wildfire, and accomplish other management goals [7]. Although open burning is an established and inexpensive method of reducing the biomass in piles, this method produces smoke and greenhouse gas emissions [8], kills soil microorganisms and destroys organic matter [9] and reduces nutrient content and availability [3,10]. The practice is banned in some places, especially locations with sensitive airsheds, and is restricted locally and nationally in some countries [11]. Moreover, open burning can sometimes lead to risky unplanned wildfires that escape suppression, especially with changing dynamics of wind speed and direction and, therefore, require special fire management strategies to control the spread of fire within

* Corresponding author.
E-mail addresses: oyiergy@yahoo.com (P.O. Oyier), han-sup.han@nau.edu (H.-S. Han), dipita.ghosh@nau.edu (D. Ghosh), nathaniel.m.anderson@usda.gov (N. Anderson), debbie.dumroese@usda.gov (D.S. Page-Dumroese), daniel.mccollum@usda.gov (D.W. McCollum), joanne.m.tirocke@usda.gov (J.M. Tirocke), derek.pierson@usda.gov (D.N. Pierson).

https://doi.org/10.1016/j.biombioe.2024.107364
Received 29 May 2024; Received in revised form 25 August 2024; Accepted 27 August 2024
Available online 6 September 2024

Abbreviations:

ACB	Air curtain burner
BDT -	Bone Dry Ton
CAT –	Caterpillar Incorporated
CB –	CharBoss
FB -	FireBox
GT -	Green Ton
USDA –	United States Department of Agriculture

the unit [12,13]. This limits open burning to relatively narrow burn windows in the spring and fall. Moreover, the risk and cost of wildfires resulting from escaped prescribed fire could outweigh the benefits of burning low-value woody residual within a harvest unit; suggesting that finding alternative uses for the material (e.g., biofuel, bioenergy, biochar) may also result in mitigating wildfire risk [14]. The high temperatures associated with open pile burning (>300 °C) alters soil physio-chemical, and biological properties in the pile burn areas [9,15,16]. According to Mott et al. [10] soil stability and aggregation are disrupted due to the loss of soil organic matter. High severity burns can also result in a "burn scar", which can persist for decades and are often sites of increased invasive or non-native species colonization [9].

These negative impacts from open slash pile burning have been the impetus to discourage or restrict open burning in some areas and the catalyst to develop viable alternatives. Examples of such tools include a wide range of mobile and modular machines called air curtain burners (ACB) that reduce the volume of low value wood quickly while reducing harmful emissions compared to open burning [17,18]. Air curtain burners (ACB) use a high velocity airflow system, referred to as an "air curtain", which steadily blows air across the burn box via a manifold running lengthwise along the top of the burnbox and above the biomass, thus blocking smoke and minimizing ember escapes and reburning gases for a cleaner, more efficient burn [19].

It has been reported that emissions can be reduced manifolds by using ACB biomass disposal technique compared to open burning [20–22]. Similarly, Susott et al. [22] reported that $PM_{2.5}$ emissions can be reduced to 0.5 kg ton^{-1} while burning ponderosa pine wood using a 217 model of ACB over pile burn (11.6 kg ton^{-1}) and understory burn (16.3 kg ton^{-1}) [22]. The study showed that increased combustion time and air turbulence leads to a complete combustion of the biomass. Another study comparing air quality impacts between ACB burning and open burning found that improved combustion conditions with lower PM and CO emissions resulted due to better air flow, containment of heat around the combustion zone, and more controlled introduction of debris [18]. A literature review conducted by Miller and Lemieux [18] on emissions from a burning biomass in Air Curtain Destructors (Air Burners Model S-127) reported the average CO concentration of 54 ppm, CO_2 levels of 0.2 % and PM concentrations of 6600 μg m^{-3}, while emission rates were reported at 0.97 kg h^{-1}.

More recently, Page-Dumroese et al. [21] reported a summary of a trailer-mounted ACB unit trials producing biochar which employs the same principle of the ACB technology, producing high-carbon content biochar as well as disposing woody biomass. This new technology further enhances environmental performance by not only reducing emissions from ACB burning but also storing carbon in a form of biochar. Further, a life cycle analysis was performed by Johannesson et al. [23] to calculate net emissions from biochar used as a carbon sink when an ACB machine (CharBoss) was used. Applying the puro.earth methodology to the activity data, this project estimated that it has the potential to generate 2403.81 metric tonnes CO_2eq of Carbon Dioxide Removal (CDR) certificates from 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 effectively improve the sustainability of the National Forests in the US. The ash component of the biomass typically remains in the bottom of the box or on the ground in ACBs that do not have an engineered floor.

One company producing ACBs is Air Burners, Incorporated (Palm City, Florida, USA). They manufacture a variety of equipment designed for mobility and heating efficiency, including the FireBox® (FB), BurnBoss® (BB), and CharBoss® (CB) machines. In general, the use of ACBs requires that biomass be loaded into the equipment using an excavator, loader, or skid-steer and arranged to maximize combustion within the system [19]. Depending on the model, ACBs reduce biomass to ash (the residual mineral fraction remaining after complete combustion) or biochar (a high carbon product for land application). Air curtain burners have been used for years for biomass management and details on the methodology and production rates can be found in Lee and Han [20]. Biochar produced on-site can be used to restore degraded soil conditions associated with roads, log landings, wildfire, erosion, past burning and mining by improving water and nutrient holding capacity and thereby facilitating vegetative cover, or removed from the site to use in agriculture, horticulture, and other applications [21,24,25].

The rate of burning of biomass using ACBs is highly variable depending on the type of equipment used, feedstock species and diameter, moisture content, and rate of loading, [20]. Lee and Han [20] compared the rates of burning and costs for two different sizes of ACBs (Air Burners, Inc. S-220 and BurnBoss), and performance in air quality and operational logistics between BurnBoss and hand piles prepared for open burning. The costs of burning per green metric ton per scheduled machine hours (SMH) were 70 % higher when using a BB as compared to the larger S-220 ACB, however the BB was 40 % more efficient and had lower smoke emissions as compared to open burning of a hand-pile. These results demonstrate that burning variability using similar biomass is related to technology type. In addition, Jang et al. [26] noted that heat transfer from open burning reached a maximum of 389 °C 1 cm beneath the soil surface but was only 133 °C at a similar depth under the BB indicating that the creation of a coal bed under the burning biomass limits heat transfer resulting in minimal impacts on soil physical and chemical properties.

As noted above, ACBs generally increase low value woody biomass management efficiency, provide greater fire control, reduce particulate matter and greenhouse gas (GHG) emissions, and have fewer negative soil impacts. ACBs make it easier to dispose of biomass and, depending on the model, result in biochar production. The CB unit has the added advantage of continuous biochar production. Furthermore, when compared to the FB, a CB is towable. Both the FB and CB are designed to burn variable infeed biomass quantities using the same burning principle, but there is a need to determine the variability in burning efficiency between FB for biomass disposal without biochar production and CB for biomass disposal and biochar production to assist land managers in determining the best tool for biomass management in specific cases. Given the recent development and deployment of the CB, there is also a need to understand the operational tradeoffs between FB and CB to guide their efficient deployment.

While previous work detailed the use of the FB S-220 series [20], the CB is a new product that has not been previously evaluated for production and costs. Since FB and CB provides alternatives to open pile burning, quantifying their operations and outputs can help increase their use by giving land managers baseline data. Therefore, our goal was to evaluate the performance of the FB for biomass disposal and CB for biomass disposal plus biochar production, including understanding the tradeoffs, benefits, and limitations of these alternatives. The specific objectives were to: i) determine the rate of biomass burning for FB and CB machines, ii) quantify the amount and rate of biochar produced using the CB machine, iii) determine the operational cost of biomass disposal using FB and CB, and iv) perform cost-benefit analysis for using FB for disposal of biomass and CB for biomass disposal and biochar production.

Fig. 1. Biomass materials used in the study: (A) biomass from fire-killed trees and (B) fresh-cut biomass with foliage.

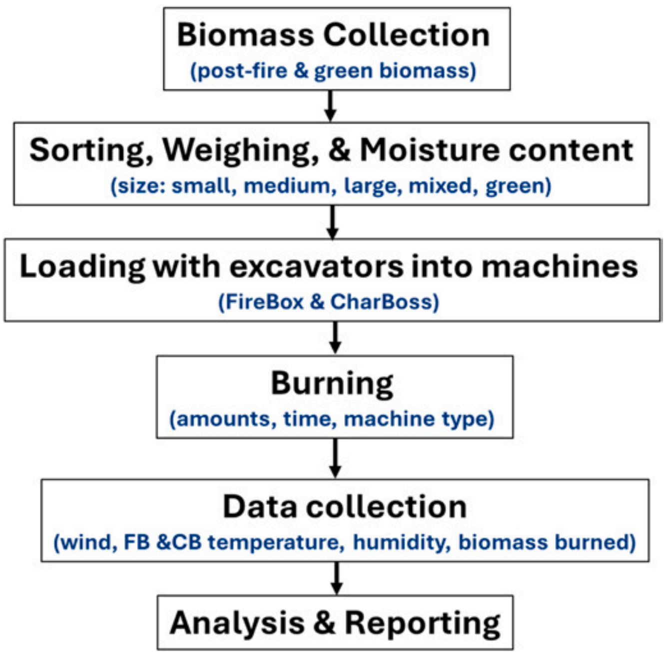

Fig. 2. A graphical flowchart depicting the study design.

We also discuss operational considerations for these machines deployed in the forest sector as an alternative to open pile burning of low-value woody biomass generated by forest management activities.

2. Materials and methods

2.1. Study area and design

The study was conducted for four-days (April 24–28, 2023) at the eastern side of Flagstaff, Arizona, at a public works facility owned and managed by the Coconino County Flood Control District that is designated for burning woody biomass. This facility is in an open area which facilitated prediction of wind speed and direction, key variables for operating FB and CB. For purposes of fire safety and operational efficiency, Air Burners, Inc. [19]. recommends burning using the FB and CB when wind speeds are below 32 km/h.

We used fire-killed ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) trees removed by the Coconino County Flood Control District, and freshly cut (green) pruning waste from a local golf course. The fire-killed trees were salvage logged and removed using rubber tracked Caterpillar Inc. CAT308 excavator and CAT299D2 skid-steer front-end loader. During the post-fire harvest the biomass tended to pick up soil as it was loaded onto dump trucks. The wood was kept in large piles for ten months prior to the experiment (Fig. 1A). Removal of trees killed by fire was not a typical timber harvesting salvage operation, but rather a cleaning process to remove flooding debris and fire-killed ponderosa pine trees in the affected district. The green biomass from the golf course was from tree trimmings and tops that were up to 20 cm in diameter (Fig. 1B). They were obtained from a local resident who considers them as woody biomass wastes from periodic property maintenance and cleaning. Foliage was not removed from the green materials. A schematic overview of the study design is shown in Fig. 2.

2.2. Data collection

2.2.1. Biomass measurements

We sorted each pile of biomass into five diameter classes (Fig. 3): i) small (<5 cm), ii) medium (5–10 cm), iii) large (>10 cm), iv) mixed (combination of small, medium, and large diameter classes), and v) mixed green (pruned biomass from golf courses). The 'mixed' biomass did not have specified size and moisture content amounts but was created to mimic a typical slash pile created from fire-killed or pruned trees. According to the Biomass Energy Foundation [27], based on proximate and ultimate analysis a typical Ponderosa pine (biomass generally has a fixed carbon of 17 %, a high volatile matter (~83 %) and an ash content of 0.29 %. It has a high elemental carbon content of ~50 % and has high content of H (5.99 %), O (44.36 %); and a trace amounts of N (0.06 %) and S (0.03 %).

Wood samples for moisture measurements were randomly chosen from the small, medium, large, and green storage piles of woody biomass material. Moisture content for samples picked from each storage pile of woody biomass was collected using Lignometer K Pin Meter designed to measure a range of moisture from 5 to 99 % [28]. To determine the moisture content in percent, the 3.8 cm long electrode pins of the Lignometer K moisture meter were driven into the woody biomass samples and moisture readings obtained from the digital display. The average moisture content for each pile of woody biomass was determined by adding the individual reading of the random samples and dividing by the total number of samples. For the large and medium biomass materials, the cross-sectional area not exposed to ambient weather was cut using a chainsaw and tree moisture readings taken diagonally across the cross-section and averaged to give the moisture reading for a randomly chosen sample. The moisture content for the mixed-size biomass was determined as the average for small, medium, and large biomass materials. For each storage pile of biomass (e.g., small, medium, large, mixed, and green), the average moisture content was recorded on a wet basis as percent of water contained within the woody biomass.

The weight of each storage pile of woody biomass by diameter class was determined by taking the difference in the axle loads of an empty and loaded truck using a portable scale (PT300 RFX Solar Weighing

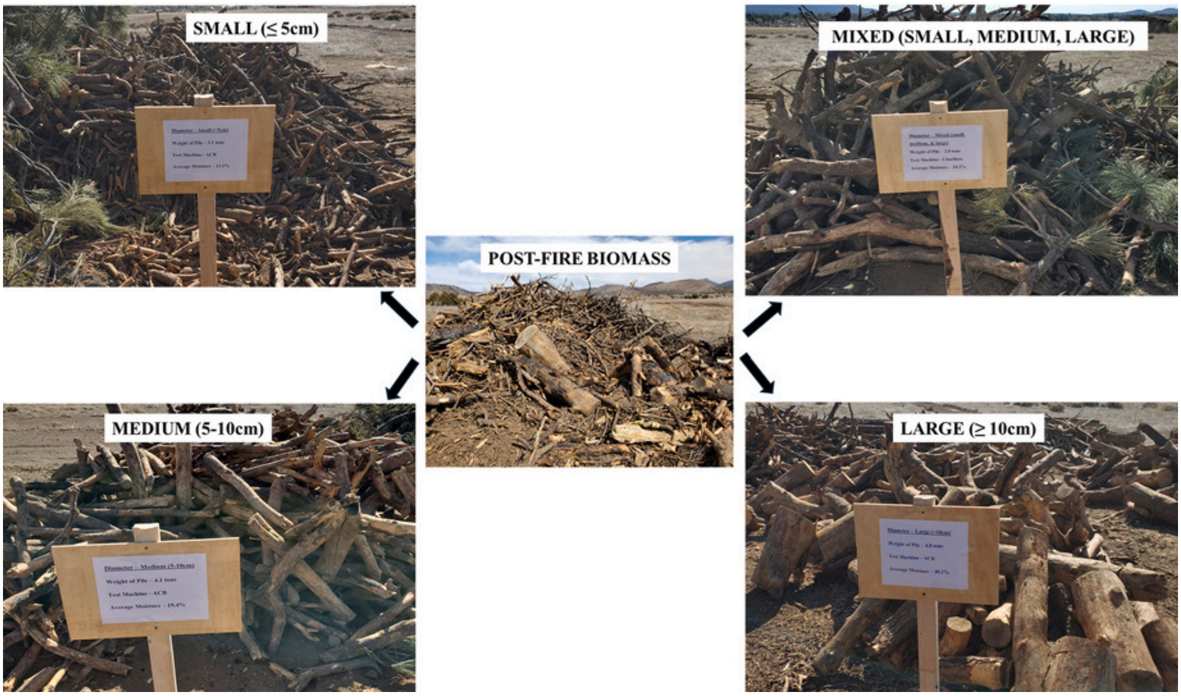

Fig. 3. Diameter classes for post-fire biomass that were used for the study.

Table 1
Summary of each size-class moisture content and mass of each type of biomass used for testing the FireBox (FB) and CharBoss (CB).

Diameter Class	Description of biomass	Average moisture (%)	Weight of biomass[a]			
			FB		CB	
			Green tons (GT)	Bone dry tons (BDT)	Green tons (GT)	Bone dry tons (BDT)
Small (<5 cm)	Biomass salvaged from a wildland fire and with no pine needles	13.1	3.1	2.7	1.5	1.3
Medium (5–10 cm)		19.4	4.1	3.3	2.6	2.1
Large (>10 cm)		40.1	4.8	2.9	2.6	1.6
Mixed (small, medium, and large)		24.2	2.8	2.1	2	1.5
Green biomass	Biomass obtained from tree trimmings toppings with up to 20 cm in diameter	43.8	12.3	6.9	4.7	2.6

[a] GT: Green ton (metric); BDT: Bone Dry Ton (metric).

System). The tare weight of the empty truck was determined by taking and summing the steering and driving axle loads when the truck was standing on the portable weighing system. The weight of the truck when fully loaded with biomass was determined by the same way. For every truck loading cycle, the weight of biomass was determined as the difference between the gross and tare weight of the truck. The total weight

Fig. 4. (A) The roll-off FireBox S-119 Air Curtain Burner and (B) CharBoss used in the current study.

Fig. 5. (A) Loading FB with CAT 308 tracked loader and (B) Loading CB with CAT299D2 skid-steer tracked loader. The four-day burning schedule was based on hourly burning throughput for FB and CB machines, predicted wind speeds, and the quantity of biomass available for burning.

of each pile of woody biomass was determined as a summation of all the truck cycle loads for each pile of biomass by diameter class in green metric tons (GT). The weight in GT of each pile of biomass by diameter class was also calculated as weight equivalent in bone dry metric tons (BDT) at zero moisture content. Table 1 is a summary of the description of biomass materials used by diameter class, average green moisture content, and weight of each pile of biomass burned by each machine.

2.2.2. *Equipment, tools and site preparation*

To facilitate travel and loading machines between the FB, CB, and biomass piles, the soil around each piece of equipment was leveled using a CAT299D2. This tracked compact skid-steer machine is commonly used for vegetation-management applications such as mastication, mulching, brush-removal, and mowing, and was equipped with a grapple bucket for this study. Piles were located at least 15 m from either machine to mitigate unintended ignition. The required burn permit was obtained from the Coconino County Fire Department. The Roll-Off FireBox S-119 and CB used for the study were manufactured by Air Burners, Inc. (Fig. 4). The FB was loaded using a rubber tracked CAT 308 excavator with a bucket and thumb (Fig. 5A). This machine is typically used for excavation tasks like digging and loading, but is effective for loading ACB when the bucket is equipped with a thumb. The CB was loaded using a combination of the CAT299D2 with grapple bucket (Fig. 5B) and manually loading by ground personnel. The skid steer dumped wood next to the CB following which ground personnel would toss wood into the CB burnbox. The CB can be loaded effectively with an excavator or loader, but the decision to hand load the CB allowed precise and consistent loading to maximize biochar productivity. Hand loading also mimics a situation where the equipment is run by a wildfire crew, which typically does not deploy heavy equipment for seasonal burning operations. Biochar exiting CB is extinguished in a quench pan full of water, which was measured during operations. Biochar is removed from the quench pan and piled using hand tools, including a landscape rake and a mud/sifting shovel. Though land application of biochar was beyond the scope of this study, biochar could then be spread on a site by a variety of manual or mechanical methods [29]. Other operational protocols are found in Page-Dumroese et al. [21]. To reduce smoke, wood is kept below the manifold producing the air curtain. Wood ignition is enhanced by using diesel fuel or some other ignition aid. Typically, a base fire is established and when approximately 2/3 of the wood is gone, then the air curtain is established. The motor generator sucks in atmospheric air and blows across the top of the combustion zone as a uniform air curtain above the biomass material. The air curtain is maintained throughout the burning period with biomass loaded at a rate consistent with the rate of burning, depending on biomass characteristics such as size and moisture content.

2.2.3. *Load timing*

The loading cycle times for the CAT308 excavator and CAT299D2 loader (for piling biomass for loading into CB machine) were determined by recording and summing the individual times for all loading cycle elements. Average loading cycle time for each loading machine was determined by dividing the total cycle times by the total number of loading cycles ($n = 79$ for CAT308 and $n = 49$ for CAT299D2). A stopwatch AX PRO (AX705 Accusplit®) was used to record each loading time decimal time measurements on a scale of 1/100 of a minute (decimal seconds). The recorded cycles for CAT308 and CAT299D machines were: i) driving empty to a pile of biomass located 15 m from either the FB or CB machines, ii) grabbing the biomass, iii) driving back loaded to the burning machine, and iv) dropping and arranging biomass material into the FB or adjacent to the CB for hand loading. Delay-free loading cycles for each of the loading machines were recorded and analyzed. Loading cycles with partial hand loading of the CAT308 and CAT299D2 buckets were excluded. It was not practical to determine the average weight of each cycle load for each loading machine because some biomass was dropped for hand loading and the loader operator used both CAT308 and CAT299D2 loaders interchangeably to load one pile of biomass into FB and drop biomass near the CB. It was also impractical to weigh each bucket load because it significantly disrupts the workflow with research delays. Accordingly, average weights were estimated based on calculations using the known weights of the biomass piles as described below.

2.2.4. *Weather measurements*

The daily relative humidity, wind speed, and atmospheric temperatures during burning were recorded using Kestrel 3500 Light Metal 3091 (Kestrel Instruments, Nielsen-Kellerman Company) weather measuring equipment. The FB could not be used on the second day due to forecasted high wind speed, similarly the CB was shut down midday. Operations were shut down approximately 2 h before departing the site to ensure the fire was out and coals cooled to reduce the chance of an unintended fire. Average daily relative humidity, wind speed, and air

Table 2
Daily average relative humidity, wind speed, and air temperature.

Day	Diameter class		Relative Humidity (%)	Wind speed (km/hr)	Air Temperature (°C)
	FB	CB			
1	Small & Medium	Small & Medium	22	13	20
2	No burning	Mixed	23	21	18
3	Green	Green	24	11	13
4	Large & Mixed	Large	13	14	22

Table 3
Variable descriptions and types that were included in regression models.

Variable name	Type	Description	Variable Type
Machine	Explanatory	Equipment type	Class (2 levels)[a]
Diameter	Explanatory	Size class of biomass	Class (5 levels)[b]
Moisture	Explanatory	Moisture content at the time of burning	Continuous
Biochar	Response	Quantity of biochar produced in BDT	Continuous
Rate	Response	Quantity of BDT of biomass burned per unit time	Continuous
Temperature	Response	Burning temperature of biomass within the FireBox	Continuous

[a] Machine: 1 = FireBox (FB),2 = CharBoss (CB).
[b] Diameter: 1 = Small (<5 cm),2 = Medium (5–10 cm),3 = Large (>10 cm),4 = Mixed materials (small, medium, and large)5 = Green biomass (≤20 cm).

temperatures are listed in Table 2. Weather conditions can impact the operation and productivity of ACBs (e.g., winter versus summer operation), but weather-related variables were not considered explicitly in this study, which focused on quantifying differences between machines under identical conditions.

2.2.5. Daily operations

Daily start and end times were recorded using a standard wristwatch. Starting time was recorded 20 min after initializing the air curtain over the FB and CB. Stop time was recorded when the biomass was fully burned. It often takes up to an hour or more for the material in the FB to burn down after the last load, and hence the shutdown time was included in the cycle time. Waiting 20 min after starting the air curtain ensured sufficient biomass ignition, preventing a strong air curtain speed from extinguishing the flames. The 20-min lag time is considered for the total cycle time which is calculated as the difference between the start and stop times for each size-class. The rate of burning or throughput was determined by dividing the volume of biomass in green tons (GT) burned by the total burning time. Since the biochar is quenched, we measured its wet weight for each diameter class by weighing the total amount of biochar collected from the start to the end of the burning period. The moisture content of the wet biochar was determined by weighing then drying at 105 °C for 24 h and weighing again. The mass of oven dry biochar was determined as bone dry tons (BDT) at zero moisture content, from which the yield was determined as percent of the infeed quantity BDT of biomass burned. The wet-based moisture content in percent of biochar was determined using the following formula:

$$\textit{Moisture Content}\ (\%) = \left(\frac{\textit{Initial Moisture Content} - \textit{Final Moisture Content}}{\textit{Initial Moisture Content}}\right) * 100$$

During burning, temperature inside the FB and CB were measured using Omegascope laser scanner-OS523E-1 (Omega Engineering, Incorporated). Peak burning temperatures were recorded when the heat waves above the air curtain manifold were visible. The laser scanner was configured to measure up to a maximum of 1371 °C at distances ranging from 1 m to 26 m [30]. The maximum burning temperatures of biomass was determined by pointing and scanning the laser gun at the target burning biomass within the FireBox positioned at about 2 m from above the FireBox.

Table 4
Cost factors and assumptions used in machine rate calculation.

Cost factors	FB	CB (Hand Loading)	CAT308
Purchase price ($)	153,383	148,861	150,000
Salvage value ($)	500	500	15,000
Economic life (years)	10	10	10
Interest, Insurance, & Taxes (% average annual investment)	12	12	10
Repair & Maintenance (% of depreciation)	47	47	47
Fuel consumption (l/hour)	7.3	4.2	6.1
Fuel cost ($/l)	1.31	1.31	1.31
Horsepower (kw)	74.5	–	74.3
Lubrication and oil cost (% fuel cost)	40	–	40
Operator wages ($/hour)	–	25	25
Fringe benefits (% of wages)	35	35	35
Scheduled machine hours (SMH/year)	1800	1800	1800
Productive machine hours (PMH/year)	1620	1620	1350
Utilization rate (%)	90	90	75
Machine cost ($/SMH)	30.14	58.30	55.66
Machine cost ($/PMH)	33.49	64.77	75.55

2.3. Economic evaluations and statistical analyses

The variables used in the statistical model were biomass diameter, equipment type, moisture content, burning rate, burn temperature, and biochar mass (Table 3). Statistical software R [31] was used for the statistical analyses apart from this, MS-EXCEL was used for graphical representation. The diameter variable was grouped by each equipment type (FB or CB) and biomass moisture content, burn rate, burn temperature, and biochar quantity were grouped by diameter size class.

Multiple linear regression and extra sum of squares F-test using a backward selection method were used to test whether the explanatory variables accounted for a significant amount of variation in *Rate* and *Biochar* while looking for correlation. In the extra sum of squares F-test, a full model was considered as the model with all the explanatory variables included, a reduced model as the model with the variable of interest removed, and an intercept only model was the model without any explanatory variable. In the backward method used in the extra sum of squares F-test, an explanatory variable was retained in the model when the $p \leq 0.05$, otherwise it was excluded. Retaining the removed variable with a low p-value in the model meant that it explained a significant amount of variation observed in the continuous response variable. All the data on continuous response variables were checked for any violation of the assumptions of normality of the distribution and constant variance before regression modeling and analysis. In the regressions models, the variation in *Rate* was determined using *Machine*, *Diameter*, and *Moisture* as explanatory variables, while variation in *Biochar* was determined using *Diameter* and *Moisture* as explanatory variables. The intercept only models for *Rate* and *Biochar* were analyzed for any significant variation in the response variable without including any of the explanatory variables. Significant variation (if any) in the response variable was first established using the intercept only model to provide the basis on which the variation in the response variable (if any) was a function of the explanatory variables used in the model.

Machine cost ($/hour) was calculated using the standard machine rate method developed by Miyata [32] and cost assumptions specific to a machine used in performing a given function. The assumptions used for

Table 5
Average loading cycle times for each cycle element for a CAT308 and CAT299D2 loader.

Loading cycle element	Mean cycle time (minutes)[a]	
	CAT308 (n = 79)	CAT299D2 (n = 49)
Drive empty to pile (average distance of 15.2 m)	0.39 (24)	0.38 (30)
Grab biomass	0.44 (27)	0.28 (22)
Drive loaded back to machine	0.47 (29)	0.40 (32)
Drop biomass and arrange in FireBox	0.29 (18)	0.20 (16)
Average cycle time	1.59 (100)	1.25 (100)

[a] Values in parentheses are percentage of the average cycle time.

the cost factors (Table 4) for FB, CB, and CAT308 machines are based on the actual values obtained from Air Burners, Inc., and sales information from equipment users (e.g., the Director of Coconino County Flood Control District). The machine costs were calculated and reported per scheduled machine hours ($/SMH) and per productive machine hours ($/PMH). The cost ($/GT) of disposing biomass was determined for base case scenarios for i) FB loaded with a CAT3038, and ii) CB loaded manually (i.e., hand loading).

Break-even analyses for the disposal of mixed diameter biomass using FB and CB machines for a base case scenario were performed to determine the point of indifference for the volume of biomass burned (GT) and the break-even cost ($/GT). The break-even volume burned and cost per unit volume burned is integral to determining the marginal cost of burning an additional unit of biomass during disposal above the point of indifference for the base case scenario. In addition to operational considerations unique to each machine, this can be used as a decision refence point in choosing the optimal method for disposal of biomass. Sensitivity analysis for disposal of mixed diameter biomass for the base case scenario was performed to evaluate the operating costs of disposing biomass by burning based on assumed annual operating hours. In the break-even and sensitivity analyses of the base case scenarios, the results of burning mixed biomass material were used because biomass is typically burned without sorting in open pile burning [20], making mixed-diameter biomass a likely field scenario. The rate of burning obtained for the mixed biomass in the economic analyses assumed there would be no economic justification in separating biomass material into various diameter classes under normal operating conditions.

3. Results and discussion

3.1. Biomass loading rates into the FireBox and CharBoss

Delay-free loading cycle times for CAT299D2 and CAT308 loading machines were determined based on complete loading cycles (Table 5). The average delay-free loading cycle time for CAT308 loader was 1.59 min, while that of CAT299D2 loader was 1.25 min. The return trip after loading accounted for the largest component of total loading cycle time for CAT299D2 (32 %) and CAT308 (30 %). During field observations, we noted that the variability in the total loading cycle time was associated with a single machine operator driving both loaders. This meant they would spend more time picking up the shorter (approximately 1 m long) biomass. In addition, the loaders would be slowed when traversing over dropped wood that was scattered along the travel path. The type and size of biomass material being handled during loading explained variation in the total loading cycle time. For example, handling freshly cut biomass with needles was more efficient with CAT308 loader while CAT299D2 loader with a bucket was the most appropriate tool for picking up wood only. As expected, hand loading freshly cut biomass that still had needles attached into CB was more difficult as compared to loading the post-fire biomass without the pine needles. Loading and arrangement of biomass into FB using the CAT308 was more efficient than the D2 loader due to its longer arm reach. Although hand loading of the CB was ideal for consistent rather than pulsed loading and resulted in higher biochar throughput, actual field use of the equipment could include a small excavator, skid steer, or loader to reduce the work of the crew.

3.2. Burning rates for various biomass types and sizes

Burning rate for the large (>10 cm) diameter biomass using the FB was 1.1 GT/h at an average burning temperature of 924 °C. Small diameter (<5 cm) biomass burned at the rate of 2.4 GT/h at an average temperature of 814 °C (Table 6). When mixed biomass was used in the FB the burning rate was 2.5 GT/h, with the highest recorded burning temperature of 1089 °C. The rate of burning for mixed sized biomass is important as it represents the typical biomass type that would likely be burned when a FB or CB are used to dispose of low value biomass. Similar to the FB, the rate of burning of biomass using the CB increased with the decrease of the size of biomass material (Table 6), but the mixed size material was similar to that of the small material. Small diameter biomass has a greater surface area exposed to the heat, which enhances heat transmission during combustion. This increased surface area allows for faster heat transfer, leading to more efficient burning. Though the combustion kinetics of the mixed materials are not precisely known in this case, the high rate for mixed materials likely has something to do with the relatively higher temperature and potentially better air flow through the fuel bed offered by the heterogeneous mix of sizes.

The FB throughput was 3.0–5.0 GT/h depending on feedstock and operating conditions, which is similar to other operations testing [19]. However, the FB's burning rate for the mixed sized materials was 2.5 GT/h in this study. Low burning throughput might have been caused by under-optimized operations by using one loader operator to feed the biomass between FB and CB machines. Occasionally the FB was not filled with biomass since this was conducted using only a loader while the CB had biomass added by hand when needed. Further, burning capacities of both machines were not maximized when loading was stopped when each size class of biomass was depleted, and the equipment readied for the next size class. The CB throughput is listed as 0.5–1.0 GT/h by the manufacturer when using typical woody feedstock such as clean wood waste and woody biomass [19].

Variability in the rates of burning for the FB was below the burning throughput for which the machines were designed, but the CB throughput was within the range detailed in the company specification

Table 6
Average feedstock moisture content, FireBox temperature, and burning rate for the FireBoxand CharBoss air curtain burner.

Diameter Class	Average moisture (%) (n = 90)	Temperature (°C)						Burning rate (GT/hr)[a]	
		Minimum		Maximum		Average			
		FB	CB	FB	CB	FB	CB	FB	CB
Small (<5 cm)	13.1	683	706	963	1027	814	826	2.4	0.9
Medium (5–10 cm)	19.4	687	721	1026	1082	886	925	2.0	0.6
Large (>10 cm)	40.1	581	541	1052	1036	924	915	1.1	0.5
Mixed (small, medium, & large)	24.2	669	683	1089	1000	879	863	2.5	0.8
Green biomass	43.8	576	642	887	961	789	836	1.9	0.9

[a] GT: Green ton (metric).

Table 7
Correlation models used with the FireBox and CharBoss air curtain burners.

Model	Explanatory variables			
1	*Intercept*	*Machine*	*Diameter*	*Moisture*
2	*Intercept*	*Machine*		*Moisture*
3	*Intercept*			

sheet. The lower rates of burning recorded for FB may be due to only one person operating both loading machines that resulted in operational delays that were not accounted for in throughput measurements based on start-stop times. In other words, a focused operator in a dedicated loader operating one burner rather than two, would likely achieve the throughput rates of 3.0–5.0 GT/h. Hand loading is not typically done for the CB, but it is likely the reason for the high burning efficiency because we were able to efficiently load and arrange biomass within the box to maximize ignition and biochar production. This method is more labor intensive but could be used if the wood is dry, cut to manageable sizes, and there is a larger (>3) crew [21].

3.3. Correlation analysis of machine types and biomass variables

A significant correlation was found between the response variable *Rate* with the explanatory variables (Table 7). Setting Model 1 as the full model and Model 2 as the reduced model, *Diameter* was not statistically significant in explaining the variation in the rate of burning (ESSF-stat = 1.8281, $df_{Numerator} = 1$, $df_{Full=}6$, p-value = 0.2251). This indicates that all biomass size classes burned at similar rates. However, in general the large diameter biomass burned slower in both machines, but at a higher average temperature when compared to other biomass sizes (Table 6). Setting Model 2 as the full model and Model 3 as the reduced model, *Machine* and *Moisture* were significant in explaining the variation in the *Rate* of burning (ESSF-stat = 13.85, $df_{Numerator} = 2$, $df_{Full} = 7$, p-value = 0.004). *Machine* and *Moisture* variables were significant, indicating that the variation in *Rate* of burning was due to differences in the functional design of the equipment and biomass moisture content, further explaining what the previous study found [20]. Model 3 was the intercept only model. The intercept was non-zero (t-statistic = 4.787, df = 9, p-value = 0.001) indicating that there was a significant variation in the rates of burning when *Machine*, *Diameter*, and *Moisture* were held constant.

One possible explanation for this is the polymers within the larger-sized material is more highly compact and denser compared to smaller-sized biomass [33]. During burning, the heat flux is faster when the wood is dry and the polymers degrade faster at low moisture contents releasing combustible gases, char, and ash [33,34]. Moreover, during thermochemical decomposition a considerable amount of time is required to expel the moisture, bond water, and volatile matter firmly held within the lignocellulosic structure of the larger woody material before heat can penetrate and decompose it [33,34]. Minimum temperatures for burning biomass dropped for both machines. A possible reason being that the addition of biomass in the burn chambers expels the moisture and bond water before active burning of the wood substrate [34].

Table 9
Models for biochar production in the CharBoss air curtain burner.

Model	Explanatory variables		
4	*Intercept*	*Diameter*	*Moisture*
5	*Intercept*		

In addition to the operator considerations noted previously, the variability in the rate of burning between machines was due to differences in the arrangement of biomass within the box and machine functional designs. It was relatively easy to load and arrange biomass within the CB using hand loading techniques as compared to machine loading used for the FB. To achieve higher burning efficiency in the FB and CB Air Burners, Inc. [19]. suggests that the loader operator constantly load biomass into the box to keep the rate of burning consistent with air curtain speed, rather than loading large pulses of material periodically. Maintaining burning efficiency minimizes pressure build-up within the box and over agitation of embers that may lead unintended fire starts. It is further advised that the ACBs should not be operated at low air curtain speeds since this allows smoke to penetrate through the air curtain thus reducing burning efficiency and increasing emissions.

3.4. Biochar production from the CB machine

The biomass used for biochar production was separated into different size classes to understand the effect of size on burning and biochar production rate in a CB (Table 8). Medium and mixed diameter classes had the highest biochar yield per unit of biomass burned. Both size classes yielded 17.2 % biochar under similar experimental conditions. We also found, however, that biochar production rate varies with burning rate and feedstock moisture content. Except for the green biomass feedstock, the quantity of biochar recovered from large diameter biomass was lower than those of small, medium, and mixed diameter classes. During the pyrolysis process, it takes longer for heat to penetrate and decompose the wood polymers as the outer surface is first reached by heat, burns, and turns into ash (or biochar) before penetrating the interior of woody material [33].

In Model 4 (Table 9), neither *Diameter* (t-stat = 0.629, df = 4, p-value = 0.594) nor *Moisture* (t-stat = −0.748, df = 4, p-value = 0.533) were significant factors, implying that biochar quantity is unrelated to wood size or moisture content.

Model 5 is the intercept only model and is non-zero (t-statistic = 6.775, df = 4, p-value = 0.0025). A non-zero intercept indicates that the quantities of biochar produced in the CB for different size classes of tested biomass were different when *Diameter* and *Moisture* were kept constant. Bartlett et al. [33] reported that pyrolysis is preceded by the movement of free water out of the wood, which evaporates when wood is heated. The moisture moves into the inner wood structure and re-condenses thereby requiring more heat energy to evaporate it further. Large cross-sectional areas of woody biomass require additional heat energy to evaporate moisture to create the dry zone within the polymer

Table 8
Biochar production, moisture content, yield, and recovery by diameter class from the CharBoss air curtain burner.

Diameter Class	Quantity of biochar		Moisture content[a] (%)	Oven dry moisture (%)	Yield (BDT)	Recovery (% BDT)
	Volume (m^3)	Wet weight (GT)				
Small (<5 cm)	0.59	0.44	64.2	35.8	0.17	13.2
Medium (5–10 cm)	1.08	0.87	62.4	37.6	0.36	17.2
Large (>10 cm)	0.39	0.40	62.0	38	0.17	10.7
Mixed (small, medium, and large)	0.74	0.64	62.8	37.2	0.26	17.2
Green biomass	0.55	0.55	62.0	38	0.23	8.8

*GT: Green ton (metric); BDT: Bone Dry Ton (metric).
[a] Moisture content of biochar when removed from quench pan.

Table 10
Productivity and cost of onsite biomass disposal by FireBox and CharBoss for a base case scenario.

Cost variable[d]	FB	CB (Hand Loading)	CAT308 Loader
Machine rate (USD$/PMH)	33.49	64.77	75.55
Burning rate (GT/PMH)	2.5	0.8	
Loading productivity (GT/PMH)[a]			4
Machine cost (USD$/GT)	13.40	80.97	18.89
Total cost of disposal (USD$/GT)			
ACB + CAT308 Team	32.28/GT[b]		
CB + hand loading	80.97/GT[c]		

[a] Average hourly biomass loading recommended for ACB machine by Air-Burners Inc.
[b] Disposal of biomass using ACB machine when loading with CAT308 loader.
[c] Disposal using CB and hand loading.
[d] GT: Green ton (metric); BDT: Bone Dry Ton (metric); PMH: productive machine hour.

structure allowing decomposition of the log interior and pyrolysis to occur. Further, vapor release slows down the removal of bound water and this occurs at higher temperatures and before pyrolysis occurs, making large diameter biomass burn slower compared to smaller pieces of wood [33]. Large wood is also denser and has a greater proportion of sapwood than small-size biomass, requiring more time for heat to expel bound water before pyrolysis can occur [32]. Large wood has a high proportion of heartwood which contains more extractives than smaller wood, making the release of volatile gases and pyrolysis of larger biomass slower [34]. Hand loading biomass into the CB meant that the wood had to be small enough to be lifted overhead and positioned within the box for maximum burning efficiency [21].

3.5. Economics of disposing biomass using FB and producing biochar using CB

The hourly cost (USD$/hour) for base-case scenarios when using i) FB and CAT308 loader, and ii) CB and hand loading is summarized in Table 10. The total cost of disposing mixed biomass material using FB and CAT loader is $32.28/GT while that of CB and hand loading is $80.97/GT, which were higher than the biomass disposal costs using ACBs that were previously reported [12]. At a higher rate of burning, more volume of biomass would be burned by both machines and more biochar would be recovered, thus reducing the unit cost of biomass disposal and production of biochar.

The point of indifference for the quantity of biomass burned for the

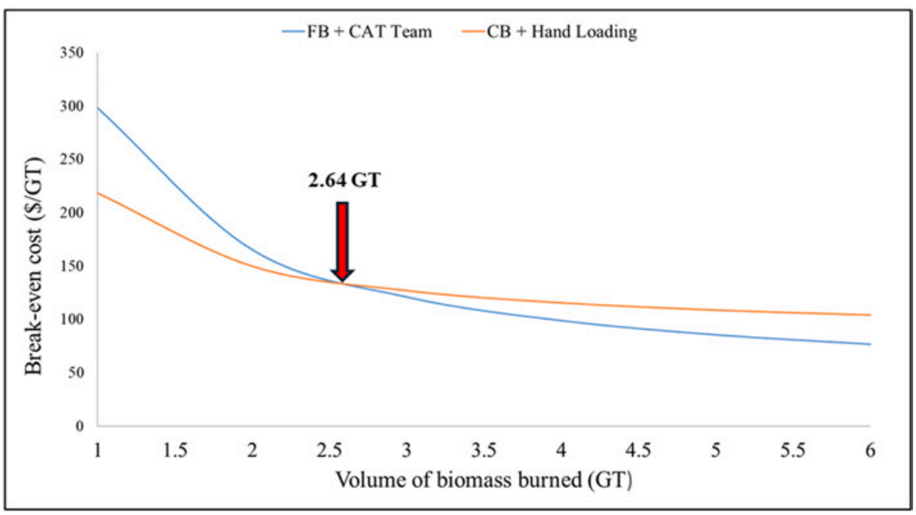

Fig. 6. Break-even analysis for biomass disposal using ACB and CB machines [GT: Green ton (metric)].

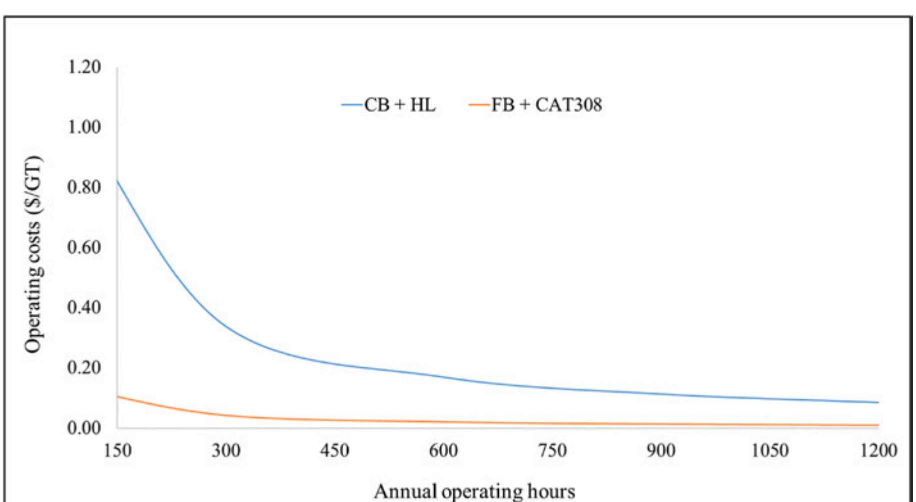

Fig. 7. Effect of annual operating hours on the total cost of disposal of biomass and production of biochar [GT: Green ton (metric)].

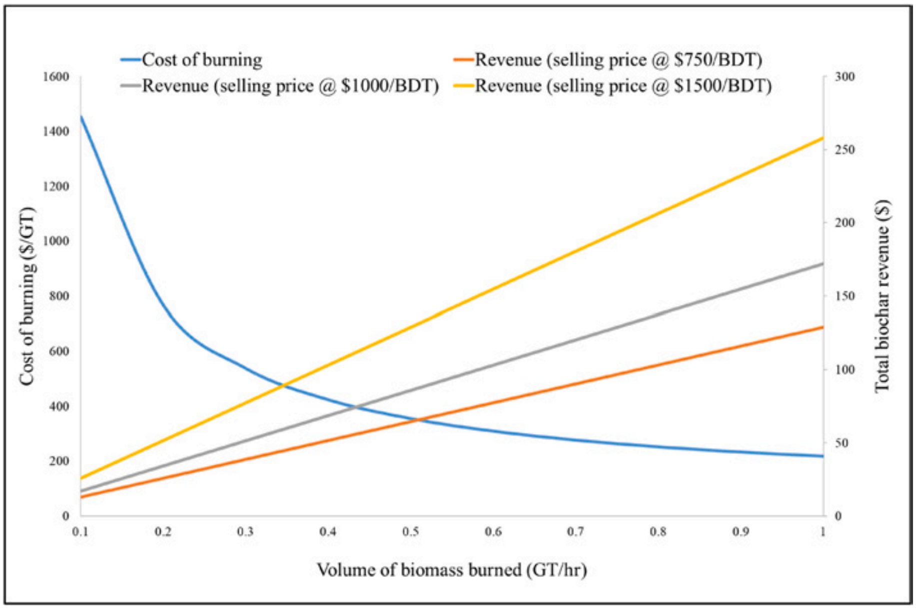

Fig. 8. Change in the cost of burning biomass and biochar revenues over different rates of biomass burned using CharBoss [GT: Green ton (metric); BDT: Bone Dry ton (metric)].

base case scenario is 2.64 GT (Fig. 6). It would be cost effective to dispose ≤2.64 GT using CB and hand loading, but when the biomass volume is > 2.64 GT using FB and CAT308 loader would be more effective and economical because of the large capacity for burning in FB. Importantly, the marginal cost of burning an additional unit of biomass decreased when the FB and CAT loader team was used.

In sensitivity analyses for the base case scenarios, hourly operational costs ($/GT) decreased with increased annual operating hours (Fig. 7) and were a function of the total volume of biomass burned, as burning for a greater length of time has the benefits of economies of scale, spreading fixed costs over higher throughput. It was observed for both machines, but the operating cost of running the CB + hand loading team decreased with the increase of annual operating hours more than the FB + CAT 308 team. This result highlights the importance of utilizing the machines throughout the year to keep the operating cost low, especially for the CB + hand loading team.

The sensitivity analysis of biochar revenue was based on market prices obtained from a study on the financial viability of biofuel and biochar by Campbell et al. [35]. The analysis was completed based on the hourly cost of burning ($/GT), volume of woody biomass, 17.2 % rate of biochar recovery from the burned biomass (GT/hour), and three market price scenarios of $750/BDT, $1000/BDT, and $1500/BDT (Fig. 8). Burning rate determines the quantity of biomass burned per hour, thus at higher rates of burning, more biomass is burned thereby reducing hourly operational costs. Similarly, the rate of burning affects biochar quantity as faster burning produces more biochar, resulting in reduced production costs. At a higher unit price of $1500/BDT of biochar produced, a combination of higher burning rates and lower operational costs results in greater revenues from biochar. In addition, if consideration is given to creating biochar for carbon credits, then it is possible that using a CB would align with sustainable development goals for climate change mitigation and result in additional income for the operator [36,37].

3.6. Operational advantages and disadvantages

The advantages and disadvantages of using FB and CB were analyzed against key machine attributes such as cost, machine capacity, operational logistics, and safety (Table 11). Benefits and limitations of using FB and CB for management of low value woody biomass were summarized based on economic analysis for the base case scenarios while focusing on the initial capital expenditure, functional design, rate of burning, mobilization, operational safety, and environmental benefits associated with each machine. We also had focused discussions with engineers from Air Burners, Inc., and machine operators during the experiment to develop recommendations for the efficient use of each machine for biomass management.

Both the FB and CB effectively disposed of biomass to result in environmental benefits compared to open pile burning. The FB and a loader are appropriate for large-scale woody residue disposal piled at a central location. Additional biomass can be hauled into the central burning site using trucks such as roll-off and dump trucks. The CB machine is appropriate for place-based biochar production and managing small-to-large piles of biomass scattered near a harvest unit where the equipment can be moved along a road or sited at a log landing. Biochar can be used locally for soil restoration purposes and as a climate change mitigation tool to sequester carbon and reduce soil greenhouse gases [38] or it can be transported for use at other sites. Hand loading is an option to maintain burn efficiency when the loading machine equipment is not readily available.

4. Study limitations

The assumptions used for the loaders and subsequent rate calculations for FB and CB were obtained from CAT dealers within Flagstaff, AZ and the Director of the Flood Control District of Coconino County, AZ. Our experimental design and biomass layout at the test site followed the machine-to-biomass pile distances recommended by Air Burners, Inc. The fire safety regulations and requirements for biomass burning were set by Coconino County. Another limitation was the use of relatively short production runs between full-startup and cool-down cycles during only four days. Extended observations of FB and CB operations using different logistical and operational settings would illustrate the concept quantified in Fig. 8. Shift-level production data over long periods of operation could be used to assess commercial production rates. Future research should evaluate operations in other settings under full production conditions and consider the machine loading of the CB compared to manual loading, as well as quantifying maximum throughput of the FB with a dedicated loader operator. Fuel treatment thinning and other forest restoration treatments can incorporate the use

Table 11
Advantages and disadvantages of the FireBox S-119 and CharBoss air curtain burners.

Machine attributes	FireBox (FB)	CharBoss (CB)
Operational costs	• Higher capital expenditure	• Lower capital expenditure
Functional design	• Appropriate for disposal of large quantities of biomass • No production of biochar	• Can be used for disposal of smaller, distributed quantities of biomass • Production of biochar, therefore complete use of forest biomass
Productivity efficiency	• Higher rate of biomass disposal • Longer average loading cycle time using CAT308 loader • Machine loading most appropriate and efficient for biomass arrangement within the box, hand loading not practical • High ash accumulation due to larger surface area • Removal of ash requires cool down to clear the box of accumulated ash	• Lower rate of biomass disposal • Shorter average loading cycle time using CAT299D2 loader • Hand loading can be efficient for arrangement of biomass within the box, can also be loaded using a machine • Low ash accumulation, significant mass removed in the form of biochar • Ash accumulates under the machine and removal requires moving the machine to a new footprint.
Portability, mobilization, and set-up	• Mobilization, transport, and set-up is expensive and requires specialized loading, hauling and off-loading equipment and skilled personnel; best for a central location	• Easy to mobilize and transport because the box is mounted on a movable trailer
Operational safety	• Requires large area for set-up. • Storage piles of biomass should be placed at least 15.2 m from ACB	• Requires relatively smaller area for set-up. • Storage piles of biomass should be placed at least 9.1 m from CB machine
Environmental benefits	• Reduces smoke • Reduces soil damage • Removes waste biomass that can be a fire risk	• Reduces smoke • Reduces soil damage • Removes waste biomass that can be a fire risk • Biochar sequesters carbon compared to open burning • Biochar has additional benefits when used as a soil amendment • Biochar conveys several nonmarket and ecosystem service benefits to society

of numerous place-based technologies [39], including mobile equipment such as the CharBoss, BurnBoss, or TrackBoss® and on operations where biomass is removed and processed simultaneously. In this case, a joint-production model of the entire restoration process could be developed and compared to pile burning. Improving emissions from biomass disposal is a critical benefit of ACB deployment, and the research team plans to conduct high resolution emissions testing on the CB under controlled conditions. In addition, other values associated with biochar, such as carbon sequestration and soil improvement along with other nonmarket goods and ecosystem services associated with production and use of biochar, could be quantified and considered in addition to the financial costs of operations.

5. Conclusion

Both the FB and CB can provide climate-smart forestry practices that reduce the volume of low-value woody biomass and, in the case of the CB, also produce a carbon-rich biochar that can improve soil properties and sequester carbon in the soil, thus adding a value-added product beyond mere disposal of low-value woody biomass waste material. Burning rates were variable with machine, diameter class, and moisture content. Mixed size biomasses are the most commonly available, and not sorting biomass saves the time and cost of sorting before processing an ACB. The rate of burning for FB was 2.5 GT/h for mixed biomass material, while that of CB was 0.8 GT/h. Both machines have been shown to reduce emissions when compared to open burning. The equipment we tested varies in how biomass is moved, i.e., central or dispersed operations, and the ability to reduce the risk of wildfire. Accummulating large quantities of biomass next to the equipment enables more efficient loading and higher burning throughput, and also reduces the need for moving the equipment frequently, which can be costly. Disposal costs and biochar production rates are representative of onsite biomass materials with no stump-to-truck thinning and hauling costs. Future research should focus on quantifying the burning rates for FB and CB under variable field conditions, site configurations, and equipment pairings over longer cycles and extended periods of field operation. Further, more rigorous economic analyses should be pursued to quantify the relative advantages/disadvantages of the FB and CB technologies.

Disclaimer

Some of the authors of this paper are employees of the United States Department of Agriculture, U.S. Forest Service. The findings and conclusions in this report are those of the authors and should not be construed to represent any official USDA or U.S. Government determination or policy. This research was supported in part by the U.S. Department of Agriculture, Forest Service. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

CRediT authorship contribution statement

Paul O. Oyier: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Data curation, Conceptualization. **Han-Sup Han:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Dipita Ghosh:** Writing – review & editing, Validation, Methodology, Investigation, Data curation. **Nathaniel Anderson:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Deborah S. Page-Dumroese:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Daniel W. McCollum:** Supervision, Methodology, Investigation, Data curation, Conceptualization. **Joanne M. Tirocke:** Resources, Methodology, Investigation, Data curation. **Derek N. Pierson:** Resources, Methodology, Investigation, Data curation.

Data availability

Data will be made available on request.

Acknowledgement

This study was conducted through a close collaboration between the Ecological Restoration Institute of Northern Arizona University, Coconino County Flood Control District, the University of Arizona Cooperative Extension, Air Burners, Inc. and U.S. Department of Agriculture, Forest Service Rocky Mountain Research Station. Funding for demonstration and research activities on the FireBox S119 and CharBoss was partially provided by the U.S. Department of Agriculture Forest Service (Joint Venture Agreement No.: 22-JV-11221636-080). The authors would like to thank everyone who worked in the field on this study, with special thanks to Jay Smith and Victor Ohumukini (Coconino County), Chris Jones (the University of Arizona Cooperative Extension), and Burke Powers and Matt Dennis (Air Burners, Inc.) for their support and guidance on the experiment. Authors are also grateful to Kevin Jump who moved the CB across the states for the study. We thank AmeriCorps crew of Flagstaff for their hard work sorting fire-killed biomass materials for this study.

References

[1] K.T. Davis, J. Peeler, J. Fargione, R.D. Haugo, K.L. Metlen, M.D. Robles, T. Woolley, Tamm review: a meta-analysis of thinning, prescribed fire, and wildfire effects on subsequent wildfire severity in conifer dominated forests of the Western US, For. Ecol. Manag. 561 (2024) 121885, https://doi.org/10.1016/j.foreco.2024.121885.

[2] J. Halbrook, H.-S. Han, Chip & Ship: Testing the Logistics of Supplying Wood Chips over Long Distances Using Intermodal Railroad Transportation. ERI Technical Report. Ecological Restoration Institute, Northern Arizona University, 2019, p. 30. https://cdm17192.contentdm.oclc.org/digital/collection/p17192coll1/id/1021/rec/2.

[3] J.E. Korb, N.C. Johnson, W.W. Covington, Slash pile burning effects on soil biotic and chemical properties and plant establishment: recommendations for amelioration, Restor. Ecol. 12 (1) (2004) 52–62, https://doi.org/10.1111/j.1061-2971.2004.00304.x.

[4] S.J. Prichard, P.F. Hessburg, R.K. Hagmann, N.A. Povak, S.Z. Dobrowski, M. D. Hurteau, P. Khatri-Chhetri, Adapting western North American forests to climate change and wildfires: 10 common questions, Ecol. Appl. 31 (8) (2021) e02433, https://doi.org/10.1002/eap.2433.

[5] C.S. Galik, M.E. Benedum, M. Kauffman, D.R. Becker, Opportunities and barriers to forest biomass energy: a case study of four US states, Biomass Bioenergy 148 (2021) 106035, https://doi.org/10.1016/j.biombioe.2021.106035.

[6] S.M. Hood, S. Baker, A. Sala, Fortifying the forest: thinning and burning increase resistance to a bark beetle outbreak and promote forest resilience, Ecol. Appl. 26 (7) (2016) 1984–2000, https://doi.org/10.1002/eap.1378.

[7] J.K. Agee, C.N. Skinner, Basic principles of forest fuel reduction treatments, For. Ecol. Manag. 211 (1–2) (2005) 83–96, https://doi.org/10.1016/j.foreco.2005.01.034.

[8] J. Aurell, B.K. Gullett, D. Tabor, N. Yonker, Emissions from prescribed burning of timber slash piles in Oregon, Atmos. Environ. 150 (2017) 395–406, https://doi.org/10.1016/j.atmosenv.2016.11.021.

[9] C.C. Rhoades, P.J. Fornwalt, Pile burning creates a fifty-year legacy of openings in regenerating lodgepole pine forests in Colorado, For. Ecol. Manag. 336 (2015) 203–209, https://doi.org/10.1016/j.foreco.2014.10.016.

[10] C.M. Mott, R.W. Hofstetter, A.J. Antoninka, Post-harvest slash burning in coniferous forests in North America: a review of ecological impacts, For. Ecol. Manag. 493 (2021) 119251, https://doi.org/10.1016/j.foreco.2021.119251.

[11] X. Han, G.E. Frey, C. Sun, Regulation and practice of forest-management fires on private lands in the southeast United States: legal open burns versus certified prescribed burns, J. Fr. 118 (4) (2020) 385–402, https://doi.org/10.1093/jofore/fvaa017.

[12] D.W. Huffman, A.J.S. Meador, M.T. Stoddard, J.E. Crouse, J.P. Roccaforte, Efficacy of resource objective wildfires for restoration of ponderosa pine (*Pinus ponderosa*) forests in northern Arizona, For. Ecol. Manag. 389 (2017) 395–403, https://doi.org/10.1016/j.foreco.2016.12.011.

[13] E.E. Knapp, J.M. Lydersen, M.P. North, B.M. Collins, Efficacy of variable density thinning and prescribed fire for restoring forest heterogeneity to mixed-conifer forest in the central Sierra Nevada, CA, for, Ecol. Manag. 406 (2017) 228–241, https://doi.org/10.1016/j.foreco.2017.08.036.

[14] G. Jones, D. Loeffler, D. Calkin, W. Chung, Forest treatment residues for thermal energy compared with disposal by onsite burning: emissions and energy return, Biomass Bioenergy 34 (5) (2010) 737–746, https://doi.org/10.1016/j.biombioe.2009.12.013.

[15] A.E.J. Esquilin, M.E. Stromberger, W.J. Massman, J.M. Frank, W.D. Shepperd, Microbial community structure and activity in a Colorado Rocky Mountain forest soil scarred by slash pile burning, Soil Biol. Biochem. 39 (5) (2007) 1111–1120, https://doi.org/10.1016/j.soilbio.2006.11.023.

[16] K.R. Hubbert, M. Busse, S. Overby, C. Shestak, R. Gerrard, Pile burning effects on soil water repellency, infiltration, and downslope water chemistry in the Lake Tahoe Basin, USA, Fire Ecol 11 (2) (2015) 100–118, https://doi.org/10.4996/fireecology.1102100.

[17] A.R. Shapiro, The Use of Air Curtain Destructors for Fuel Reduction. 02511317 SDTDC, U.S. Department of Agriculture, Forest Service: San Dimas, CA, 2002. Available from: THE USE OF AIR CURTAIN DESTRUCTORS (usda.gov).

[18] C. Miller, P. Lemieux, Emissions from the burning of vegetative debris in air curtain destructors, Air Waste Manag. Assoc. 57 (8) (2007) 959–967, https://doi.org/10.3155/1047-3289.57.8.959.

[19] Air Burners, Inc, The principle of air curtain burning, Tech. Memo. (2017). Available from: https://www.airburners.com/air_burners_principle_of_operation-1.pdf.

[20] E. Lee, H.-S. Han, Air curtain burners: a tool for disposal of forest residues, Forests 8 (8) (2017) 296, https://doi.org/10.3390/f8080296.

[21] D.S. Page-Dumroese, J.M. Tirocke, N.M. Anderson, J.G. Archuleta, D. W. McCollum, J. Morisette, C. Rodriguez-Franco, Continuous in-woods production of biochar using a trailer-mounted air curtain burner, J. Vis. Exp. 206 (2024), https://doi.org/10.3791/206.

[22] R. Susott, R. Babbitt, E. Lincoln, W.M. Hao, Reducing PM2.5 emissions through technology: results from a recent study evaluating the effectiveness of an air curtain incinerator, Available from: https://airburners.com/files/technical-reports/reducing-pm25-emissions-through-technology-results-from-a-recent-study-evaluating-the-effectiveness-of-an-air-curtain-incinerator.pdf, 2002.

[23] G. Johannesson, S. Boles, L. Shumaker, U.B. Initiative, GHG Life Cycle Assessment of CharBoss® Biochar Production and Potential Use for CDR Certificate Generation. Available from: biochar-us.org/sites/default/files/presentations/USFS_USBI-CharBoss-LCA-Report-FEB-29-2024-FINAL.pdf.

[24] D. Ghosh, D. Page-Dumroese, H.-S. Han, N. Anderson, Role of biochar made from low-value woody residues in ecological sustainability and carbon neutrality, Submitted to Soil Sci. Soc. Am. J. (2024) (under review).

[25] D. Ghosh, S.K. Maiti, Can biochar reclaim coal mine spoil? J. Environ. Manag. 272 (2020) 111097 https://doi.org/10.1016/j.jenvman.2020.111097.

[26] W. Jang, D. Page-Dumroese, H.-S. Han, Comparison of heat transfer and soil impacts of air curtain burner burning and slash pile burning, Forests 8 (8) (2017) 8, https://doi.org/10.3390/f8080308.

[27] T. Reed, The updated Biomass Energy Foundation: proximate and ultimate analyses, Available from: https://drtlud.com/BEF/proximat.htm, 2024.

[28] Lignomat, Moisture meters for wood and building materials, Retrieved from, https://lignomatusa.com/product/lignometer-k-pin-lumber-moisture-meter/, 2023.

[29] N. Anderson, H. Gu, R. Bergman, Comparison of novel biochars and steam activated carbon from mixed conifer mill residues, Energies 14 (24) (2021) 8472, https://doi.org/10.3390/en14248472.

[30] Omegascope, Retrieved from, https://www.manualslib.com/manual/114806/Omega-Engineering-Omegascope-Os523e.html, 2023.

[31] R Core Team, R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2023. URL: https://www.R-project.org/.

[32] E.S. Miyata, Determining fixed and operating costs of logging equipment. Gen. Tech. Rep. NC-55. St. Paul, MN, US Dept. of Agriculture, Forest Service, North Central Forest Experiment Station (1980) 55, https://doi.org/10.2737/NC-GTR-55.

[33] A.I. Bartlett, R.M. Hadden, L.A. Bisby, A review of factors affecting the burning behaviour of wood for application to tall timber construction, Fire Technol. 55 (1) (2019), https://doi.org/10.1007/s10694-018-0801-0.

[34] Y.B. Yang, H. Yamauchi, V. Nasserzadeh, J. Swithenbank, Effects of fuel devolatilisation on the combustion of wood chips and incineration of simulated municipal solid wastes in a packed bed, Fuel 82 (18) (2003) 2205–2221, https://doi.org/10.1016/S0016-2361(03)00128-7.

[35] R.M. Campbell, N.M. Anderson, D.E. Daugaard, H.T. Naughton, Financial viability of biofuel and biochar production from forest biomass in the face of market price volatility and uncertainty, Appl. Energy 230 (2018) 330–343, https://doi.org/10.1016/j.apenergy.2018.09.114.

[36] A. Salma, L. Fryda, H. Djelal, Biochar: a key player in carbon credits and climate mitigation, Resour. 13 (2) (2024) 31, https://doi.org/10.3390/resources13020031.

[37] S.H. Xie, W.A. Kurz, C. Smyth, Z. Xu, D. Roeser, Forest products circular economy in an export-focused jurisdiction: can it fill the emission reduction gap? Clean. Circ. Bioeconomy (2024) 100096 https://doi.org/10.1016/j.cleanc.2024.100096.

[38] C. Rodriguez Franco, D.S. Page-Dumroese, D. Pierson, T. Nicosia, Biochar utilization as a forestry climate-smart tool, Sustainability 16 (5) (2024) 1714, https://doi.org/10.3390/su16051714.

[39] K. Wilson, W. Bekker, J. Archuleta, D. McAvoy, D. Page-Dumroese, Mobile Biochar Production by Flame Carbonization: Reducing Wildfire Risk and Improving Forest Resilience. RMRS-GTR-439, U.S. Department of Agriculture, Rocky Mountain Research Station, Fort Collins, CO, 2024, https://doi.org/10.2737/RMRS-GTR-439.