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Article

Air Curtain Burners: A Tool for Disposal of Forest Residues

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Received: 17 July 2017; Accepted: 10 August 2017; Published: 14 August 2017

Abstract: Open pile burning (OPB) forest residues have been limited due to several concerns, including atmospheric pollution, risk of fire spread, and weather conditions restrictions. Air Curtain Burner (ACB) systems could be an alternative to OPB and can avoid some of the negative effects that may result from OPB. The main objective was to compare the burning consumption rates and costs of two types of ACB machines, the S-220 and BurnBoss. In addition, we tested a hand-pile burning (HPB) consumption rate for a comparison with BurnBoss unit. The S-220's burning consumption rates ranged between 5.7 and 6.8 green metric ton (GmT)/scheduled machine hour (SMH) at a cost between US $12.8 and US $10.8/GmT, respectively. Costs were 70% higher when using the BurnBoss unit. Burning residue consumption rates and cost of disposal were considerably different: they were highly dependent on machine size, species, and fuel age of forest residues. Particularly, BurnBoss test burned over 40% more than HPB method and produced clean burn by airflow. The results from this study suggest that ACBs can be a useful tool to dispose of forest residues piled in many forests areas with less concerns of air quality and fire escape risks.

Keywords: open pile burning; burning consumption rates; costs; hand-pile burning; clean burn

1. Introduction

Forest residues include tree tops, limbs, and other tree parts generated from forest operations and can provide opportunities for production of bioenergy and bioproducts such as briquettes or biochar [1–3]. However, a low level of market demand for wood-based energy in the Northwestern U.S. have caused forest residues to be piled and left in the forests and sawmills [4]. It is also often financially unviable to use forest residues due to high costs of collection and transportation, and low market price [5,6]. In addition, leaving large piles of forest residues near houses or within public parks have been a concern due to high risk of fire hazard and other forest management issues (i.e., growing and rehabilitation). For this reason, open pile burning (OPB) has been widely used in the Western U.S. to dispose of forest residues, to reduce wildfire hazard, and improve forest and productivity [7,8]. This forest residues disposal method has been extensively used as it provides a cost-effective option for disposal of forest residues [9,10].

However, OPB could be potentially damaging to forests by increasing the wildfire hazard and obstructing regeneration [11,12]. This method has not only been shown to generate greenhouse gas (i.e., carbon monoxide (CO) and carbon dioxide (CO_2)) emissions and release particulate matter (PM) to the health hazard levels, but it also emits nuisance of smoke and objectionable odor to an ambient air [10,13]. For this reason, intentional burning of slash piles was often strictly controlled in public and residential areas [13]. OPB also requires the prevention of embers from escaping as well as monitoring weather conditions hourly: burning is allowed only if extremely narrow conditions are met [14,15]. For example, when planning a pile burn, ambient temperatures have to be less than 32 °C, the maximum wind speed should not exceed 8 km/h and relative humidity ought to be below 35%. These requirements would prohibit OPB from 1 June to 14 November in most areas in the Western U.S. Another drawback of OPB is the severe, undesirable effects on forest soil properties compared to wildfires or broadcast burning [12,16]. The extreme flaming temperatures (400 °C) with 60 h can be intense and penetrate at 0–20 cm soil depth which can destroy the chemical and biological soil properties [17]. Overall, the OPB method can result in poor air quality, smoke production, fire escape, and soil damage [7,18].

An alternative technology to dispose of forest residues is to use an Air Curtain Burner (ACB), which is designed by Air Burners Inc., Palm City, FL, USA (also called as Air Curtain Destructor or Incinerator; Figure 1). ACBs are divided into two main types, stationary (positioned at the centralized landing area) and mobile applications (half-ton pick-up truck mounted system). These machines were developed in compliance with US Environmental Protection Agency's 40 Code of Federal Regulation Part 60 regulation that determines allowable emissions from biomass burning [19,20].


(**a**) (**b**) (**c**)

Figure 1. The Air Curtain Burners used to test burning of forest residues in (**a**) S-220 in Jacksonville, Florida; (**b**) BurnBoss in Groveland, California; and (**c**) BurnBoss installed with ember screen in Volcano, California. The loader is used to load the forest residues in S-220 operation while BurnBoss operation is loaded by hand.

ACBs have been primarily used to dispose of woody residues, such as stumps and root wads [21], waste wood and landscape wastes [22], debris generated by hurricanes [23] and floating (water-borne) woody debris from natural disasters (e.g., tsunami and heavy rainfall) [19]. Details on how the ACBs FireBox efficiently burn woody materials is shown in Figure 2. These machines operate by blocking various air pollutant emissions including greenhouse gases and PM by using a high velocity (1600–2000 revolution per minute; RPM) of airflow from the air blower part which is referred to as "air curtain". In addition, air pollutant emissions is returned by circulation of air flow. Past studies showed that ACBs can reduce CO and PM emissions by 80% compared to OPB and reduce smoke opacity [23,24]. In addition, it also minimizes escaping embers, soil damage, and burn scars by creating an air curtain across the box [23,25,26]. Air Burners Inc. stated that adding air into the FireBox effectively improved burning consumption rate since by adding more oxygen to the forest residue pile in the FireBox during the burning [19]. As a result, ACB's forest residues treatment method is considered as a clean and air pollution control burning method to dispose of forest residues, but burning consumption rates and cost of disposal of forest residues for different ACB systems are largely unknown.

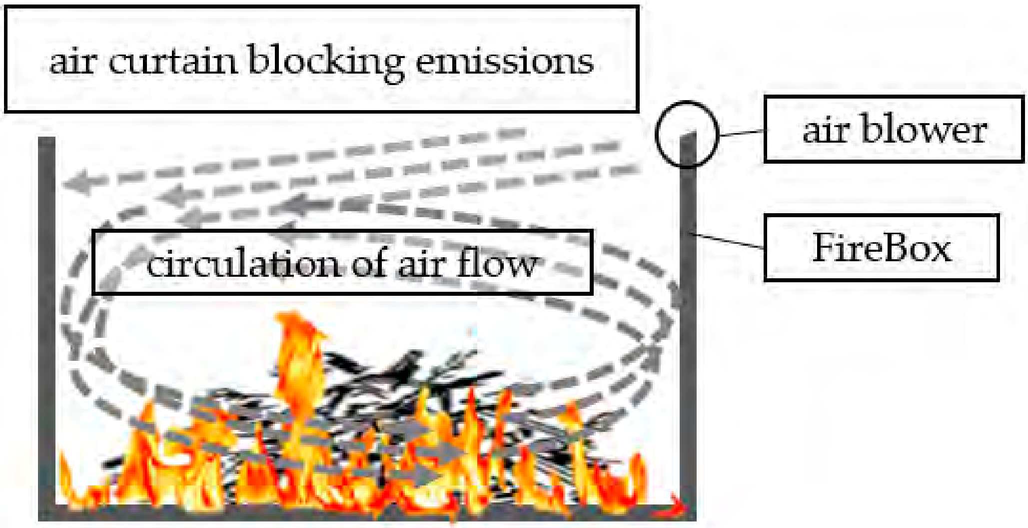

Figure 2. Principle of an Air Curtain Burner: the air curtain blocking emission and circulating the air inside FireBox is created when turning on the air blower.

Therefore, in this study, we examined an alternative method of disposing of forest residues using an ACB (Figure 3). The overall objective was to determine the performance of ACBs and evaluate the economic feasibility of burning slash piles using the S-220 and BurnBoss, which are ACB models that are commonly used for forest residue disposal. Specifically, this study sought to: (1) determine the forest residues burning consumption rate (green metric ton (GmT)/scheduled machine hour (SMH)) and cost of disposing forest residues ($/GmT) through field-based experiments, and (2) establish the logistics to an ACB burning operation. This study focused on disposal of forest residues resulting from fuels reduction treatments in green waste yards near residential areas and public parks. In order to assess the potential of BurnBoss units, we observed hand-built-pile burn's consumption rate next to the BurnBoss test at the same time.

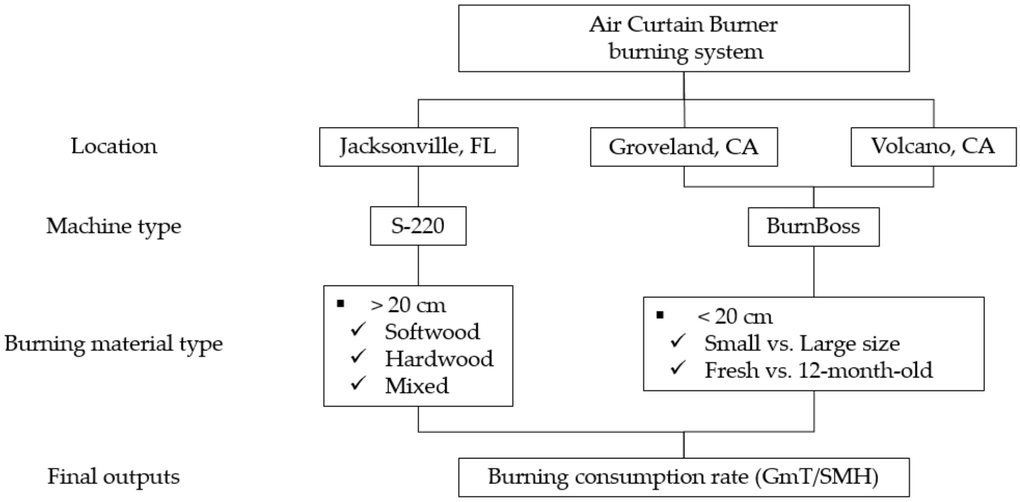

Figure 3. Integrated Air Curtain Burner burning system flow chat.

2. Materials and Methods

2.1. An ACB Burning System Set-Up and Description

During the study, we noticed that ACB operations followed five steps: putting the machine in place, first loading and kindling, air blower startup, loading (i.e., second loading), and burning it down to ash. For an initial set up of an ACB operation, these machines need to be placed on open, clear, flat ground (slope < 10%) with dry surface conditions [27]. The area should be located at least 30 m away from the outer edge of burning materials and any fire fuel [28].

Following the set-up, the operator needed to fill up a space in the ground and the inside of the FireBox with dirt to prevent the escape of smoke and embers since the FireBox is bottomless. The first loading, which is piled about 1/3 of the FireBox height consists of smaller materials (less than 10 cm in diameter) for kindling, and is then ignited with diesel fuel and a propane gas torch. At this time in the burning, greenhouse gases and smoke can temporarily be generated as the diesel fuel ignites, as there is some wait time for the materials to ignite. If the operator uses clean materials with lower moisture content (<20%) at this stage, there will be reduced emissions of CO and PM with the smoke [27,29,30]. For this reason, the materials used were not contaminated with dirt. Thus, prior to the start of air blower, a number of preparation activities should be done, including site selection, set-up, and kindle a fire. Further, first loading and kindling work can vary depending on operator and machines.

The next process for the burning is to turn on the air blower and load additional residues into the FireBox as needed to maintain combustion until the materials are burned down to ash. It should be noted that the second and following loadings should not be higher than the height of the box to retain the emissions, ember, and smoke reduction by the air curtain [19]. These processes are dependent on the type of ACB; S-type (i.e., S-220) and BurnBoss. S-220 burning operation, in which a large amount of residues were fed to a 0.5-m height below the top at a time with 25-GmT amount of residues, had a burn down time of approximately 14 h before the next experiment [31]. Thus, the S-220 or other S-types of ACB are designed to run for one day (24 h). On the other hand, when loading fuels with the BurnBoss, they should be added to 1/3 the depth of the FireBox and additional fuels added when there is enough space [27,32]. These processes were repeated until the last materials were loaded. Once the last materials were loaded, the last stage should take one or two hours to burn it down to ash. Thus, BurnBoss unit can be operated for eight hours a day.

2.2. Description of ACBs Used in the Experiments

The S-220 was a mid-sized model equipped with a 45-kW diesel engine to blow air into the FireBox. The dimensions of the FireBox used in the S-220 are 6.0-m × 1.9-m × 2.2-m (length × width × height) with 0.7-m thick steel walls filled with thermo-ceramic materials. This machine type can efficiently dispose of larger diameter (>20 cm) forest residues [26]. A potential average through-put of burning ranges from 5 to 7 GmT/h at an average fuel consumption rate of 9.5 L/h [19].

The BurnBoss was a portable prototype machine that can be moved around with a half-ton pick-up truck and a FireBox that is raised and lowered by a hydraulic lift system. This unit is only applied to off-road vehicles that do not exceed 60 km/h. The FireBox dimensions are 3.7-m (L) × 1.2-m (W) × 1.2-m (H) with 0.1-m thick thermos-ceramic material walls. It had a small (9-kW) diesel engine with a fuel consumption rate estimated at 1.1 L/h [19]. Generally, the burning consumption rate of this technology is approximately 1/2 to 1 GmT/h. The BurnBoss unit was typically loaded by hand with small (<20 cm) forest residues such as hand-pile residues and windrow along the road during the burning process.

2.3. Description of Material Types Used in the Experiments

Burning tests were conducted using two ACB machines, S-220 and BurnBoss, in three different locations. The first test was conducted over three days (4–6 August 2015) on a S-220 unit in a green waste yard located in Jacksonville, Florida. The S-220 unit was positioned at a designated location such as large green waste disposal yard or a large open area for an extended time (>6 months or year) and was used in conjunction with a rubber-tired front-end loader using a standard log grapple. The species burned for this study were loblolly pine (*Pinus taeda*), laurel oak (*Quercus laurifolia*), sand live oak (*Quercus geminate*), and myrtle oak (*Quercus myrtifolia*) trees. These materials were mainly chunk woods ranging 20 to 40 cm in diameter and 1 to 3 m in length, collected from in-forest, mill processing, and urban wood residues (Table 1). For the purpose of our study, we separated the wood fuels into three different types (softwood, hardwood, and mixed species) at an amount of 25 GmT for each burning trial test. There was no significant difference in the size and moisture content of fuel types ($p > 0.05$).

Table 1. Description of material types and weather conditions for Air Curtain Burner tests in three different locations.

Locations	Air Temperature (°C)	Relative Humidity (%)	Wind Speed (km/h)	Average Material Size in Diameter (cm)
Jacksonville, Florida (S-220)				
softwood	30	95	N/A [a]	27
hardwood	31	87		29
mix	30	85		28
Groveland, California (BurnBoss)				
small size (<10 cm)	24	38	1.8	5
large size (10 to 20 cm)	20	60	1.5	20
Volcano, California (BurnBoss installed with ember screen)				
fresh residues				
small size (<10 cm)	24	29	0.8	6
large size (10 to 20 cm)	20	38	0.5	16
12-months-old residues				
large size (10 to 20 cm)	30	36	0.3	16

[a] Data not avaliable; Note: the wind speed did not affect during ACB burning system.

A second burning test was carried out over two days (26–27 March 2016) with a BurnBoss unit in a community green waste yard area in Groveland, California (CA). Forest residues used for this test were from urban and residential fire hazard reduction and landscaping treatments, and consisted of Ponderosa pine (*Pinus ponderosa*, 80%) mixed with manzanita shrubs (*Arctostaphylos glauca*, 20%) that were less than 6-months in age. A backhoe sorted and piled approximately 10 GmT of two different fuel sizes; small-diameter fuels (<10 cm) and large-diameter fuels (10–20 cm). Larger than 10 cm fuels in diameter ranged from 1 to 2 m in length, while less than 10 cm materials were in a variety of lengths and forms. The third burning experiment was conducted in a California State Park camp ground located in Volcano, CA, USA over three days (13–15 June 2016). The BurnBoss used for this test was equipped with a cage placed on the top of the FireBox to prevent any embers from flying from the FireBox (Figure 2). An ember screen is optional to buy and helps avoid the spread of ember during the loading and burning process [19]. At this site, three different types of fresh (less than one-month-old or immediately after felling and bucking fuels) and 12-months-old Ponderosa pine (*Pinus ponderosa*) residues from commercial thinning operations were burned (Table 1). The 12-months-old residues burned were only large-diameter (10–20 cm). Fresh residues, which were from drought or insect damage, were burned immediately after felling and bucking and included small (<10 cm) and large-diameter (10–20 cm). Large fuels were generally around 1 m in length, but small materials were in a variety of lengths and forms including leaves. There was a significant difference in the moisture content of fuel depending on age ($p < 0.05$).

In both BurnBoss tests, we compared burning consumption rates with hand-pile burning (HPB) option when burning forest residues on a site. For the purpose of comparison of consumption rates, the HPB was set next to the ACB unit observed at each day of burning (Figure 4). The HPB was 3.7-m wide × 1.2-m long × 1.2-m high.

Figure 4. Comparison of the smoke occur from BurnBoss and hand-pile burning for the same types of forest residues; (**a**) Groveland and (**b**) Volcano, California. BurnBoss burnings shows little smoke and air pollutants, compared to hand-pile burnings.

2.4. Field Data Collection and Analysis

Prior to burning, the fuel material types were characterized by material species and diameter for each experiment. To measure burning consumption rates, fuel weights were measured with a PT300TM RFX portable wheel-load scale (Intercomp, Medina, MN, USA) installed on site. The weight of testing material used for this study was pre-measured and prepared by the research collaborator, following the researchers' requests. Before each burning test, moisture content was measured with a BD-2100 moisture meter (Delmhorst Instrument CO., Towaco, NJ, USA) by sampling 2 cm thick cookies of fuel samples for the greater than 10 cm slash piles. For materials less than 10 cm in diameter, we sampled portions of branches and needles to measure moisture contents. All samples were dried at 105 °C for 48 h since it was doubtful to measure a moisture content of fuels. Water content was not statistically different between BD-2100 and sampling methods ($p > 0.05$). When performing each test we also collected weather condition data such as air temperature, humidity, and wind speed using a Kestrel 3000 (Nielsen-Kellerman Co., Boothwyn, PA, USA) (Table 1).

ACBs' burning consumption rates (GmT/SMH) for each equipment and material were calculated using a time and motion study method. The burning times were recorded to the hundredths of a minute using a stopwatch. We recorded for second loading and burning time only, excluding the time prior to starting the air blower and burndown stage. This is because the preparation process was totally independent from operator control in the studied work phase. In addition, although S-220 and BurnBoss use the same principal of ACB for its burning mechanism, loading and the last stage, burndown, were different. For this reason, pure burning cycle times were recorded from air blower startup to second loading (from turned on air blower to when last fuels were loaded) during the ACB burning. The following describes how the S-220, BurnBoss, and HPB burning cycle times were measured:

- S-220 burning cycle time: For the S-220 burning test, we started recording the burning time when the air blower was turned on and stopped right after the last materials were loaded. Further, to determine the pure burning cycle time, second loading and waiting times sum up to gross-cycle times and determine to SMH.
- BurnBoss burning cycle time: For the BurnBoss burning test, we started recording the burning time when the air blower was turned on and stopped right after the last materials were loaded, producing comparable burning consumption rates (S-220 vs. BurnBoss). In addition, we continuously recorded until the materials were burned down completely to ash, because we also focused on feasibility to compare the burning consumption rates of BurnBoss with HPB.

- HPB burning cycle time: We started recording the burning time when a second loading started and completed our time measurement when the materials were burned down completely to ash. Thus, to determine the pure burning cycle time of HPB, second loading and perfectly combustion times sum up to gross-cycle times and determine to SMH. Additionally, when there were partially burned larger materials (>10 cm) in the pile, we picked them up and weighed them for evaluating the burning consumption rate of HPB.

Every test started with a "cold start" method, which means that each burn started on the bare ground (i.e., no ash from a previous fire) and required the ignition of kindling, followed by the addition of larger fuels until the fire continued on its own.

The machine rate calculation methods were used to evaluate hourly machine costs for the ACBs [33]. Fuel consumption rate, machine utilization rate, and wage were collected from the contractors (Table 2). Overhead or indirect, profit allowance cost, move-in, and transportation of residues costs were not obtained. Thus, total system costs included only the operational costs associated with supporting equipment (loader and personnel pick-up truck).

Table 2. Summary of input values and assumptions used to estimate hourly machine cost of S-220 and BurnBoss systems test in this study. The S-220 system include a loader while the BurnBoss oeprations were loaded by hand.

Cost Factors	S-220	Loader	BurnBoss [a]	Pickup Truck
Purchase price(US $)	106,000	135,000	48,900	40,000
Fuel consumption (L/h)	9.5	11.4	0.5	2.9
Utilization rate (%)	75.0	40.0	75.0	7.5
Wage (US $/h)	24.0	24.0	15.0	0.00
Hourly cost (US $/SMH)	53.9 [b]	19.2 [b]	28.5 [b]	0.7

[a] Excluding ember screen price for the machine used in Groveland and $1000 added to install ember screen for the machine used in Volcano. [b] Wage including benefits for one-man crew.

In addition, during the BurnBoss and HPB tests, we measured the flaming temperature (°C) using a Therma CAM SC640 IR camera (FLIR Systems, North Billerica, MA, USA) and Amprobe IR-750 thermometer (Amprove, Everett, WA, USA) in 10-min intervals until flame-out for each experiment. We recorded above the top of the FireBox and piles.

3. Results

The inventory data in Table 3 describe an ACB's burning consumption rates and cost. The S-220 unit was capable of burning rates of 5.7 to 6.8 GmT/SMH at a cost of US $12.8 and $10.8/GmT, respectively (Table 3). These burning operations (softwood, hardwood, and mixed species) indicated that combustion of softwood residues was 15% more efficient than both materials. During these trial tests, burning consumption rates strongly depended on the species. However, there was no significant difference in the moisture content of fuel sizes ($p > 0.05$).

In the BurnBoss tests in Groveland and Volcano, the machine's combustion rate of disposal ranged between 0.6 to 1.7 GmT/SMH at a cost between US $17.9 and $47.7/GmT, respectively (Table 3). The results indicated that there was no considerable difference in burning consumption rate between fuel size (diameter) less than 10 cm and 10–20 cm under less than 6-months age or fresh conditions. However, noticeable differences were detected by fuel age (fresh vs. 12-months-old) in Volcano. When burning 12-months-old residues after the fuel reduction operations, burning consumption rates were 70% greater compared to fresher fuels with a higher moisture content (27% and 36%). In addition, costs were high (US $47.7/GmT) when disposing of the fresh material.

Burning consumption rates were considerably different between burning options (BurnBoss vs. HPB), even though the burning experimental material properties were statistically similar ($p > 0.05$). The BurnBoss's burning consumption rate was 40–80% faster than HPB in this case study (Table 3). However, the average combustion temperature was not significantly different between the two burning options ($p > 0.05$). The smoke as indicated by pictures, is low for BurnBoss burning, which produced plumes with very low opacity only during the air blower start (Figure 4). For this reason, the ACB burning system was more an efficient and environmentally sound option to dispose of forest residues.

Table 3. Burning consumption rate, cost, maximum flame temperature of disposing forest residues using Air Curtain Burners (ACB) and hand-pile burn.

Locations	Burning Consumption Rate (GmT/SMH) [a]	Cost of Disposal (US $/GmT)	Moisture Content (%)	Ave. Flame Temperature [b] (°C)
Jacksonville, Florida (S-220)				
softwood	6.8	10.8	37	N/A [c]
hardwood	5.7	12.8	36	
mix	6.0	12.2	33	
Groveland, California (BurnBoss)				
small size (<10 cm)	0.7 (0.5 vs. HPB [d]: 0.3) [e]	40.9	26	955 (HPB [d]: 926)
large size (10 to 20 cm)	0.6 (0.5 vs. HPB [d]: 0.2) [e]	47.5	27	953 (HPB [d]: 945)
Volcano, California (BurnBoss installed with ember screen)				
fresh residues				
small size (<10 cm)	0.7 (0.3 vs. HPB [d]: 0.2) [e]	40.9	19	953 (HPB [d]: 916)
large size (10 to 20 cm)	0.6 (0.3 vs. HPB [d]: 0.1) [e]	47.7	36	957 (HPB [d]: 938)
12-months-old residues				
large size (10 to 20 cm)	1.7 (1.3 vs. HPB [d]: 0.1) [e]	17.9	17	955 (HPB [d]: 934)

[a] Green metric tons per scheduled machine hour; [b] Average temperature of combustion zone; [c] Data not avaliable; [d] Hand-pile burning method; [e] Burning cycle time was from air blower turned on to burn it down to ash.

4. Discussion and Conclusions

Utilizing forest residues for production of bioenergy and bioproducts effectively reduce the fire hazard and emissions from OPB, but collection and transportation of forest residues to power plants is often cost-prohibitive [4]. For this reason, one of the options used to reduce a huge amount of woody residues is to incinerate fuels. However, OPB has restrictions and challenges including fire hazards and emissions. The main contribution of this study was to introduce the environmental friendly forest residue disposal option of using an ACB and evaluate the economic feasibility. Therefore, this study was designed to evaluate two types of ACBs (S-220 and BurnBoss) and compare one with pile burning using a variety of forest residue types. We focused on a burning consumption rate based on the time to consume the materials loaded until the last materials are loaded. The ACB's burning consumption rates ranged between 0.6 and 6.8 GmT of forest residues/SMH at a cost US $47.5 and US $10.8/GmT, respectively. The S-220 offers a higher (85%) burning consumption rate and incurs a lower cost than the BurnBoss. The BurnBoss's burning consumption rate was 40–80% greater than HPB in this case study. In addition, BurnBoss burning produced much less smoke than the HPB.

We noticed that the S-220 unit was a good fit with a centralized operation with forest residues delivered for burning, while the BurnBoss could be frequently moved to the place where forest residues are located. For this reason, we do not suggest that one of the machines might be more effective than the other. However, it would be helpful to see the burning consumption rates and disposal costs of ACBs to select an optimal unit that meets operational needs. The burning consumption rate of the BurnBoss unit was smaller in quantity of fuels than the S-220 operation during our burning tests. A BurnBoss machine can be cost-effectively used to access the location where a small volume of fuels (e.g., hand-piled slash, small forest residues volumes along a roadside, and a few scattered drought/insect damaged trees in public parks) are piled and left for disposal. However, these options are often not carried out on harvesting sites due to the inaccessibility of forest roads such as steep, narrow, and winding conditions and tended to produce higher transportation cost of forest residues [34,35]. Particularly, in the Western U.S., a typical chip-van had limited access to harvest units due to forest roads that were constructed for a stinger-steered logging truck [35]. BurnBoss machines are easily transported with half-ton pick-up trucks [19]. For this reason, this unit was effectively used to remove forest residues that were not accessible with size reduction machines. In addition, it is effective for disposal of small volume of fuels such as hand-pile slash, paper trays or small forest residues volumes along a roadside, and a few scattered drought/insect damaged trees in public parks, which improves financial viability. On the other hand, the S-220 offers other applications and has the potential to succeed where there are large amounts of fuels on landing areas and high wildfire risk areas without local bioenergy facilities.

The burning rate or flammability was affected by species [36], moisture content or fuel ages [37,38], and airflow rate [39]. The calorific heating values (CV), which is defined as the amount of generating heat energy while a fuel is completely burned, were dependent on the species composition including differences in lignin content, hemicellulose, and density [40–42]. A softwood had a 10% greater CV because of the higher lignin content and lower hemicellulose and density than most hardwood [36,42,43]. Therefore, with S-220 burning activities, softwood burning rate was much higher than hardwood and mixed fuel tests, which explains in part the increase in CV for softwood burning relative to hardwood and mixed residues burning activities.

Moisture in fuels is one of the most important parameters in its combustion process and fresh fuels will not burn easily [44]. Dimitrakopoulos et al. [45] found that slash piles wetted could lead to a reduction in the combustion efficiency and obstruct ignition. During the BurnBoss tests, burning consumption rates were 2–3 times greater when disposing of 12-months-old material (17% moisture content) because the dry fuels require a shorter residence time to burn down to completion compared to fresh materials. Even though several studies indicated that material properties including size and volume were the primary factor driving burning rate [46], tree size did not have any effect in this case study. Thus, we noticed that dried forest residues led to shorter times for the materials to burn down completely to ash.

Previous studies have been carried out to observe the influence of airflow rate on burning rates [47,48]. If the amount of air supplied is increased, the combustion rate is greater than a critical flow rate [47–49]. Particularly, the high velocity airflow creating the air circulation supplied an oxygen-enriched environment in the FireBox that accelerated the burning process on ACBs burning system [23,26]. In addition, the high airflow tends to be attributable to a greater burning rates causing a larger high heat transfer from the flame [24,39], even though the flame temperature were not significantly different between the BurnBoss and HPB burning tests in this case study. On the other hand, OPB of fuels was limited by the supply of sufficient oxygen in natural (open-air) condition [50]. As a result, this high-speed air blower boosted and burned fuels more quickly and improved the burning consumption rates since the airflow rate was better than natural conditions.

ACB machine application can block the fugitive air pollutant emissions into the atmosphere since high velocity air created an air curtain on top of the FireBox [22,23,26]. Four previous studies, Fountainhead Engineering, Inc. [22], Zahn [24], Schapiro [26], and Miller and Lemieux (2007) found that ACB burning methods produced fewer greenhouse gases (i.e., CO), smoke (i.e., PM), and 90% less opacity than OPB when the air blower velocity was 1600 or 2000 RPM. Therefore, ACB operations were typically more efficient (e.g., reduction air pollutant emissions and smoke) within an incinerator compared with an OPB [19,23]. Further, it is expected that burning disposal methods will be adopted in forests to reduce potential environmental and fire hazards especially at the wildland-urban interfaces.

In conclusions, this was the first study to evaluate the burning consumption rates and costs of an ACB to better understand a centralized biomass disposal operation concept (S-220) and movable and mounted on a pick-up truck prototype (BurnBoss) machines. This study's findings have shown that S-220 and BurnBoss burning had considerably different burning consumption rates and disposing costs. Therefore, forest managers should consider the potential benefits and limitations of each machine to justify optimization efforts. For example, the BurnBoss is accessible to remote areas by a pick-up truck and suited for disposing of small size and volume forest residues. The ACB burning option seems to be commonly adopted in many forests to control emissions, smoke, and embers and to improve oxygen and heat supply by high velocity of airflow during the burn. Thus, this technology would be much more efficient and reduces the negative environmental and societal impact of burning forest residues. Further study is need to compare the weather condition, fuel age, amount of fuel load (i.e., second loading volume) to find the burning rates.

Acknowledgments: This project was funded by the Agricultural Research Institute, California State University: Award number 15-06-001. The authors are grateful to Woongsoon Jang and Joel Bisson for their contribution. Specially, our appreciation goes to Brian O'Connor (Air Burners, Inc., Palm City, FL, USA), Rick Whybra and Lester Scofield (PURFIRE), and Stephen Bakken (California State Park, CA, USA) for their cooperation on the operational aspects of the study.

Author Contributions: Han-Sup Han produced, designed and performed the experiments; Eunjai Lee collected and analyzed the data and wrote the article.

Conflicts of Interest: The authors declare no conflict of interest.

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