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Mobile Biochar Production by Flame Carbonization: Reducing Wildfire Risk and Improving Forest Resilience

Kelpie Wilson, Wihan Bekker, James Archuleta,
Darren McAvoy, and Deborah Page-Dumroese

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Abstract

Forest managers are searching for better approaches to manage low-value material resulting from fuels management and timber harvest. The conventional practice of slash pile burning emits pollutants and greenhouse gases, and leaves behind burn scars that degrade forest soils and inhibit regeneration of native plants. While sometimes this low-value material can be chipped and removed for beneficial uses elsewhere, such options are costly and logistically difficult on many remote forest sites.

Biochar production presents a promising alternative, reducing the need for costly material transport, mitigating the environmental drawbacks of slash pile burning, and providing numerous benefits when applied to forest soils. Like slash pile burns, making biochar in place involves combustion, but the methods described in this paper are much cleaner and safer than unmanaged burn piles, emitting fewer embers, particulates, and greenhouse gases. Biochar also sequesters carbon because it is not easily degradable and can hold water and dissolved nutrients in soils—a significant benefit for forest health as the climate continues to warm and dry forest soils. This report examines several alternatives for making biochar in place using newly designed equipment as well as modifications of existing methods.

Keywords: Biochar, kilns, slash piles, conservation burn piles, air curtain burners, low-value material, coarse woody debris

Cover: An air curtain burner, one type of technology for biochar production, reduces slash piles left from a postfire salvage operation (at top; courtesy photo by Kelpie Wilson, Wilson Biochar, used with permission); workers use another technology, flame-cap kilns, to produce biochar from slash (on left; U.S. Department of the Interior, Bureau of Land Management photo by Ashley Durham. Photo illustration.); biochar is spread out and crushed by an excavator bucket (on right; courtesy photo by Darren McAvoy, Utah State University, used with permission); biochar provides many ecosystem services that support plant health (courtesy photo by Kelpie Wilson, Wilson Biochar, used with permission).

Authors

Kelpie Wilson is an engineer and consultant who has worked in the biochar industry since 2008. She develops systems for making biochar from waste biomass and sells biochar production tools through her company, Wilson Biochar, LLC. She is a founding board member of the U.S. Biochar Initiative and served on the board from 2010 to 2022. She earned a B.S. degree in mechanical engineering from California State University, Chico. She is the author of "The Biochar Handbook," published in 2024.

Wihan Bekker is a Civil Engineer based in Cape Town, South Africa, with a specialized focus on life cycle assessments (LCAs) and advanced data management. He graduated from Stellenbosch University with a B.S. in civil engineering. He combines his engineering expertise and passion for environmental sustainability by merging data science and technology with ecological stewardship.

Jim Archuleta (retired) was a district Soil Scientist on the Umpqua National Forest and a forest Soil Scientist on the Umatilla National Forest. He was the Pacific Northwest Region's Wood Innovations Coordinator as a Physical Scientist with the U.S. Department of Agriculture, Forest Service's State, Private, and Tribal Forestry in Portland, Oregon. He completed an A.S. degree in natural resources at Haskell Indian Nations University before completing a B.S. in crop and soil science at Oregon State University.

Darren McAvoy is an Extension Associate Professor of Forestry at Utah State University. He is an expert at low-tech biochar production methods and the inventor of Big Box biochar kilns. He owns and operates Darren McAvoy Consulting, an international forestry consulting firm. After graduating from Colorado State University with a B.S. in forestry, he was a sawyer on the Flathead Hotshot Crew in Columbia Falls, Montana and a consulting forester in Sandpoint, Idaho. He received an M.S. degree in communications from Utah State University.

Deborah Page-Dumroese is a Senior Research Soil Scientist with the Rocky Mountain Research Station in Moscow, Idaho. She completed a B.S. in natural resource management at Grand Valley State University, an M.S. in forest soils at Michigan Technological University, and a Ph.D. in forest soils at the University of Idaho.

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INTRODUCTION

Around the world climate change, drought, overstocked stands, reductions in prescribed fire, and invasive species have created a wildfire crisis that threatens ecosystems and communities. Uncontrolled wildfires release vast quantities of particulates and greenhouse gases, harming human health and fueling climate change. For example, the 2020 wildfires in California were estimated to have released approximately 127 million megatons of greenhouse gas emissions, which is nearly twice the amount of California's total greenhouse gas emission (see glossary for definition of terms) reductions from 2003 to 2019 (Jerrett et al. 2022).

In 2022, the Forest Service, U.S. Department of Agriculture (hereafter, Forest Service) launched a 10-year strategy to address the wildfire crisis in places where there is an immediate threat of fire. This strategy was designed to reduce hazardous fuels by increasing forest treatments by up to four times the current level of work. The implemented harvest treatments produce millions of tons of unmerchantable woody residues that are routinely piled and burned. In-woods biochar production aligns with the goals of the Wildfire Crisis Strategy (USDA FS 2022) by reducing wildland fuels and creating a high-carbon product that can improve soil health and provide a myriad of other ecosystem services (e.g., habitat provision, biodiversity, and pest regulation).

While pile burning efficiently reduces fire risk from fuels remaining on the landscape, it creates both immediate and long-term problems. Despite being cost-effective, this practice generates an abundance of smoke and particulates. It also damages the surface soil layer, leaving burn scars that inhibit tree regeneration (Rhoades et al. 2021) and promote invasive species (Sexton et al. 2020). In addition to being a wildfire risk, slash piles can create a habitat for damaging insects (Dost 1967; Oregon Department of Forestry 2021). Traditional slash incineration represents a land management cost with wildfire risk reduction as its only benefit.

In contrast to traditional slash disposal, in-woods (or place-based) biochar production offers a way to restore a crucial element to forest soils—pyrogenic carbon—which has been lost due to historical fire suppression (Savage and Swetnam 1990) and reduced burning by Indigenous people (Barnett and Arno 1982). Fixing carbon into biochar through pyrolysis prevents its potential release as atmospheric carbon dioxide (CO2) through decomposition. This process represents a form of CO2 removal (Lefebvre et al. 2023) and contributes to long-term carbon sequestration efforts for climate change mitigation (Lorenz and Lal 2014).

Beyond carbon sequestration, biochar offers other benefits for soil health and ecosystem function. As a soil amendment, it enhances water retention and availability (Blanco-Canqui 2017), reduces nutrient leaching (Blanco-Canqui 2021), and neutralizes soil acidity (Chintala et al. 2014). Further, biochar improves aggregate stability, particularly in clay soils, leading to better water infiltration and reduced runoff (Sun and Lu 2014). These improvements promote plant health and create favorable habitat for beneficial microorganisms (Palansooriya et al. 2019).

This report examines existing biomass disposal methods and explores various alternatives that convert biomass to biochar. The biochar production approach offers a “greater good” relative to pile burning, by adding monetization potential, reducing emissions, protecting soil health, and expanding the operational window for woody biomass disposal. Though we do not expect open slash pile burning to be completely eliminated, our objective is to provide information and data on a variety of other tools and methods to help transform woody biomass management practices.

Biochar created in-woods can be left in place to improve soil health and ecosystem resilience, or it can be transported off-site as a valuable forest product for use in agriculture and environmental management in other locations. Here, we specifically examine eight options for place-based biochar production in forests. We discuss the suitability of each option for different kinds of landscapes, fuel types, resources, access, and seasonality. The technologies range from hand piles to portable kilns to specially designed air curtain burners. We describe the functionalities of the different technologies and identify opportunities and best-use cases for each type of technology.

SCOPE OF THE OPPORTUNITY: ALTERNATIVES TO CURRENT SLASH DISPOSAL METHODS

Forest health and fire risk reduction rely on managing woody biomass generated from a wide array of sources, including strategic fuels reduction, postharvest residues, and disturbances like wildfire, drought mortality, and pest outbreaks. Though off-site transport for timber, pulp, biomass energy, or other uses is sometimes economical, in many cases the most affordable option is to burn or masticate the biomass on-site.

Burning woody biomass is generally done in hand-built or machine-built slash piles. Slash piles may be composed of different species and sizes of material. Piles of smaller fuels are often made by hand while larger slash piles are primarily built using machinery at log landings or within timber harvest units. In recent years, changes to timber harvesting methods and equipment have led to larger machine-built piles. For example, to reduce the cost of timber sale residue disposal, whole tree harvesting is conducted. This method moves entire trees to a log landing and results in fewer, but far larger, piles of slash. Large piles burn longer and with greater heat than small piles, and they can continue smoldering outside the operational burn window (USDA FS 2023b).

There are many objectives for forest harvesting, but only a portion of the material removed is merchantable timber. Every harvest operation also produces low-value woody material (LVM or biomass), which in some cases can be monetized if located within an appropriate haul distance to a market (Keefe et al. 2014). Feasible transport distances depend on the LVM's intended use and associated handling costs: typically, around 50 road miles (80 km) for wood energy, and 30 miles (48 km) for composting. Without monetary incentives for transporting LVM, open burning of slash piles is the default disposal method.

Example of Biomass Use From the Western United States

The Deschutes National Forest (Oregon) provides an example of biomass use and the potential to expand its use. A priority landscape has been delineated on the national forest that includes the communities and property most vulnerable to wildfire spread (fig. 1a; USDA FS 2020). Both Bend and Oakridge, Oregon (which are close to the priority landscape area) are shown with a 30-mile (48 km) radius, and this area is where collection and utilization of LVM could be financially feasible (fig. 1b). The air miles illustrated in this example are likely to underestimate the greater road distances and resulting gaps between collection circles due to the road networks through the mountainous terrain. However, if a biomass use or collection radius were also established around Sisters, Oregon, it would allow for continuous landscape monetization of LVM. The proximity of these communities to the priority landscapes encourages the collection of LVM across several high-risk firesheds, thereby creating economically attractive alternatives to open burning of piles. In many locations across the United States, centralized collection opportunities are absent and other methods to monetize LVM and manage biomass are needed. Place-based (mobile) biochar production, which can be used to monetize LVM for forest managers, can be a way to manage slash piles that produces a beneficial product at less environmental cost.

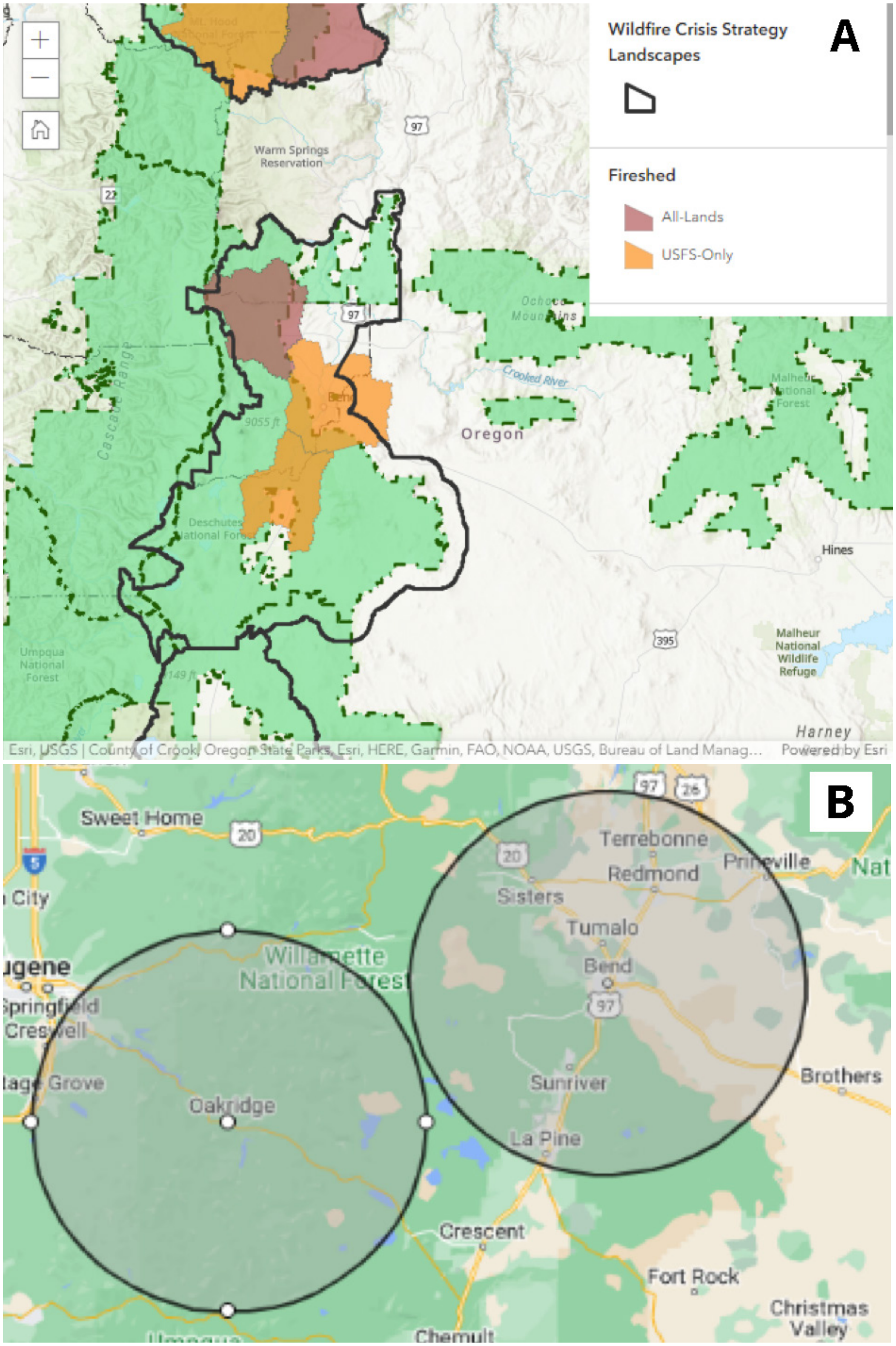


Figure 1—(a) An area was identified as most vulnerable to wildfire spread on the Deschutes National Forest in Oregon. (b) Within a 30-mile (48 km) radius of two towns near the national forest, collection and utilization of low-value material has the potential to be economically feasible. USDA Forest Service maps by the Pacific Northwest Region.

Current Alternatives for Slash Disposal

Following are the most common forms of LVM biomass disposal, arranged from the lowest cost and labor (low intensity) to the greatest cost and labor (high intensity).

Leave On-Site to Decompose (low-intensity disposal with no product potential)

When the risk of ignition and fire escape is low, leaving slash on-site to slowly decompose is a low-cost option for land managers. Decomposition of LVM is commonly associated with precommercial thinning operations that are used to reduce tree competition. This method often involves “lop and scatter” techniques which disperse cut vegetation across the harvest unit to avoid concentrations that can create hotspots should a wildfire occur. Further, by making large pieces small (e.g., mastication), decomposition may be accelerated and reduce the fuel load. Leaving slash piles to decompose reduces greenhouse gas emissions relative to open burning but can also result in the loss of productive forest area (Ter-Mikaelian et al. 2016). Only a small portion of the biomass carbon is retained in the soil once the piles decompose (Lehmann et al. 2006). Generally, the cost of leaving piles to decompose is low, but few soil benefits are gained (table 1).

Table 1—Advantages and disadvantages of leaving low-value woody material to decompose in piles.

Decomposition pros	Decomposition cons
Slash disposal costs are minimal.	Depending on the ecosystem, an increased risk of wildfire ignition is present.
Decomposition is a passive disposal method.	Drier and colder environments will have slower decomposition; as the wood becomes more decayed, greater amounts of methane are emitted.
Carbon is left on-site.	Little carbon is returned to the mineral soil, but the total amount depends on climatic regime.

Pile Burns—Hand and Machine Construction (moderate-intensity disposal with no product potential)

Slash pile burns are the first consideration when a harvest activity requires LVM disposal. A slash pile is used to concentrate fuel accumulations. There are generally two types of slash piles: hand and machine built (using a bulldozer, log loader, or excavator). This disposal method has advantages and disadvantages (table 2).

Table 2—Advantages and disadvantages of piling and burning low-value woody material.

Type of pile	Burn pile pros	Burn pile cons
Any burn pile	Biomass is concentrated for disposal by burning, chipping, or biochar production.	Timing of pile burn can be limited, leading to unburned piles.
	Permits are limited to burn windows and appropriate weather conditions.	Reporting of PM2.5 to meet Clean Air Act is expected.
	Pile burns are a fast, low-cost disposal method.	Activity may be limited by local air quality restrictions.
		Heat-altered soils can limit future trees (Rhoades et al. 2021). Very little of the biomass carbon is retained on-site (Lehmann et al. 2006).
Hand piles	Avoiding use of heavy equipment limits soil impacts.	Excess smoke is created if the pile is burned wet.
	This alternative can be done while staging fire crews.	Labor costs go up if project pays for pile construction.
Machine piles (non-whole tree harvesting)	Properly constructed smaller burn piles offer shorter duration heat and fewer soil impacts.	More piles mean higher cost and more time spent piling.
	This alternative can be constructed with equipment on hand (dozers, loaders, or excavators).	Dozer construction can be problematic (dirty piles and hold-over fires).
		Equipment move-in or move-out (or both) costs are high.

Hand Piles

Hand piles are usually built compactly with minimal airspace in order to burn completely and not fall apart. Small piles are generally left to dry (season) for a year before burning. Often the piles are covered with a small sheet of plastic to keep the center of the pile dry for ignition. Hand piles are usually built near areas with roadside clearing and vegetation management for fuel load reduction, highway maintenance for line-of-sight visibility, clearing for wildlife forage or habitat passage, and in the wildland-urban interface. Heavy equipment is not used to build these burn piles and they are generally small, so they pose little risk of long-term soil effects. However, even hand-built piles may also produce a water-repellent burn scar with reduced infiltration (Hubbert et al. 2015).

Machine Piles

Large piles are built using equipment on-site, such as excavators, bulldozers, or grapplers. In the last century, slash piled using equipment was generally confined to the harvest unit boundaries and clearcut harvesting had minimal restrictions on pile location or size. Piles were constructed post-harvest and were often built in the center of the harvest unit to prevent residual tree damage outside the harvest unit. During this era, pile construction was done using a bulldozer so the work could be completed quickly and at the lowest cost. If the piles were built without a mounted brush rake or by an operator with a poor understanding of objectives, the base of the pile could be covered with mineral soil, including some surface organic horizons, resulting in some of the wood being buried. Buried wood can carbonize from the high heat generated during burning when coupled with the low-oxygen environment in the mineral soil. Under the right conditions, however, buried wood could be a potential ignition source and spread embers.

Changes in pile construction were implemented after adoption of the Northwest Forest Plan in 1994 (Davis et al. 2015). The plan promotes regeneration harvest operations that require retention of 15 percent of live trees, and machine piles are contractually held to a specific size. For example, on the Umpqua National Forest (Oregon) the contractual fuels reduction clause limited pile size to 15 feet × 15 feet × 15 feet (5 m × 5 m × 5 m) and piles were placed so that the flames would not scorch the remaining tree crowns. Furthermore, on many national forests, stand thinning is conducted to reduce the number of standing trees and provide better growing conditions for the remaining trees. Given that a greater number of live trees are left in harvest units, finding openings to build slash piles that prevent live tree damage is more difficult. Less slash may also become available to pile in the case of timber harvest operations with whole tree processor equipment, which quickly delimbs logs and cuts them to the desired length as it traverses a harvest unit. The discarded limbs are intentionally laid down to create a slash mat over which the equipment will drive. The use of slash to mitigate equipment trafficking impacts (e.g., compaction) has also limited the creation of slash piles due to reduced available biomass or unsuitable biomass which is now mixed with soil. However, any excess slash is often still piled and burned.

The use of whole tree harvest methods eliminates the need for, and cost of, multiple machine piles throughout the harvest unit. Felled trees are brought to the landing with tops and branches attached. The trees are delimbed, and the slash is piled at the landing. On gentle topography (<35 percent slope), whole tree harvesting decreases heavy equipment movement among the residual trees and limits soil impacts. Harvesting and removing whole trees means there is often little biomass remaining within the harvest unit, which can be left to decompose.

The slash pile in figure 2 was created during a thinning project outside of Flagstaff, Arizona. Unfortunately, this harvest operation was conducted without a robust market for the wood. With no mills or wood-energy facilities near the harvest site, the wood was piled and left. Pile size was approximately 4 acres (1.6 ha) and 20 feet (6 m) deep. Before the wood could be brought to market, it was consumed in a wildfire.

Figure 2—Logs and slash piled near Flagstaff, Arizona covered 4 acres (1.6 ha) and were 20 feet (6 m deep). This pile was assembled but never taken off-site due to the lack of forest products manufacturing facilities nearby. The 2019 Museum Fire subsequently consumed the pile. Courtesy photo by Markit! Forestry, used with permission.

Mastication

Mastication reduces the size of forest vegetation by grinding, shredding, or chopping fuels created during harvesting. Mastication, for the purposes of this report, can take two forms: a trailer-mounted chipper fed by a crew of 5 to 20 workers or a mechanized chipper or masticator mounted on a skid steer, backhoe, or excavator. Generally, the chipped material is thrown directly onto the soil surface. Regardless of the method used, the intensity of this work makes it expensive.

Mastication is usually conducted along roadsides to remove brush and improve roadway line of sight, or during other work to realign or build new roads. When mastication is used within a harvest unit, it is usually during restoration efforts to improve stand structure and increase the growth of desired species. Masticated vegetation is generally small diameter material (<6 inches or 15 cm) that has little commercial value. There are several advantages and disadvantages to masticating vegetation (table 3), but overall, it produces no merchantable product to offset the cost of work and costs are typically high (Halbrook 2006).

Table 3—Advantages and disadvantages of masticating low-value woody material.

Mastication pros	Mastication cons
Treatment is effective for wildfire risk.	Most material treated is small diameter. Excess large wood tends to increase costs.
Green materials reduced in mastication can add a pulse of nutrients for short-term soil development.	Resulting short-lived (~5 years) mulch can lead to unintended fuel loading and elevated risks, if vegetation treated is too large and leaves a thick mulch on soil surface, especially in dry environments.
This alternative can avoid the indirect cost of increased road maintenance from chipping and hauling equipment.	If mulch is present during a wildfire, it may induce soil hydrophobicity as wood forms hot gases that can cool and condense, sealing pores in the soil.
Masticated wood on the soil surface can act as a mulch to increase water storage.	If mastication equipment is heavy and fails to ride slash to buffer weight over moist soils, it can induce long-term soil compaction. Equipment and mobilization costs are high.
	Masticated wood generally adds <10% carbon to the soil.

Chipping and Hauling (high-intensity disposal with product potential)

Of all the conventional slash disposal methods, only chipping and hauling offers the opportunity to capture a meaningful product to offset or cover the cost of biomass removal. Woodchip market value and transportation distances will determine whether this is feasible. However, the woodchip market is extremely volatile and may not be a reliable income source for a company. Chipping and hauling requires additional large equipment to remove piles and it is an additional expense for the contractor. In addition, large chip vans and chippers may not be able to drive on narrow forest roads. In general, activities that produce large amounts of LVM (e.g., timber sales, road building) are the most common scenarios for generating the volumes of biomass required to achieve economies of scale.

The chipping industry faces several challenges when bringing large equipment (e.g., tub or horizontal grinders) into the forest. Haul trailers rated for the weight of the equipment tend to be very long and site access can be a limiting factor when deciding whether such equipment will be used on a given project. Additionally, grinders require equipment for loading, which adds to the financial burden of this work.

Any hauling operation needs to consider the route. Moving large machinery to a forest site using a paved highway takes planning and permitting. Often long-distance transport requires both lead and chase vehicles. Well-developed public roads are designed for this equipment, so corners, switchbacks, and uphill grades are built to allow for moving the equipment. Forest roads, however, are often designed to fit the environment and their topographic changes leads to tight intersection turns, switchbacks on narrow roads, drivable dips instead of culverts, and seasonal limits on traffic. In addition to road considerations, chipping and hauling LVM has other advantages and disadvantages (table 4).

Table 4—Advantages and disadvantages of chipping and hauling low-value woody material.

Chipping and hauling pros	Chipping and hauling cons
This alternative can create merchantable products from forest slash.	Merchantability is limited by distance to use site; for wood energy the assumed distance is ~50 road miles (80 km).
Commercially available equipment and contractors can do the work.	Most equipment is designed to operate at industrial conditions in mill yards. Forest road access limits mobility because of tight corners, drivable dips, and steep grades.
Chipping and hauling can remove larger piles, without fire.	Chipping and hauling requires additional equipment at remote locations.
	The impact and degradation of road integrity from the use of this method may lead to higher road maintenance costs.
	Merchantable wood is not sorted out before it is chipped.
	Some harvest methods have small landings, which may require short hauls of slash to a nearby location where wood can be chipped and loaded into chip vans for transport, adding to project costs.
	Equipment move-in or move-out (or both) costs are high.

The Biochar Alternative for Slash Disposal

While current strategies for disposing of LVM have their pros and cons, in-woods biochar production offers several unique advantages. The biochar creation process burns wood cleaner than pile burning and can significantly reduce particulate and greenhouse gas emissions. Additionally, it avoids emissions associated with transporting LVM to offsite facilities. The biochar generated can be applied directly on-site for soil improvement, road decommissioning, revegetation, and more (for further discussion of the benefits of biochar, see the section *Value and Application of Biochar to Meet Management Needs*).

If biochar is not used on-site, its open-market value offers various income opportunities. Selling biochar to industries like agriculture, water filtration, waste management, and abandoned mine reclamation can help to offset LVM disposal costs. Finally, non-Federal forest landowners may be able to monetize the carbon sequestration value of biochar.

Biochar production converts 30 to 50 percent of the carbon found in wood into a stable (recalcitrant or durable) form that remains in the soil for centuries. Biochar carbon removal credits are increasingly available and have become an important factor for the growing biochar industry.

IN-WOODS MOBILE BIOCHAR PRODUCTION

Making biochar involves pyrolysis, the separation of biomass components by heat in the absence of oxygen. Pyrolysis can also occur in the presence of limited air, as in gasification and flame carbonization, because solid fuels such as wood burn in stages (fig. 3). In the initial stage, heat forces water evaporation (dehydration). Next, volatile gases containing carbon, hydrogen, and oxygen are released and burn in a flame, fueling the ongoing process (devolatilization). This occurs alongside char formation, also known as pyrolysis. As volatile gases escape, the remaining carbon transforms into aromatic carbon, or char. Finally, with sufficient oxygen, the char oxidizes into mineral ash (Boateng et al. 2015).

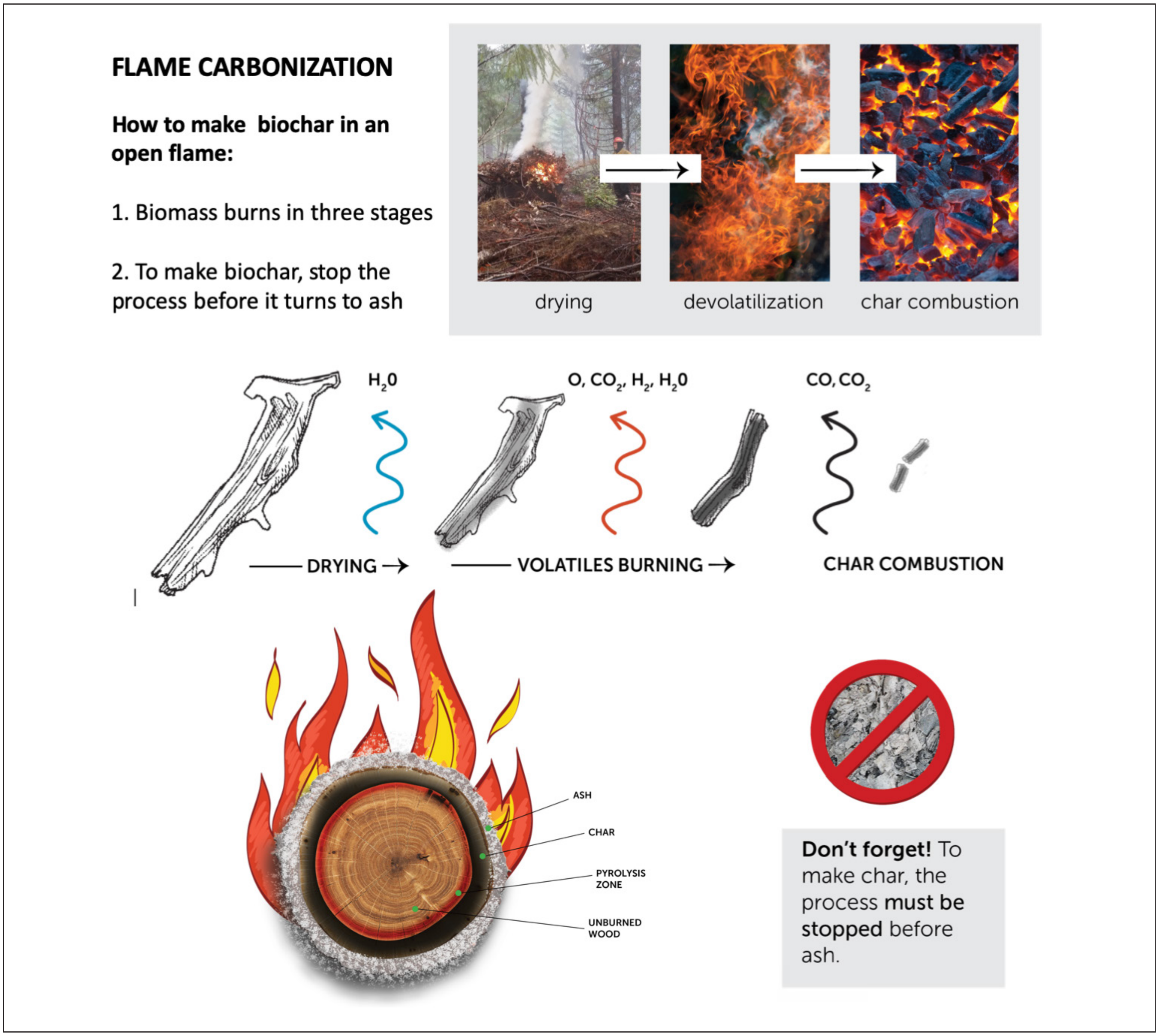


Figure 3—The process of flame carbonization entails three stages of combustion: dehydration, devolatilization, and char combustion. The key to making biochar is to stop the combustion process before it is completed. Image concept by Kelpie Wilson, Wilson Biochar. Courtesy graphic designed by Jessica Brothers, Quivira Coalition, used with permission.

Many different industrial pyrolysis installations are in operation that can produce both biochar and useful energy. This equipment is generally not designed to be mobile. Even where plants can be transported to different locations, such equipment is often not suitable for use in remote areas (e.g., forests) because it requires access to electricity and extensive preprocessing of feedstocks, including comminution (fragmenting by grinding, milling, or similar action) and drying. These processes require complex biomass handling systems in large open areas.

To produce biochar effectively and economically from slash materials which are distributed across large, remote landscapes, a different approach is needed that is highly mobile and does not require comminution but can utilize slash materials in raw form. The technologies that meet this requirement are called flame carbonization.

How Flame Carbonization Works

The discrete phases of open combustion offer an opportunity to stop the burning process after char formation by removing air or heat. In biochar kilns, burning ceases when new material is added and the hot char is buried to cut off the flow of oxygen to the already formed coals. Hot charcoal accumulates in the bottom of the kiln and is prevented from burning to ash as long as flame is present, because flames consume most of the available oxygen. When all the fuel has been added, the flame begins to die down, and at that point the charcoal can be preserved by halting combustion, usually by quenching with water (Cornelissen et al. 2016).

There are three methods for using staged combustion to produce biochar by flame carbonization and the next three sections explain how they work. These methods are:

- Conservation burn piles (CBPs)—specially constructed and managed burn piles that optimize flame carbonization.
- Flame-cap kilns (FKs)—simple containers that manage airflows and preserve char by excluding air.
- Air curtain burners (ACBs)—insulated fireboxes with active countercurrent air flow for better process control.

Each of these three categories also has several variations (table 5) which accommodate different sizes and amounts of LVM and are adapted to different forest operating and site conditions.

Table 5—Examples of in-woods biochar production technology.

Technology type	Name	Loading method	Deployment
Conservation burn pile (CBP)	Hand pile	Hand	In woods
	Machine pile	Machine	In woods, landings, skid trails, roadsides
Flame-cap kiln (FK)	Ring of Fire Kiln®	Hand or machine	In woods, landings, skid trails, roadsides
	Oregon Kiln	Hand	In woods, landings, skid trails, roadsides
	Big Box Kiln	Hand or machine	Landings, skid trails, roadsides
Air curtain burner (ACB)	BurnBoss®	Machine	Landings, skid trails, roadsides
	CharBoss®	Machine	Landings, skid trails, roadsides
	Tigercat 6050	Machine	Landings, skid trails

Conservation Burn Piles

There are two main types of CBPs—hand piles and machine piles—and they are similar to conventional burn piles except that more attention is paid to pile construction and management. The CBP technique was pioneered by the Sonoma Biochar Initiative, a project of the Sonoma Ecology Center. This organization offers educational materials and ongoing training opportunities to teach the technique through its website (Sonoma Biochar Initiative 2022).

Hand-built Piles

Hand-built CBPs are similar to standard 6-foot (1.8 m) diameter piles. The main differences between conventional and hand CBPs are the beginning (lighting) and end (quenching) stages. There is also a recommended pile construction method (see the following modification to the pile building method) that will optimize clean burning and biochar production. Hand CBPs are lit to produce flaming combustion as quickly as possible, which reduces the amount of smoldering combustion. Smoldering in piles results in a slower, cooler burn with greater emissions. Flaming combustion is cleaner and provides more heat to burn and char the wood quickly. Conservation burn piles are lit near the top so that flames develop at the top of the pile to burn more of the particulates in the smoke (fig. 4). Heat from the flame transfers downward into the unburned pile by radiation. At the end of the burn, when all material has been charred, the glowing coals are quenched with water or raked out to preserve the biochar.

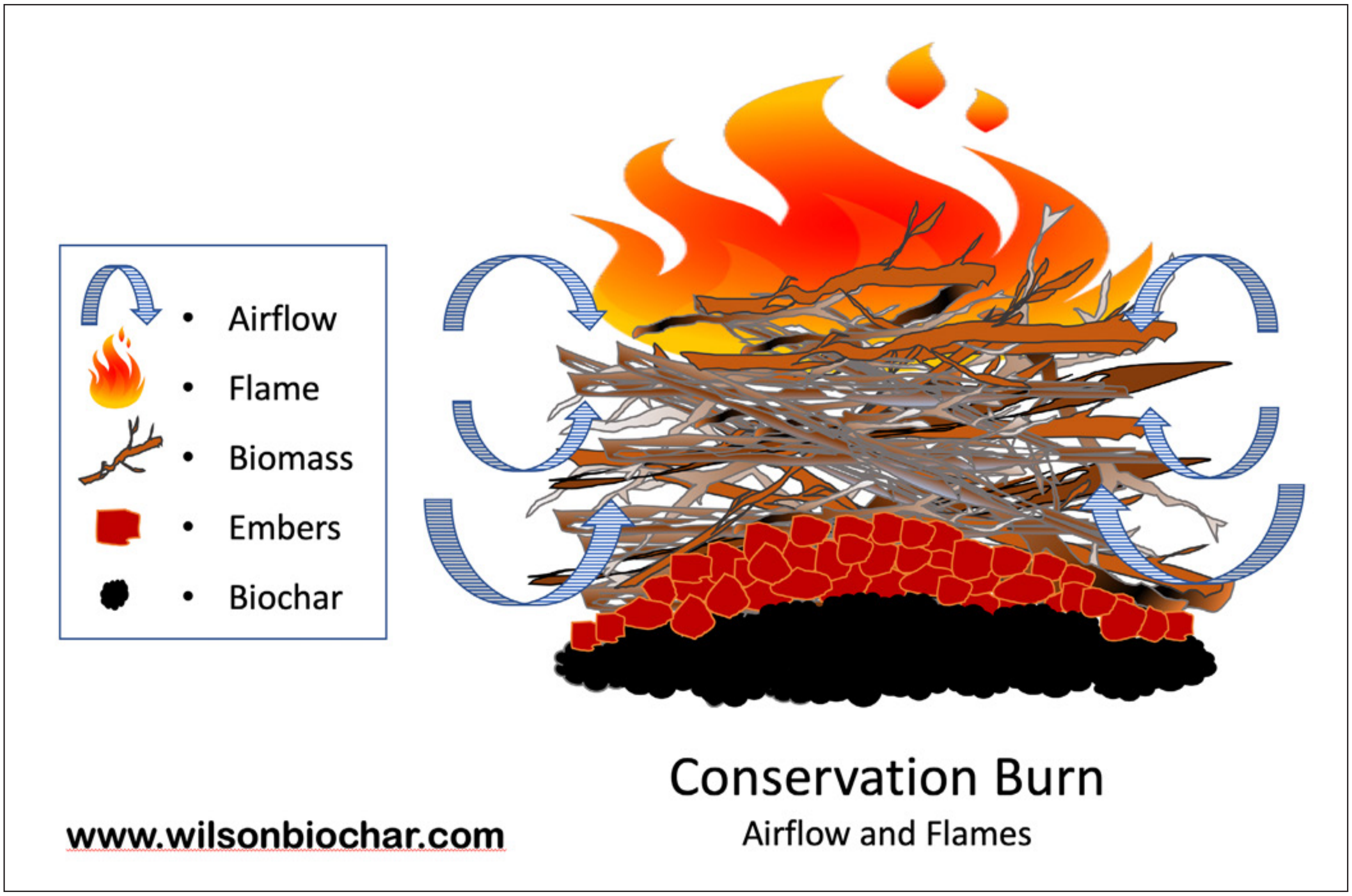


Figure 4—This diagram of a small hand-built conservation burn pile shows the flames developing at the top and hot embers and coals developing in the bottom of the pile. Courtesy image by Kelpie Wilson, Wilson Biochar, used with permission.

Here are modifications to standard pile burning practices that can enhance biochar production and reduce smoke emissions during pile burning:

- Choosing fuels—In most cases, it is not necessary to burn large (3–8 inch; 8–20 cm) diameter material. This material is also called 1000-hour fuels because it can take up to 1,000 hours to adjust to moisture conditions (NOAA 2023). Instead of burning larger logs, scatter them as coarse woody debris and allow them to decompose to provide habitat and water storage. In addition, larger logs are difficult to char completely, and they tend to create more smoke than smaller pieces of wood. The environmental benefits of coarse woody debris on the ground, combined with reduced emissions, make this approach a better option in most cases.
- Pile building method—Build piles in layers of branches laid in parallel. Pile branches and then place any larger logs in a cone shape arranged radially around the pile of smaller fuels (fig. 5). The larger logs effectively conserve heat within the burn pile, causing the smaller material in the middle to char quickly. The logs tend to fall inward, staying in the flames for better combustion. This method can also be used to construct larger machine piles.

- Light near the top—Place a kindling pocket near the top of the pile and cover with a sheet of plastic to keep it dry. Lighting the pile near the top reduces smoke emissions as the flame rises to the top of the pile more quickly to burn the smoke. It is not necessary to rely on convective heat transfer to ignite the pile from below because the flame transfers heat in all directions by radiation.
- Optimizing heat—Flaming combustion is hotter, faster, and cleaner than smoldering combustion, so maintaining flaming combustion will reduce burn time.
- Tending piles—As the material burns down, additional char will be produced if piles are managed by moving unburned pieces into the flames.
- Quenching with water—When most of the material has been reduced to a pile of glowing coals, extinguish the coals with water to form biochar. Raking char into a thin layer will dissipate the heat faster as it is being sprayed with water (fig. 6). It is usually possible to quench one hand pile with 5 gallons (19 liters) of water. Mixing the char with wet soil or snow can also help extinguish the coals.
- Quenching by raking—If burning on a wet day, it can be sufficient to just rake out the burning coals before they turn to ash and let rain put them out. This simplifies the job, allowing more piles to be treated per day.
- Managing the “bones”—Some larger pieces of wood will not char completely (bones), but they are valuable for ecological benefits. Once they are extinguished, scatter them to provide habitat for insects and fungi.
- Caution with stumps—Do not rake coals onto stumps where they can burn into root systems.

Figure 5—Recommended pile burning method for hand-built conservation burn piles is to (a) stack smaller branches, lay bigger logs around in a cone shape and (b) light the pile on top. (c) The pile retains its structure as it burns because the bigger logs making the cone configuration hold the slash together. Courtesy photos by Kelpie Wilson, Wilson Biochar, used with permission. Photo illustration.

Figure 6—The sequence for recovering biochar from a burn pile is to (a) light piles near the top to achieve flaming combustion quickly, (b) quench when embers begin to ash, (c) spray and rake the biochar into a thin layer to promote rapid heat loss with minimum water consumption and scatter the partially charred "bones" for ecological benefits. Photo illustration. (d) Several cubic feet of biochar can be produced. Courtesy photos by Kelpie Wilson, Wilson Biochar, used with permission.

Utilizing small hand-built CBPs is the most efficient method to reduce fuels that are widely distributed across the site. Making small piles minimizes the distance to hand-carry material. In some cases, especially when burning green branches, a hand pile can be operated by continually adding new material to a burning pile. This method is called a "swamper burn," and by adding branches one at a time to the pile, the flame is maintained, and the pile burns hot and quick. A swamper burn will often build up a large pile of embers that can be quenched and saved as biochar.

Machine Piles

Large CBPs are machine built and they are an alternative method for slash disposal (Page-Dumroese et al. 2017). Similar to hand-built CBPs, they can reduce smoke and soil impacts while also creating biochar. One technique for building a machine CBP is to construct a platform of large logs placed on the soil surface with enough gaps to promote air movement. The log layer helps to ensure the heat of the pile does not cause long-term damage to the underlying soil. Clean slash is then piled on top of this log base and the improved air flow will help to dry the pile quickly.

As with hand CBPs, a machine CBP is lit near the top to promote flaming combustion. Maintaining flaming combustion allows most of the particulate matter in the smoke to burn, reducing emissions. Flaming combustion proceeds much faster than smoldering combustion, so burn piles can be reduced to coals in less than 1 workday. As the pile burns down, it forms a heap of glowing coals. When most of the material has been reduced to coals, spray water from a water tender while raking the coals to a thin layer to cool. The same machinery used to build the pile can also be used to rake the biochar out to cool as it is being sprayed with water.

This process will leave some partially burned material mixed with biochar and soil. While a mixture of biochar, soil, and partially burned wood is a benefit for onsite soil health, its inconsistency makes it inappropriate for collection and transport to markets.

One example of equipment for building clean, large piles is an excavator. The grapple head on an excavator can lift small loads of slash, shake off the soil, and then drop the material onto a pile from above (fig. 7). The resulting pile is less compacted and allows good air flow to promote flaming. Flaming combustion should continue throughout the burn until most of the material has become glowing coals and begins to ash (fig. 8). Once the flames die down, the hot coals are ready to quench.

Figure 7—An excavator is a good tool for building machine conservation burn piles. Dropping material from above keeps soil out the piles. USDA Forest Service photo by Jim Archuleta.

Figure 8—This machine-built conservation burn pile is at the stage where coals are forming; the pile will be quenched before it all burns to ash. Courtesy photo by Kelpie Wilson, Wilson Biochar, used with permission.

Conservation Burn Pile Data

The specification sheets for the two types of CBPs (see end of this section) were compiled based on a limited number of trial-and-error field projects. In Josephine County, Oregon, the Illinois Valley Fire Resiliency Oversight Group coordinated fuels reduction projects at the wildland-urban interface and assisted landowners in conducting CBP burns. Wilson Biochar, LLC (Cave Junction, Oregon) managed about 50 hand CBPs to recover biochar on 2 different pile burning projects in 2023. Biochar produced in the piles was quantified by scooping up the biochar and packing it into 5-gallon buckets. Most piles yielded about 3 buckets of biochar, or 2 cubic feet (57 liters). We used the Piled Fuels and Biomass Emission calculator (Wright and Vihnanek 2015) to estimate the dry biomass of typical hand piles at about 300 pounds (136 kg) each. To convert biochar volume to mass, we used an average biochar dry bulk density of 230 pounds per cubic yard (136 kg per cubic meter), based on multiple test results from biochar made in burn piles and small FKs by Wilson Biochar. We then calculated conversion efficiencies of biomass to biochar for three piles to arrive at an average of about 5 percent by dry mass.

We asked Sean Hendrix, base commander for Grayback Forestry (Merlin, Oregon), to estimate the number of piles that could be burned and quenched in this way with a five-person crew during a normal work shift. He estimated that the crew could treat 150 piles scattered over a 6-acre (2.4 ha) site (Sean Hendrix, personal communication, December 20, 2023).

To estimate the potential of the machine CBP technique for making biochar, we consulted with Jack LeRoy of Forest Energy Group, LLC (Central Point, Oregon) about the feasibility of producing biochar from machine piles built along a forest road. Forest Energy Group was established in 2004 to compete and perform on forest health stewardship contracts. Notably, Forest Energy Group was contracted to implement ground-based thinning and forest road construction and maintenance for the Ashland Forest Resiliency Project located in the watershed of Ashland, Oregon.

Given his extensive experience, LeRoy recommended that piles be constructed with a 15-foot × 15-foot (4.6 m × 4.6 m) base and about 12 feet (3.7 m) tall using only material that is 12 inches (30 cm) in diameter or smaller. The pile is built by laying the smaller material in parallel stacks and placing larger logs in a cone shape around the smaller material, as in the hand CPB method. A kindling pile is constructed under a polyethylene sheet near the top of the pile. A log loader with a brush grapple is the best equipment for building this kind of pile. Material larger than 12 inches (30 cm) in diameter should be cut into short lengths and left on-site in contact with the ground to provide the ecological benefits of coarse woody debris (Jack LeRoy, personal communication, December 22, 2023).

LeRoy speculated that a crew of 5 people could burn, rake, and quench 30 piles a day, if placed for easy access along a mile (1.6 km) or so of forest road. The crew requires a log loader or similar equipment to break apart the pile of coals, along with 300 gallons (1,136 liters) of water per pile provided by a water tender following behind the log loader. Water could be made available on-site by staging portable water tanks filled ahead of time to refill the water tender. The hand crew would finish raking the char to a thin layer.

We used the Piled Fuels calculator (Wright and Vihnanek 2015) to estimate the biomass of a machine pile constructed to the specifications recommended by Forest Energy Group. For example, a packing ratio of 20 percent for a pile composed of 60 percent Douglas-fir (*Pseudotsuga menziesii*) and 40 percent ponderosa pine (*Pinus ponderosa*) and pile dimensions of 15 feet wide × 15 feet long × 12 feet high (4.6 m × 4.6 m × 3.7 m) yielded a total biomass of 3.3 tons (3 metric tonnes) per machine pile. We assumed that the conversion efficiency of a machine CBP would be less than that of a hand CBP because there might be more large pieces that did not completely char. Using a conversion efficiency of 3 percent, we estimated that one machine CBP could produce about 0.9 cubic yard (0.7 cubic meter) of biochar. As with the hand CBP, partially burned logs are safe to leave on-site where they can provide ecological benefits.

The production rates reported in the following data sheets are estimates for a typical scenario using these techniques. These data are approximate and variable, but the results demonstrate that significant amounts of biochar can be produced from CBPs.

SPEC SHEET FOR ONE TECHNOLOGY UNIT

HAND CBP

Hand-built Conservation Burn Piles are lit on top to produce flaming combustion. Glowing coals are quenched with water or raked out to preserve the biochar.

FEEDSTOCK INFO

Loading method: Build hand piles 6 feet (2 m) in diameter during thinning or fuels removal work, leave to dry and season
Max length: 6 feet (1.8 m)
Max Diameter: 4 inches (10 cm)
- **Acceptable moisture content:** 25%

Sorting required: Yes
Sorting method: Use stacked or teepee pile construction methods to effectively utilize mixed-sizes

AT A GLANCE

SIZE

- Hand piles 6 feet (2 m) in diameter

TEAM SIZE REQUIRED

- One supervisor and 4 hand crew can complete 6 acres (2.4 ha) in 8 hours (150 piles), producing 11 cubic yards (8 m^3) of biochar

PRODUCTION DATA

Continuous or batch: Batch
Run time: 3 hours per pile
Biochar production, per piles: 2 cubic feet (57 L)
Feedstock processed, per pile: 300 lbs (136 kg)
Quenching method: Spray and rake
Water requirements per pile: 5 gal (19 L)
Ignition method: Drip torch or propane torch

SUPPORT EQUIPMENT NEEDED

Loading equipment: None
Water: Water tender or trailer, optional ATV for water trailer
Mobilization: Hand crew transport

BIOCHAR APPLICATIONS

- Quenching and raking will deposit biochar on site for soil improvement.
- After it is fully quenched, biochar can be further raked and lightly incorporated into the soil surrounding the burn footprint
- Seeding with native species can speed recovery of healthy forest understory

PROS

- Least expensive option
- Prevents burn pile scars and protects soil
- Quenching and raking will deposit biochar on site and incorporates biochar in forest soil
- Provides employment for unskilled labor
- Can be done by volunteers

CONS

- Requires extensive hose lays or carrying heavy bladder bags
- More difficult to manage water quenching on steep slopes
- Ignition fuel is required to light each pile, increasing the amount of fuel used per ton of biomass processed

SPEC SHEET FOR ONE TECHNOLOGY UNIT

MACHINE CBP

Conservation Burn Piles built with machines must be free of dirt to allow flaming combustion. Glowing coals are quenched with water to preserve the biochar.

FEEDSTOCK INFO

Loading method: Build piles during logging operations with excavator or brush rake, 15 feet x 15 feet x 12 feet (4.6 m x 4.6 m x 3.7 m) (leave to dry and season)
Max Length: 15 feet (4.6 m)
Max Diameter: 12 inches (30 cm)
- **Acceptable moisture content:** 25%

Sorting required: Yes
Sorting Method: Use stacked or teepee pile construction methods to effectively utilize mixed-sizes

PRODUCTION DATA

Continuous or batch: Batch
Run time: 5 hours per pile
Biochar production, per pile : 0.9 cubic yards (0.7 cubic meters)
Feedstock processed, per pile: 3.3 tons (3 MT)
Quenching method: Spray and rake
Water requirements, per pile: 300 gal (1,136 L) per pile
Ignition method: Drip torch or propane torch

AT A GLANCE

SIZE

- Maximum pile footprint 15 foot (4.6 m) diameter

TEAM SIZE REQUIRED

- 4 crew for pile burning and quenching
- 1 machine operator for raking char to quench
- Each team can complete 30 burn piles with an estimated dry weight of 99 tons (90 MT) of low-value woody material (LVM) in one shift, producing 27 cubic yards (21 m^3) of biochar

SUPPORT EQUIPMENT NEEDED

Loading equipment: Excavator or loader with brush rake for raking to quench
Water: Water tender or trailer, or pumped from water body
Mobilization: Trailer for excavator or loader, hand crew

BIOCHAR APPLICATIONS

- Quenching and raking will deposit biochar on site for soil improvement
- Some portion can be scooped up and transported elsewhere
- Mix of particle sizes and dirt will preclude most commercial uses, but biochar can easily be used for erosion control, decompaction, and soil improvement on nearby sites

PROS

- Disposes of large diameter LVM that is hard to process with other low-tech options
- Easy access as piles will be on or near roadside
- Prevents burn pile scars and protects soil
- Biochar left onsite helps with revegetation and recovery

CONS

- Harder to control smoke emissions than smaller piles
- More challenging to quench than smaller piles

Flame-cap Kilns

An FK is a simple container that holds burning woody debris. The container has a solid bottom or a bottom sealed with dirt so that all air for combustion comes from above. The top of the container is open with no restrictions, and the width of the container is greater than the height, to facilitate air flow from the top of the kiln to the bottom.

The container is loaded with slash materials and lit on top. Once the initial material has burned down to glowing coals, operators continually load additional material into the kiln. After several hours of burning, the full kiln of hot coals is extinguished to conserve the biochar.

Counterflow combustion in an FK enables biochar production with fewer emissions and safety risks than a CBP. Counterflow combustion keeps the flame length low and reduces embers or sparks. The flame also burns most of the smoke, which reduces emissions. The following principles explain the operation of counterflow combustion in FKs (fig. 9).

- Gas flows upward while combustion air flows downward.
- Countercurrent flow is established as burning fuel draws air downward.
- Flames stay low and close to fuel, minimizing ember escape.
- Smoke burns near the flaming material.
- Since combustion air comes from above, it is consumed by the flames.
- Very little air reaches the unburned coals that fall to the bottom of the kiln.
- Coals are preserved until the end of the process when they are quenched.

Small mobile hand-loaded kilns are operated much like a burn pile, except that once the initial wood burns, more material is added. Operation is similar to the widely used “swamper burn” technique for continually adding new material to a small, hot burn pile. Once the container is full of coals, it is quenched with water and raked out into the forest soil.

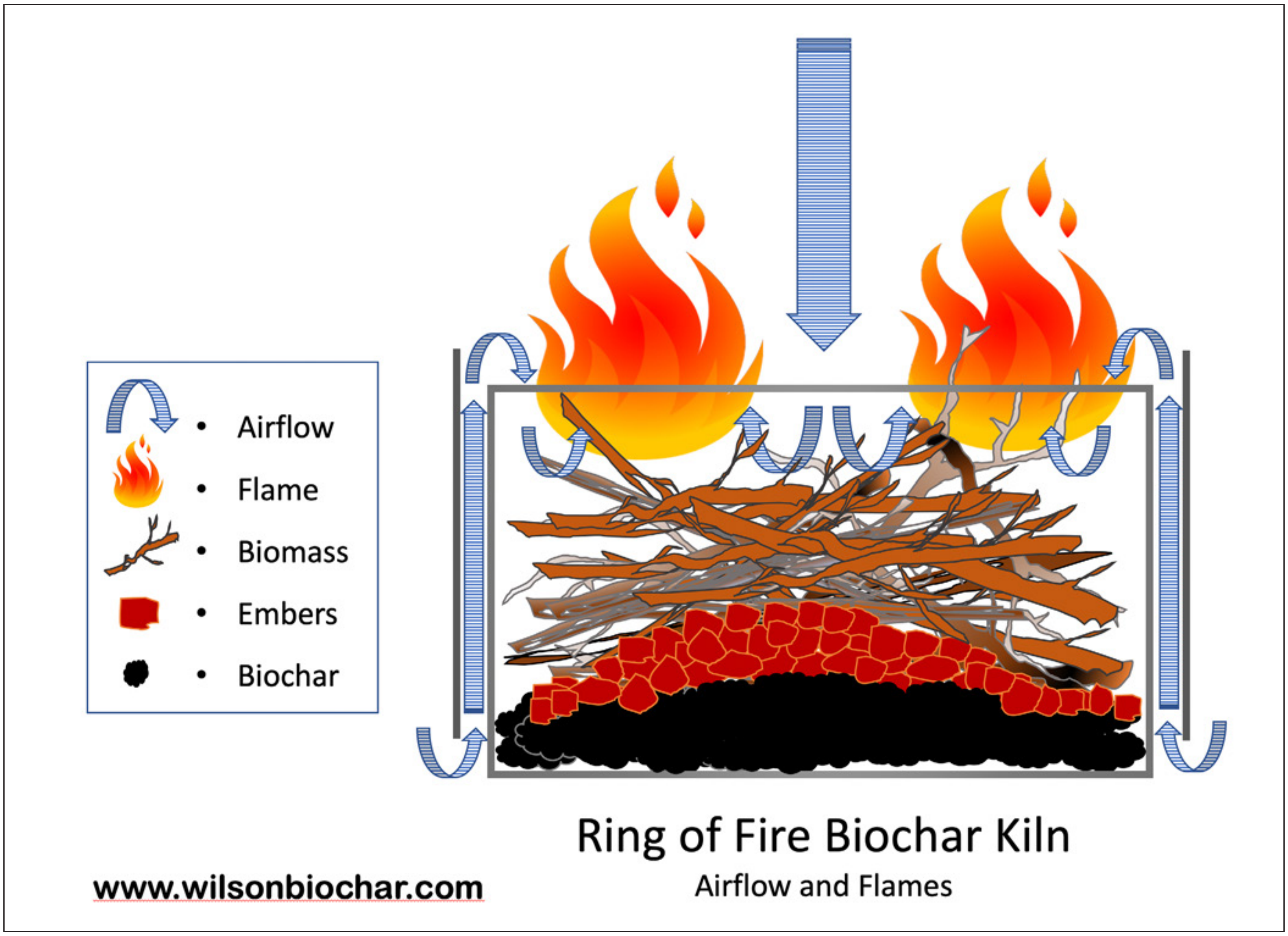


Figure 9—Airflow and flames are shown in the Ring of Fire Kiln®, a flame-cap kiln. Courtesy image by Kelpie Wilson, Wilson Biochar, used with permission.

Ring of Fire Kiln®

The Ring of Fire Kiln® is a modular design made of panels of sheet steel that are bolted together to make a ring (fig. 10). This kiln has no bottom and when the char is finished, the kiln is taken apart so the char can be raked out and quenched. This quenching step is identical to the method for quenching a CBP. The Ring of Fire Kiln can be extended to make a larger kiln by adding more panels. The larger kilns are often loaded by an excavator or other equipment. See step-by-step instructions for operating the Ring of Fire Kiln and using a monitoring, reporting, and verification app for carbon accounting in Wilson et al. (2024).

There are other FK designs that are one-piece containers with a bottom. These are called bin kilns and they can be quenched by flooding with water.

Figure 10—(a) Multiple Ring of Fire Kilns® are at work in a walnut orchard. Courtesy photo by Ken Scherer, the Biochar Coalition, used with permission. Photo illustration. (b) Countercurrent airflow in the Ring of Fire Kiln tends to draw smoke back into the flames, where it burns. Courtesy photo by Kelpie Wilson, Wilson Biochar, used with permission. (c) This kiln is near the end of the process, almost ready to quench. Courtesy photo by Kelpie Wilson, Wilson Biochar, used with permission. Photo illustration.

Oregon Kiln

A smaller bin kiln called the Oregon Kiln (developed by Kelpie Wilson, Wilson Biochar) is loaded by hand (fig. 11). This kiln weighs 200 pounds (90 kg) and can be operated off-road in rough terrain. Typically, several kilns are distributed near the concentrations of LVM. Depending on the distance that biomass must be moved, one worker can feed one or two kilns.

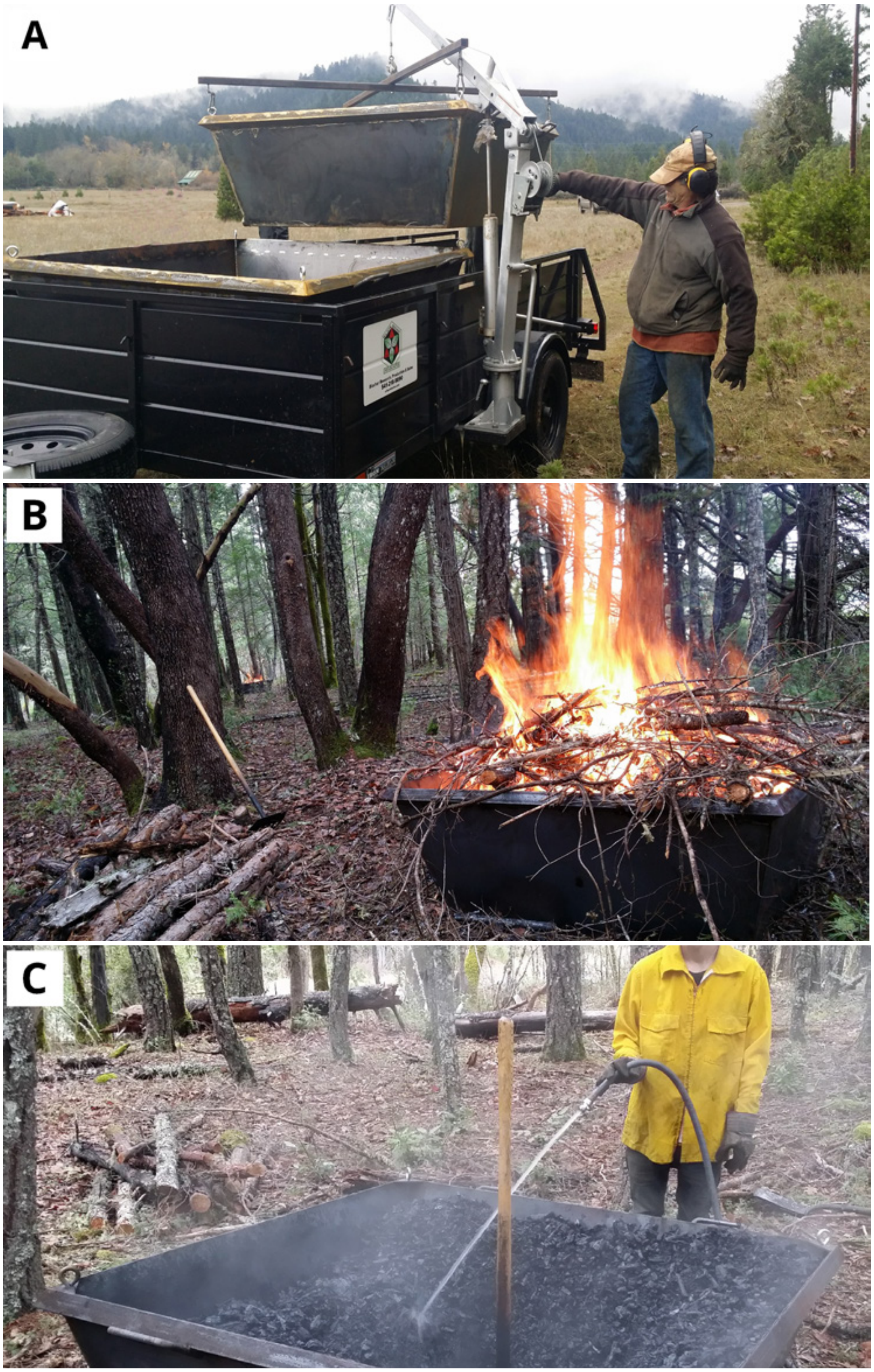


Figure 11—(a) The Oregon Kiln can be transported in a small trailer. Photo illustration. (b) The Oregon Kiln is being used to char piled fuels in the woods. (c) Biochar is quenched in the Oregon Kiln. Courtesy photos by Kelpie Wilson, Wilson Biochar, used with permission.

Big Box Kiln

The Big Box Kiln (developed by Darren McAvoy, Utah State University) is a 6 foot wide × 12 foot long × 4 foot high (1.8 m × 3.6 m × 1.2 m) double-walled bin kiln that is usually loaded by machinery (fig. 12). This bin kiln can be operated to maximize either biochar production or hazardous fuels reduction. If biochar production is the primary goal, the feedstock can be sorted into like sizes and the kilns loaded with similar size-class material and quenched frequently to preserve the coals. If hazardous fuels reduction is the primary goal, then the kilns can be loaded randomly and quenched only when the kiln is full of coals. Often, the process has a mixture of goals, and the kilns are operated between these two extremes. See step-by-step instructions for operating the Big Box Kiln in McAvoy (2024).

Bin kilns can be flood quenched to avoid the step of raking the char, but flood quenching requires more water. Bin kilns have a drain plug that can be removed to allow the quenching water to drain before unloading the char. Because the char does not have to be raked out to cool, it can be loaded directly into a bag or container for removal off-site. Open-source plans for constructing both the Oregon Kiln and the Big Box Kiln are available online at https://www.appropedia.org.

Flame-cap Kiln Data

The specification sheets for three types of FKs (see end of this section) were compiled based on several years of field experience by the kiln developers, Kelpie Wilson and Darren McAvoy. The volume of biochar produced in FKs is easy to measure before the char is unloaded from the kiln because it is sufficient to just measure the level of the char in the container of known volume. However, if the feedstocks are loaded too quickly, the kiln can fill up with unburned or partially burned material as the flame moves up in the kiln and feedstocks near the bottom begin to cool. These “bones” need to be removed from the finished biochar and subtracted from the biochar volume produced. Well-trained and experienced operators understand the proper loading rate for different kinds of feedstocks to avoid leaving partially charred material in the kilns.

We have tested samples of char produced in these kilns and in most cases, the bulk density and carbon content of biochar made from woody debris in FKs is consistent for softwood feedstocks. For purposes of this analysis, we use a dry bulk density of 230 pounds per cubic yard (136 kg per cubic meter) as an average value.

The production efficiency of FKs is difficult to understand accurately in the field because of the challenges of measuring the dry mass of the LVM. In addition, biochar conversion efficiencies vary depending on feedstock characteristics and operating conditions. A range of values for conversion efficiency of FKs has been reported in the limited published literature (Cornelissen et al. 2016; Inoue et al. 2011). Of these datasets, the average value of conversion of a woody feedstock to biochar in a metal kiln is approximately 17 percent by dry mass. We use this value to estimate how much biomass was processed in the kilns to produce the amount of biochar product which we could easily measure by volume.

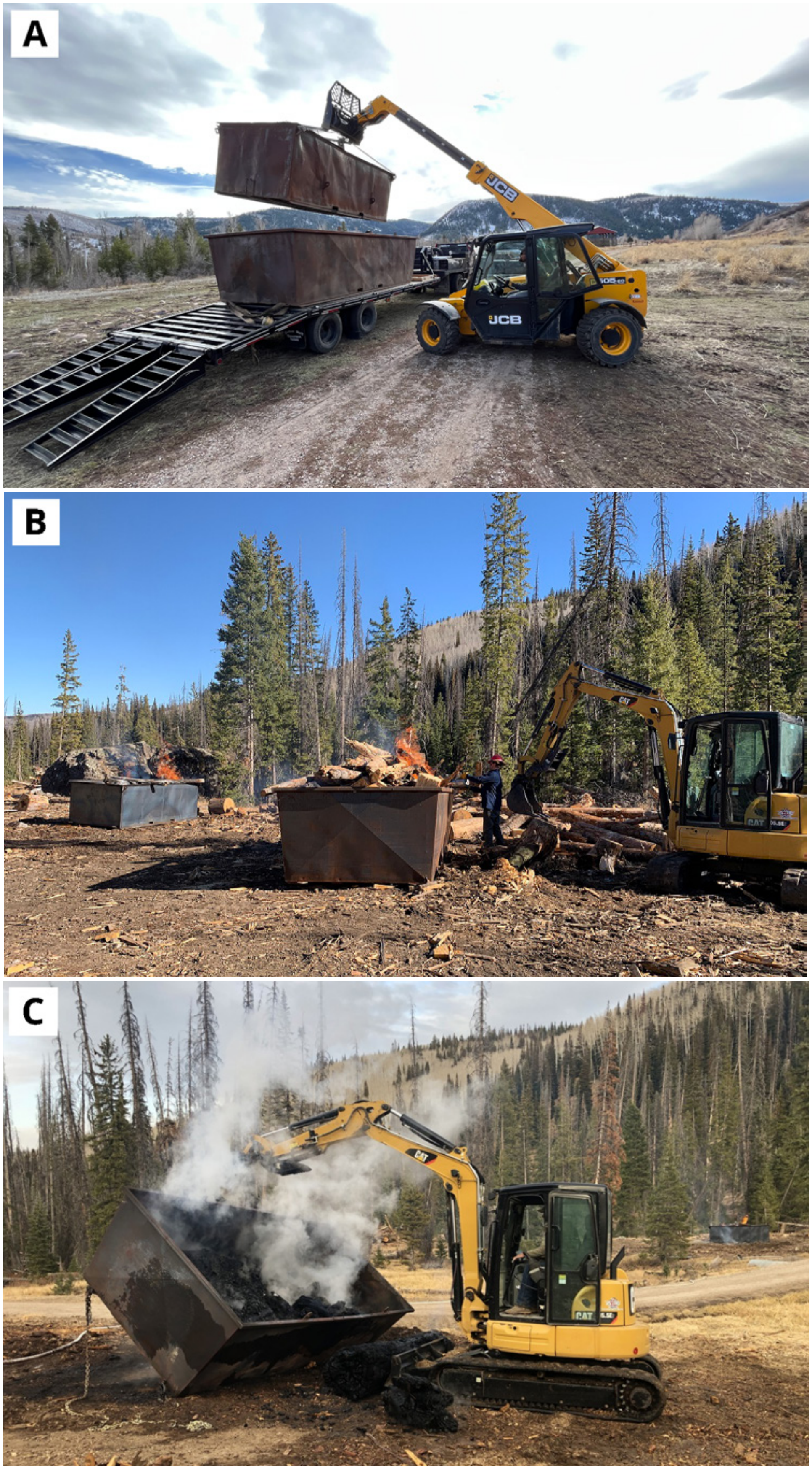


Figure 12—(a) Two Big Box Kilns are nested for transport. (b) One loading machine can service two Big Box units. (c) At the end of the burn, the excavator tips and dumps the kilns. Courtesy photos by Darren McAvoy, Utah State University, used with permission.

SPEC SHEET FOR ONE TECHNOLOGY UNIT

RING OF FIRE

The Ring of Fire Kiln® is a metal container for converting woody biomass into biochar. This panel kiln has an inner wall and a heat shield to protect hand crews and increase burn efficiencies.

ringoffire.earth

FEEDSTOCK INFO

Loading method: Hand or mini-excavator
Max Length: 6 feet (1.8 m)
Max Diameter: 4 inches (10 cm)
- **Acceptable moisture content:** 25%

Sorting required: Yes
Sorting size classes: The initial load is small, dry brush. Then load in layers of the same size class

PRODUCTION DATA

Continuous or batch: Batch
Run time: 5 hours at 25% moisture
Biochar production, per kiln: 3 cubic yards (2.3 m^3)
Feedstock processed, per kiln: 2 tons (1.8 MT)
Quenching method: Spray and rake
Water requirements, per kiln: 150 gal (568 L)
Ignition method: Drip torch or propane torch

SUPPORT EQUIPMENT NEEDED

Loading equipment: Not required but can be used
Water: Water tender, trailer, pickup truck bulk container, or pumped from water body; optional ATV for water trailer
Mobilization: Kilns transport as flat panels in back of pickup truck; hand crew transport

BIOCHAR APPLICATIONS

- Quenching and raking will deposit biochar on site for soil improvement
- Some portion can be scooped up and transported elsewhere
- Mix of particle sizes and dirt will preclude most commercial uses, but biochar can easily be used for erosion control, decompaction, and soil improvement on nearby sites

AT A GLANCE

SIZE

- 8 foot (2.5 m) diameter footprint
- Weight: 330 pounds (150 kg), assembled. Panels weigh 37 (17 kg) pounds each

TEAM SIZE REQUIRED

- 1 supervisor
- 4 hand crew can operate 4 kilns
- Producing 12 cubic yards (9.2 m^3) of biochar from 8 tons (7.2 MT) of low-value woody material (LVM) per shift

PROS

- Low capital cost kilns
- Provides employment for unskilled labor - can be done by volunteers
- Heatshield improves kiln efficiency, protects workers from heat, and reduces emissions
- Kilns are easier for hand crews to move off-road
- Can operate on slopes where there are small flat spaces
- Can expand kiln size by adding more panels
- Can load with machinery or by hand

CONS

- Kilns must be disassembled to remove char
- Spray and rake quenching makes it more difficult to recover clean biochar without dirt or organic material

SPEC SHEET FOR ONE TECHNOLOGY UNIT

OREGON KILN

The Oregon kiln is a small flame-cap bin kiln that can be used on uneven or steep terrain.

FEEDSTOCK INFO

Loading method: Hand Crew
Max Length: 6 feet (1.8 m)
Max Diameter: 4 inches (10 cm)
- **Acceptable moisture content:** 25%

Sorting required: Yes
Sorting size classes: Initial load is small, dry brush. Then load in layers of the same size class

PRODUCTION DATA

Continuous or batch: Batch (2 batches per shift)
Run time: 3 hours per batch at 25% moisture
Biochar production, per kiln batch: 1 cubic yard (0.8 m^3)
Feedstock processed, per kiln batch: 1,350 pounds (612 kg)
Quenching method: Flood quench and drain
Water requirements per kiln batch: 50 gal (189 L)
Ignition method: Drip torch or propane torch

SUPPORT EQUIPMENT NEEDED

Loading equipment: None
Water: Water tender, trailer, pickup truck bulk container, or pumped from water body; optional ATV for water trailer
Mobilization: Truck or trailer for kilns; hand crew transport

BIOCHAR APPLICATIONS

- Dumping quenched char on the ground will deposit biochar in-place for soil improvement
- Some portion can be scooped up and transported elsewhere
- Clean biochar can also be loaded directly from bins into containers for transport

AT A GLANCE

SIZE

- 5 feet x 5 feet (1.5 m x 1.5 m) kiln footprint
- Weight: 200 pounds (91 kg)

TEAM SIZE REQUIRED

- 1 supervisor and 4 hand crew can complete 2 kiln batches per day in 6 kilns, producing a total of 12 cubic yards (9.2 m^3) of biochar from 8 tons (7 MT) of low-value woody material (LVM)

PROS

- Low capital cost kilns
- Provides employment for unskilled labor - can be done by volunteers
- Makes 2 to 3 times more biochar than open burns
- Flood quenching allows easier recovery of char for use off-site
- Kiln can be used on rougher terrain and slopes where there are small flat spaces

CONS

- Kilns are heavy to move very far with hand crews, limiting off road use, although they can be skidded with an ATV
- No heat shield and small volume with less heating power results in slower charring than other kilns

SPEC SHEET FOR ONE TECHNOLOGY UNIT

BIG BOX BB-12

The Big Box Kiln is a large double-walled flame-cap bin kiln that can be loaded with machinery and utilize large material.

FEEDSTOCK INFO

Loading method: Machine loading
Max Length: 10 feet (3 m)
Max Diameter: 12 inches (30 cm)
- **Acceptable moisture content:** 25%

Sorting required: Yes
Sorting Method: Initial load is smaller, drier material. Then load in layers

PRODUCTION DATA

Continuous or batch: Batch
Run time: 6 hours at 25% moisture
Biochar production, per kiln: 8 cubic yards (6 m^3)
Feedstock processed, per kiln: 5.4 tons (5 MT)
Quenching method: Flood, drain, and tip the box to unload char
Water requirements, per kiln: 300 gal (1,136 L) for flood quenching, 150 gal (568 L) for tip-and-stir quenching
Ignition method: Fuzee, drip torch or propane torch

SUPPORT EQUIPMENT NEEDED

Loading equipment: Small excavator or log loader, skid-steer with grapple bucket
Water: Water tender, trailer, pickup truck bulk container, or pumped from water body; optional ATV for water trailer
Mobilization: Trailers for kilns and loader

BIOCHAR APPLICATIONS

- Dumping quenched char on the ground will deposit biochar on site for soil improvement; some portion can be scooped up and transported elsewhere
- Clean biochar can be loaded directly from kiln into containers for transport

AT A GLANCE

SIZE

- **Footprint:** 12 feet x 6 feet (3.6 m x 1.8 m)
- **Weight:** 2000 lbs (907 kg)

TEAM SIZE REQUIRED

- One machine operator per project and one hand crew per kiln
- Crew can operate two kilns producing 16 cubic yards (12.2 m^3) of biochar from 10.8 tons (9.8 MT) of low-value woody material (LVM)

PROS

- Heatshield and large box size increase heat energy and biochar production efficiency
- Large box can handle larger feedstocks
- Low capital cost
- Can be skidded off-road and used on slopes with flat spots
- Flood quenching allows for easier char collection for removal offsite
- One loader can service two kilns for greater economy

CONS

- Machinery needs to be hardened against heat to avoid burning hydraulic lines
- Box is heavy and can be difficult to move and tip for unloading
- Heavy materials/equipment present safety hazards

Air Curtain Burners

An ACB is an insulated firebox on skids, wheels, or tracks with a blower to control the airflow in and out of the firebox. The blower establishes counterflow combustion, much like an FK, except that the blower allows for more control of airflow and emissions. The powerful air jet (or curtain) across the top of the firebox recirculates emissions from the burning material, helping to consume smoke particulates and thereby reduce impacts on air quality. This is especially helpful when burning wet fuels. By stoking the fire, the blower also makes it possible to consume large logs that would not burn completely in a passive FK (fig. 13). The ACB technology was originally developed for complete incineration of the feedstock. However, ACBs can make more or less biochar depending on whether the priority is biomass removal or biochar production. When producing biochar is the priority, the operator will select feedstocks that are smaller in diameter and have less fuel moisture. However, when only large, wet, green material is available, ACBs will still produce some biochar at a conversion efficiency of about 3 percent by dry mass.

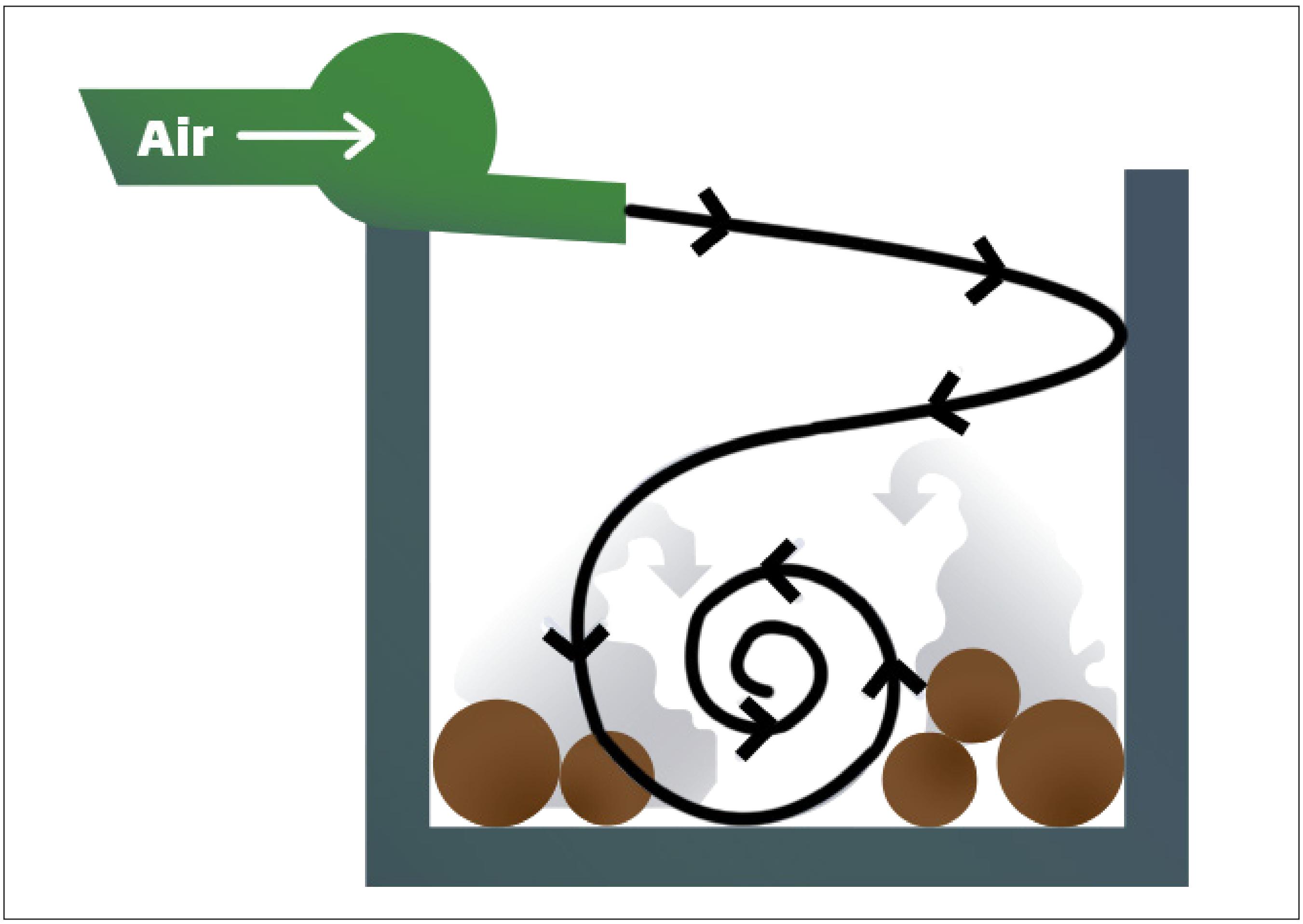


Figure 13—The blower directs airflows in an air curtain burner for greater control of airflow and emissions. Courtesy image by Air Burners, Inc., used with permission.

The conversion efficiency of biomass to biochar for ACBs is inherently less than that of FKs because the blower provides a much greater volume of air to the feedstock, promoting more complete combustion of materials to ash. On the other hand, ACBs can process more biomass per hour and are more efficient at reducing fuels. Air curtain burners are also much more capable of processing wet, green, and large feedstocks, including large, wet logs.

Air curtain burners are loaded by an excavator, log loader, or other mechanical equipment. Loading follows a similar strategy as loading FKs. Some ACBs are configured as batch systems, where loading continues until the firebox is full of biochar, which is then unloaded and quenched with water. Other ACBs produce biochar continuously and coals are quenched when they exit the firebox. Air curtain burners can run as continuous processors for multiple shifts. There are three types of onsite ACBs currently used to make biochar: BurnBoss® (Air Burners, Inc., Palm City, Florida), CharBoss® (Air Burners, Inc.), and Tigercat 6050 (Tigercat, Inc., Brantford, Ontario, Canada).

BurnBoss®

The smallest and simplest ACB is a unit that was designed as an incinerator, the BurnBoss, which is a towable unit for in-woods applications (fig. 14). Operators have developed best practices for maximizing biochar production by controlling the loading rate and size of material. When the firebox is full of hot coals, the operator lifts the firebox sidewalls before pulling the BurnBoss trailer unit forward, allowing the biochar to drop out. This step needs to be done quickly to avoid scorching the tires on the unit. The coals are then quenched with water to preserve the biochar.

CharBoss®

Air Burners, Inc. partnered with the Forest Service to develop the patented CharBoss, a towable ACB designed to produce biochar continuously (fig. 15). The firebox is filled using an excavator or similar machinery and all sizes of woody material can be used. The wood is agitated by a shaker panel which dislodges the biochar that forms on the outside of each piece of material (see figure 3). The exfoliated char then drops through a slot in the bottom of the unit onto a conveyor belt and into a quench pan. Because biochar is continually produced and quenched in small amounts, the process uses very little water. The Forest Service has conducted emissions testing on the CharBoss. Although the results have yet to be published, they are likely to be similar to results for the BurnBoss, as reported in the section Operations, Safety, and Permitting.

Figure 14—(a) A BurnBoss® operating on a golf course was able to make multiple batches of biochar in one day. (b) Smoke emissions from a conventional burn pile seen in the background contrast with the smokeless operation of the BurnBoss. Courtesy photos by Ryan Ramage, Valley Environmental, used with permission.

Figure 15—(a) A CharBoss® reduces slash piles left from a postfire salvage operation on the Umpqua National Forest. (b) The USDA Forest Service is conducting emissions testing on the CharBoss and other biochar production technologies near Toole, Utah. Courtesy photos by Kelpie Wilson, Wilson Biochar, used with permission.

Tigercat 6050

The Tigercat 6050 is a large ACB also designed for continuous biochar production (fig. 16a). It uses three water-cooled augers to remove and quench the hot coals, preserving them as biochar. As the biochar exits the back of the machine, the material can be loaded directly onto a conveyor belt, which deposits it into a metal collection container (fig. 16b). Alternatively, it can be dropped into a collection pond for further cooling before being scooped out and loaded into a container for transport. Weighing in at

92,000 pounds (41,730 kg), the Tigercat 6050 requires a heavy hauling rig for transport to the site. Once on location, it can move around on its tracked undercarriage. Given the large size of this unit, it can handle much larger material than the other options.

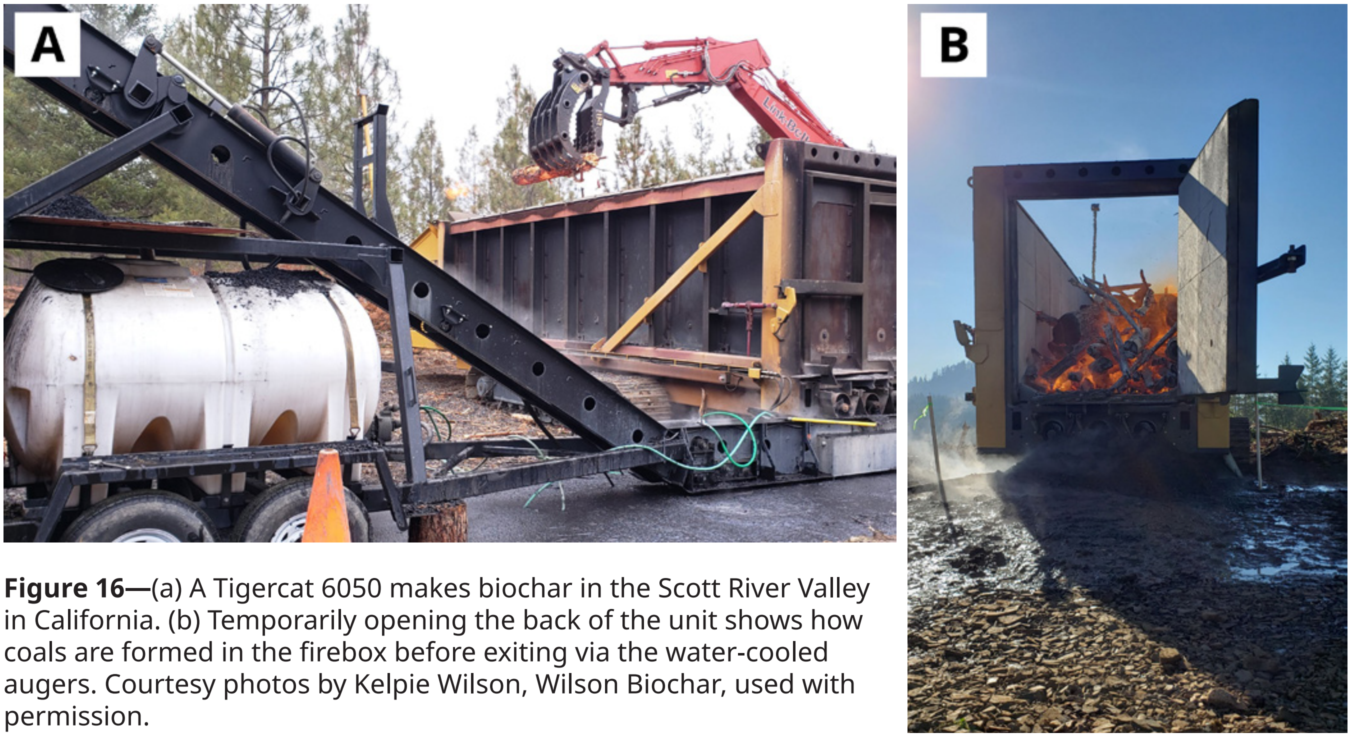


Figure 16—(a) A Tigercat 6050 makes biochar in the Scott River Valley in California. (b) Temporarily opening the back of the unit shows how coals are formed in the firebox before exiting via the water-cooled augers. Courtesy photos by Kelpie Wilson, Wilson Biochar, used with permission.

Air Curtain Burner Data

As with the FKs, actual production efficiencies of ACBs depend on the feedstock characteristics and the operational conditions. The amount of biochar that an ACB can produce is dependent on feedstock characteristics and operator skill. It takes some practice to operate the loading machinery and to understand the best approach for placing the material in the firebox. Operator loading rate is critical because loading too slowly will allow the ACB to incinerate more material to ash. Ambient environmental conditions like temperature and humidity can also affect production rates.

We spoke with operators of these units to gather information on the capabilities and logistical considerations for deploying the different ACB units (see specification sheets at the end of this section). Based on their reports, the dry mass conversion efficiency of LVM to biochar for standard ACB units is estimated at approximately 4 percent. Note that the specialized biochar production ACB the CharBoss achieves a higher conversion efficiency than standard ACBs by incorporating a material agitator and conveyor belt to help remove the biochar from the firebox and limit excess combustion. We used the following deployment information shared with us to generate the site plan scenarios presented in the section Matching Biochar Technologies to Site Conditions and Resource Availability.

Ryan Ramage of Valley Environmental (Canby, Oregon) operates the BurnBoss with a firebox volume of 4 cubic yards (3 cubic meters). Ramage noted that when processing orchard and forestry LVM into biochar, the box can be filled three-quarters full to make about 3 cubic yards (2.3 cubic meters) of biochar in one batch. Each batch takes about 3 hours to complete. Biochar production can be optimized if shorter pieces are loaded crosswise alternating with longer pieces. When a batch is complete, the firebox is lifted using the hydraulic controls on the unit, and pulled forward for about 50 feet (15 m), leaving a trail of biochar behind. It takes about 250 gallons (946 liters) of water to quench the pile of hot coals, supplied from a 300-gallon tank on a pickup truck. The tank is refilled for quenching the second batch. In general, two batches of biochar are produced in a day, utilizing one machine operator and one helper on the ground (Ryan Ramage, personal communication, December 7, 2023).

Joanne Tirocke with the Forest Service has been responsible for operating the CharBoss at several demonstration projects conducted by the Forest Service. In her experience, the machine can produce between 50 and 100 gallons (189–378 liters) of biochar an hour. During field trials, the CharBoss was able to achieve a conversion efficiency of biomass to biochar of 11 percent. Quench water amounts range from 19 to 33 gallons per hour (72–125 liters per hour). The unit can operate for about 8 hours per day before it needs to be stopped to remove ash accumulation on the soil under the conveyor belt. Three workers are required to operate the unit: a machine operator, a person to unload the quenched char, and a spotter to help the machine operator load material strategically. As the operators learn more about the best strategies for choosing and loading feedstocks, the capability of the units will improve (Joanne Tirocke, Biological Science Technician, USDA Forest Service, Rocky Mountain Research Station, personal communication, December 19, 2023).

We spoke with East Bay Regional Park District [California] Fuels Reduction Coordinators Givonne Law and Pablo Cepero, who are implementing a fuels reduction project in the park district using a Tigercat 6050. This equipment is capable of producing about 2 cubic yards (1.5 cubic meters) per hour. They estimate that the unit processed 7 tons (dry weight; 6.4 metric tonnes) of eucalyptus (*Eucalyptus* spp.) logs per hour. They also noted that the eucalyptus was green and wet, and that the machine could process a greater amount of material if it were dry. Diesel fuel consumption for the Tigercat 6050 is approximately 5 gallons an hour (19 liters per hour) and the loader used an additional 5 gallons an hour. The crew that is needed to operate the unit consisted of a loader operator, a supervisor, and two additional helpers (Givonne Law and Pablo Cepero, personal communication, December 14, 2023).

Jeff Elder of Greenside Construction, Inc. (Happy Valley, Oregon) contributed his experiences operating his Tigercat 6050. He has about 2,000 hours of experience with this equipment, including a contract with the Forest Service to conduct postfire salvage logging LVM cleanup operations on the Mount Hood National Forest (Oregon). Elder operates the machine for 12 hours a day, including several hours to reach the optimum operating temperature in the morning and about 2 hours to shut down at the end of the day. He is able to produce between 20 and 30 cubic yards (15–23 cubic meters) of biochar per day. Water use averages about 4,500 gallons (17,034 liters) per day. A 50,000-pound (22,680 kg) capacity excavator is used to load the LVM and a smaller excavator is used to transfer finished biochar out of the quenching pond (Jeff Elder, personal communication, December 20, 2023).

SPEC SHEET FOR ONE TECHNOLOGY UNIT

BURNBOSS

The BurnBoss® is a conventional air curtain burner from Air Burners, Inc. that can make biochar if hot coals are unloaded and quenched with water.

airburners.com

FEEDSTOCK INFO

Max Length: 10 feet (3 m)
Max Diameter: 12 inches (30 cm)
Acceptable moisture content: 50%; Optimum moisture content: <25%
Sorting Method: Initial load is smaller, drier material. Then load in layers of the same size class
Loading method: Machine loading
Loading strategy: Load predominantly from the side that has the air manifold. Ensure that an area 50 feet (15 m) deep is cleared and monitored for embers on the opposite side (downwind) of the air blower

PRODUCTION DATA

Continuous or batch: Batch (two batches per shift)
Burn time: 3 hours
Biochar production, per batch: 3 cubic yards (2 m^3)
Feedstock processed, per batch: 6 tons (5.5 MT)
Quenching method: Spray and rake
Water requirements, per batch: 250 gal (946 L)
Ignition method: Drip torch
Technology fuel: 0.35 gal/hr diesel (1.3 L/hr)

SUPPORT EQUIPMENT NEEDED

Loading equipment: Mini-excavator or skid steer loader
Water: Water tender, trailer, pickup truck bulk container, or pumped from water body
Mobilization: BurnBoss is towable by large pickup truck. Trailer needed for loader

BIOCHAR APPLICATIONS

- Quenching and raking will deposit biochar in-place for soil improvement
- Some portion can be scooped up and transported elsewhere
- Mix of particle sizes and dirt will preclude most commercial uses, but biochar can easily be used for erosion control, decompaction, and soil improvement on nearby sites

AT A GLANCE

SIZE

- 20 feet x 8 feet (6 m x 2.4 m)
- Weight: 9,980 lbs (4,526 kg)
- Tongue weight: 1,200 lb (544 kg)

TEAM SIZE REQUIRED

- One hand crew
- One machine operator
- Produce a total of 6 cubic yards (5 m^3) of biochar in two batches in one day, from 12 tons (11 MT) of low-value woody material (LVM)

PROS

- Emissions tested by the Oregon Department of Environmental Quality and permit eligible
- Very low emissions
- Can also function as an incinerator if needed
- Can produce two batches in one day with two workers

CONS

- Batch operation requires moving and re-sealing kiln bottom before starting new batch
- High capital cost
- Limited off road use

SPEC SHEET FOR ONE TECHNOLOGY UNIT

CHARBOSS

The CharBoss is a self-contained, completely assembled above-ground Air Curtain Burner with a refractory lined burn-container and internal system to create biochar from the waste materials.

airburners.com

FEEDSTOCK INFO

Max Length: 10 feet (3 m)
Max Diameter: 12 inches (30 cm)
Acceptable moisture content: 50%; Optimum moisture content: <25%
Sorting method: Initial load is smaller, drier material. Then load mixed sizes
Loading method: Machine loading
Loading strategy: Load predominantly to one side, ensure that an area 50 feet (15 m) deep is cleared and monitored for embers on the opposite side (downwind) of the air blower

PRODUCTION DATA

Continuous or batch: Continuous
Run time: 8 hours
Biochar production, per hour: 0.75 cubic yard (0.6 m^3)
Feedstock processed, per hour: 0.6 tons (0.5 MT)
Quenching method: Continuous quench in water bath
Water requirements, per hour: 30 gal (114 L)
Ignition method: Drip torch
Technology fuel: 0.9 gal/hr (3.4 L/hr) diesel

SUPPORT EQUIPMENT NEEDED

Loading equipment: Mini-excavator or skid steer loader
Water: Water trailer pickup bulk container
Mobilization: CharBoss is towable by class A or B CDL driver.

BIOCHAR APPLICATIONS

- Continuous process delivers water quenched biochar with uniform particle size that can be scooped out of the water bath and used on-site or loaded into containers for transport
- A consistent particle size makes a product that can be marketed for off-site use

AT A GLANCE

SIZE

- 22 feet x 8 feet (7 m x 2.4 m)
- Weight: 17,500 lb (17,500 kg)
- Tongue weight: 1,400 lb (635 kg)

TEAM SIZE REQUIRED

- One supervisor, one machine operator, one hand crew
- Producing 6 cubic yards (5 m^3) of biochar from 5 tons (4 MT) of low-value woody material (LVM) in 8 hours burn time

PROS

- Can process any size of material if LVM removal is top priority
- Agitation of burning material helps natural charcoal exfoliation as materials burn
- Continuous process delivers water quenched biochar with uniform particle size that can be scooped out of the water bath and loaded directly into containers for transport
- Low air emissions can enable use in air quality limited areas

CONS

- High capital cost
- High mobilization cost
- Limited to use on roadside and landings

SPEC SHEET FOR ONE TECHNOLOGY UNIT

TIGERCAT 6050

The Tigercat 6050 is a large air curtain burner (ACB) designed for continuous biochar production using three water-cooled augers to remove and quench the hot coals, preserving them as biochar.

www.tigercat.com

FEEDSTOCK INFO

Max length: 20 feet (6 m)
Max Diameter: 18 inches (46 cm)
Acceptable moisture content: Up to 50%; Optimum moisture content: <25%
Sorting method: Initial load is drier material to aid ignition.
Loading method: Large excavator or log loader
Loading strategy: Load predominantly to one side, ensure that an area 50 feet (15 m) deep is cleared and monitored for embers on the opposite side (downwind) of the air blower

PRODUCTION DATA

Continuous or batch: Continuous
Run time: Up to 24 hours/day
Biochar production, per hour: 2 cubic yards (1.5 m^3)
Feedstock processed, per hour: 7 tons (6 MT)
Quenching method: Char is continuously quenched through auger conveyance system
Water requirements, per hour: 375gal (1,400 L)
Ignition method: Fuzee or drip torch
Technology fuel use: 5 gal/hr (19 L/hr) diesel

SUPPORT EQUIPMENT NEEDED

Loading equipment: Excavator or log loader for feedstock and small loader and dump truck for char removal
Water: Water tender, trailer or pumped from water body
Mobilization: Trailers for air curtain burner, feedstock loader and biochar loader

BIOCHAR APPLICATIONS

- Continuous process delivers water quenched biochar with uniform particle size that can be scooped out of the quenching pond and loaded directly into containers for transport
- Consistent particle size makes a product that can be marketed for off-site uses

AT A GLANCE

SIZE

- 40 feet x 12 feet (12 m x 3.6 m)
- Weight: 92,000 pounds (41,723 kg)

TEAM SIZE REQUIRED

- 2 machine operator
- 2 hand crew
- Producing 16 cubic yards (12 m^3) of biochar from 56 tons (51 MT) of low-value woody material (LVM) in 8 hours burn time

PROS

- Can process any size of material if LVM removal is top priority
- Best for large jobs that need to be finished quickly
- Agitation of burning material helps natural charcoal exfoliation as materials burn
- Continuous process delivers water quenched biochar with uniform particle size that can be scooped out of the water bath and loaded directly into containers for transport.
- Track mounted unit can move along roadside to access feedstock piles
- Low air emissions can enable use in air quality limited areas

CONS

- High capital cost compared to other technologies
- High mobilization cost
- High demand for quenching water
- Limited to large landings or other hardscapes

Comparison of Technology Capabilities

The eight technologies include piles, kilns, and ACBs that vary widely in production rates, feedstock capabilities, and site and support needs (table 6). Technology deployment logistics are discussed further in the next section. Table 6 compares the LVM reduction and biochar production capacity of each technology over one 8-hour shift, as deployed in a typical scenario for each type of technology.

When deciding which biochar production technology to use, consider the underlying goals for making biochar as opposed to a focus on incinerating LVM for disposal. Will the biochar be used where it is produced? Is there a need to use it within a watershed to improve soil water holding capacity for seed germination and vegetation establishment? Or is the intended use off-site to a biochar market? The most appropriate technologies for onsite use are CBPs and FKs, while ACBs produce a more consistent biochar better suited for markets (table 7).

Table 6—Biochar productivity comparison (based on one 8-hour shift).

Technology type	Typical scenario	Hand crew per shift	Machine operator for loader per shift	Biomass processed per shift by dry mass, tons (metric tonnes)	Biochar production per shift by volume, cubic yards (cubic meters)	Total water required per shift, gallons (liters)
Conservation burn pile (CBP)	Hand piles (150 piles)	5	N/A	22 (20)	11 (8)	1,000 (3,800)
	Machine piles (30 piles)	4	1	99 (90)	27 (21)	9,000 (34,000)
Flame-cap kiln (FK)	Ring of Fire Kiln® (4 kilns)	5	N/A	8 (7)	12 (9)	600 (2,300)
	Oregon Kiln (6 kilns, 2 batches)	5	N/A	8 (7)	12 (9)	600 (2,300)
	Big Box Kiln (2 kilns)	2	1	11 (10)	16 (12)	600 (2,300)
Air curtain burner (ACB)	BurnBoss® (1 unit, 2 batches)	1	1	12 (11)	6 (5)	500 (1,900)
	CharBoss® (1 unit, continuous)	2	1	5 (4)	6 (5)	300 (1,100)
	Tigercat 6050 (1 unit, continuous)	2	2	56 (51)	16 (12)	3,000 (11,300)

Table 7—Potential best applications for biochar produced with each technology.

Technology type	Name	Rake into soil on-site	Scoop up and apply nearby	Package and transport to markets
Conservation burn pile (CBP)	Hand pile	x		
	Machine pile	x	x	
Flame-cap kiln (FK)	Ring of Fire Kiln®	x	x	x
	Oregon Kiln	x	x	x
	Big Box Kiln	x	x	x
Air curtain burner (ACB)	BurnBoss®	x	x	x
	CharBoss®		x	x
	Tigercat 6050		x	x

MATCHING BIOCHAR TECHNOLOGIES TO SITE CONDITIONS AND RESOURCE AVAILABILITY

Each of the flame carbonizing methods and technologies has different capabilities and requirements in terms of feedstocks, water, and fuel requirements, supporting equipment, hand labor needs, skilled machine operator needs, siting and logistical considerations, and seasonality of operations. Having many options available allows land managers to choose an approach that works best for a particular situation. This section reviews the logistical considerations and how they apply to making biochar on-site.

Feedstock

The characteristics of the LVM feedstocks are the first consideration when choosing an approach to onsite biochar production. Feedstock size and moisture content are critical for the nonpowered methods and technologies, but even ACBs will work more efficiently and produce more biochar from fuels that are smaller and drier. Fuels with average moisture content below 25 percent work best. However, if most of the material is fairly dry, some of it can be wet or green and still burn well.

Consider the need to leave an appropriate amount of large woody debris for ecological functions (Jurgensen et al. 1997). The amount of wood left to decay after harvesting depends on the type of ecosystem and climatic regime. There are a variety of methods to describe the amount of fuel loadings on a site (Keane 2012), but the goal of in-place biochar production is to remove the most flammable material and leave the remainder. If the objective for a site is to reduce wildfire risk, then large material may not need to be treated and could be left in contact with the ground to decay naturally (fig. 17). Smaller materials pose the risk of wildfire ignition and spread. Therefore, use one of the biochar technologies to reduce the smaller material and then large material can be safely left on-site. Using only the smaller material also makes biochar production faster and more efficient.

Figure 17—(a) Large logs greater than 4 inches (10 cm) in diameter are best left on-site and in contact with the soil to slowly decompose and provide ecosystem benefits (b) such as habitat for fungi. Courtesy photos by Kelpie Wilson, Wilson Biochar, used with permission.

All of the mobile biochar technologies can process most types of woody feedstocks, including slash, tree prunings, vineyard prunings, reeds, canes, stalks, invasive woody shrubs, logs, partially burned trees, limbs, salvage logged material, or diseased wood, if they are the right size for the technology (table 8). If the objective is to reduce the volume of LVM, the larger kilns and ACBs are capable of processing feedstocks that are larger and wetter than the limits for optimum biochar production.

Although it is most efficient to process LVM that has been air-dried and seasoned, there are cases where it is possible or desirable to process freshly cut wood. Some species, when freshly cut, have a high content of volatile compounds such as terpenes that readily burn and provide additional energy during combustion, generating part of the heat needed to vaporize water. Drying and seasoning releases volatile organic compounds along with water, so seasoned wood generally has less volatile matter that can burn and provide energy. However, seasoned wood also has less water that must be vaporized and will burn more cleanly with fewer emissions. The least viable type of feedstock for producing biochar is dried, seasoned wood that is subsequently rained upon to the degree that it has a moisture content approaching 50 percent.

Current practices for reducing flammable fuels in the wildland-urban interface and elsewhere often include single-entry jobs, where a hand crew will cut brush and burn it immediately in swamper burn piles. Finishing the job in one entry, without waiting for pile material to season, is often the best use of scarce resources. The Oregon Department of Forestry, working with Wilson Biochar and the Illinois Valley Fire Resiliency Oversight Group, completed a fuels reduction project in 2022 that used this approach to clear a ceanothus (*Ceanothus* spp.) brush field encroaching on an oak woodland. The crew recovered significant amounts of biochar from the swamper burn piles of green ceanothus by quenching them with water. The biochar was left on-site to improve soils around the oaks (*Quercus* spp.).

Successful charring of green feedstocks depends on the technology used and the size-class of the fuels. Green feedstocks can be added once an FK or ACB is hot, but for optimum biochar production operators should use only smaller diameter material.

While most types and sizes of woody debris can be processed in at least one of the technologies examined here, the exception is very small particles such as sawdust, woodchips, or nutshells. Small particles clump together and cut off the air needed for combustion. A burning pile of woodchips cannot sustain a flame and will only smolder and smoke. Small-particle feedstocks are appropriate feedstocks for gasifiers, furnaces, and other equipment that is designed to create heat and biochar (Wilson and Miles 2019) or for use in biomass electric power generation.

Table 8—Recommended feedstock size limits for optimizing biochar production. Larger material can be processed, but will have lower biochar yields.

Biochar production method	Seasoned feedstock diameter or thickness inches (cm)			Acceptable average moisture content percent		Green feedstock diameter or thickness inches (cm)			Feedstock length feet (m)		
	4 (10)	12 (30)	18 (46)	25	50	3 (8)	6 (15)	12 (25)	6 (1.8)	10 (3)	20 (6)
Hand pile	X	—	—	X	—	X	—	—	X	—	—
Machine pile	—	X	—	X	—	—	X	—	—	—	X
Oregon Kiln	X	—	—	X	—	X	—	—	X	—	—
Ring of Fire Kiln®	X	—	—	X	—	X	—	—	X	—	—
Big Box Kiln	—	X	—	X	—	—	X	—	—	X	—
BurnBoss®	—	X	—	—	X	—	X	—	—	X	—
CharBoss®	—	X	—	—	X	—	X	—	—	X	—
Tigercat 6050	—	—	X	—	X	—	—	X	—	—	X

— Indicates no data.

Water Use

Water is essential to all the technologies for quenching and preserving hot coals as biochar. The timing of the application of water differs across the technologies. Small burns, such as CBPs, the Oregon Kiln, or the Ring of Fire Kiln, will need water at the end of the process. Water can be applied using a hose laid from a roadside water truck, water trailers transported by an all-terrain vehicle (ATV), or backpack bladder pumps. Staggered ignition of the small burns helps ensure that the need for quenching water will also be staggered. Job planning should allow enough time for all the piles or batches to be quenched.

The Big Box Kiln and the BurnBoss are large-batch processes that also require water at the end of the process, but the water is needed in only one or two batches. Deployment of quenching water is thus less complicated than for the widely distributed smaller kilns and CBPs.

The Tigercat 6050 requires a constant water feed for quenching the char through the auger removal system. This water can be provided by a water tender hookup. Some operators have devised a system to capture the water in a pool and pump it back through a filter for reuse. The CharBoss has a water-bath quenching system that reuses water in a pan with periodic refilling. A small truck-mounted water tank is adequate for keeping the pan supplied.

Water for all these processes can be staged ahead of time, if needed. Collapsible water tanks can be prefilled on the job site. Quenching water can also be pumped from a nearby stream, pond, or reservoir.

Labor Needs

Each technology requires a different combination of hand labor, machine operators, and support equipment. Labor needs will change depending on the size of the job and the number of kilns deployed. Hand crews can be composed of off-season firefighters, conservation corps crews, trainees, students, and even volunteers. Chainsaw certification is not required, although at least one person on the crew should be able to use a chainsaw in case there is a need to further cut up fuels. Hand crews should have a basic understanding of fire and will need a few hours of on-the-job training to operate FKs or ACBs successfully. Likewise, hand crews will need to understand the objective of making biochar when firing and then quenching CBPs.

Supervisors should have a solid understanding of the technology used, the basics of the pyrolysis process, and how to organize the work to maximize biochar production and efficiency of LMV reduction. Supervisors should also understand how the biochar will be applied so they can make sure that it is properly prepared for loading and removal from the site, or staged for later use on-site.

Where machinery is used for loading ACBs and the larger FKs, operators need to understand the pyrolysis principles and the importance of the loading rate as well as strategies for placement of fuels for most efficient conversion to biochar. They also need to take steps to harden and protect hydraulic controls from flames and heat.

Workforce Development

Work with FKs and small CBPs is ideal for workforce development programs that are engaged in training for productive work. Working outdoors around a fire is satisfying to many people and may be a healing experience for those who have been traumatized by life circumstances (fig. 18). In our experience, making biochar is a great team-building activity and can help workers gain confidence for other jobs in the future. Making biochar is an appropriate activity for the youth conservation corps that exist in many states (Wilson 2021). Wilson Biochar has participated in several youth corps projects, including the annual Forestry On-Ramp Camp sponsored by Project Youth Plus and the Table Rock Foundation (Grants Pass, Oregon).

Figure 18—(a) U.S. Rake Force, a veteran-owned forestry contractor (Toledo, Washington), gets ready for its first biochar burn. (b) The Project Youth Plus Forestry On-Ramp Camp introduces youth to potential careers in forestry and ecological restoration, including biochar production. Photo illustration. Courtesy photos by Kelpie Wilson, Wilson Biochar, used with permission.

Support Equipment and Site Needs

Each type of process will need support equipment and each operational site will need to be evaluated for suitability. Planning a biochar job requires attention to the staging needs of all necessary equipment, including equipment transport trailers, water supplies, and crew transport. Heavy equipment can cause site compaction and should be limited to already impacted areas such as roadsides and landings.

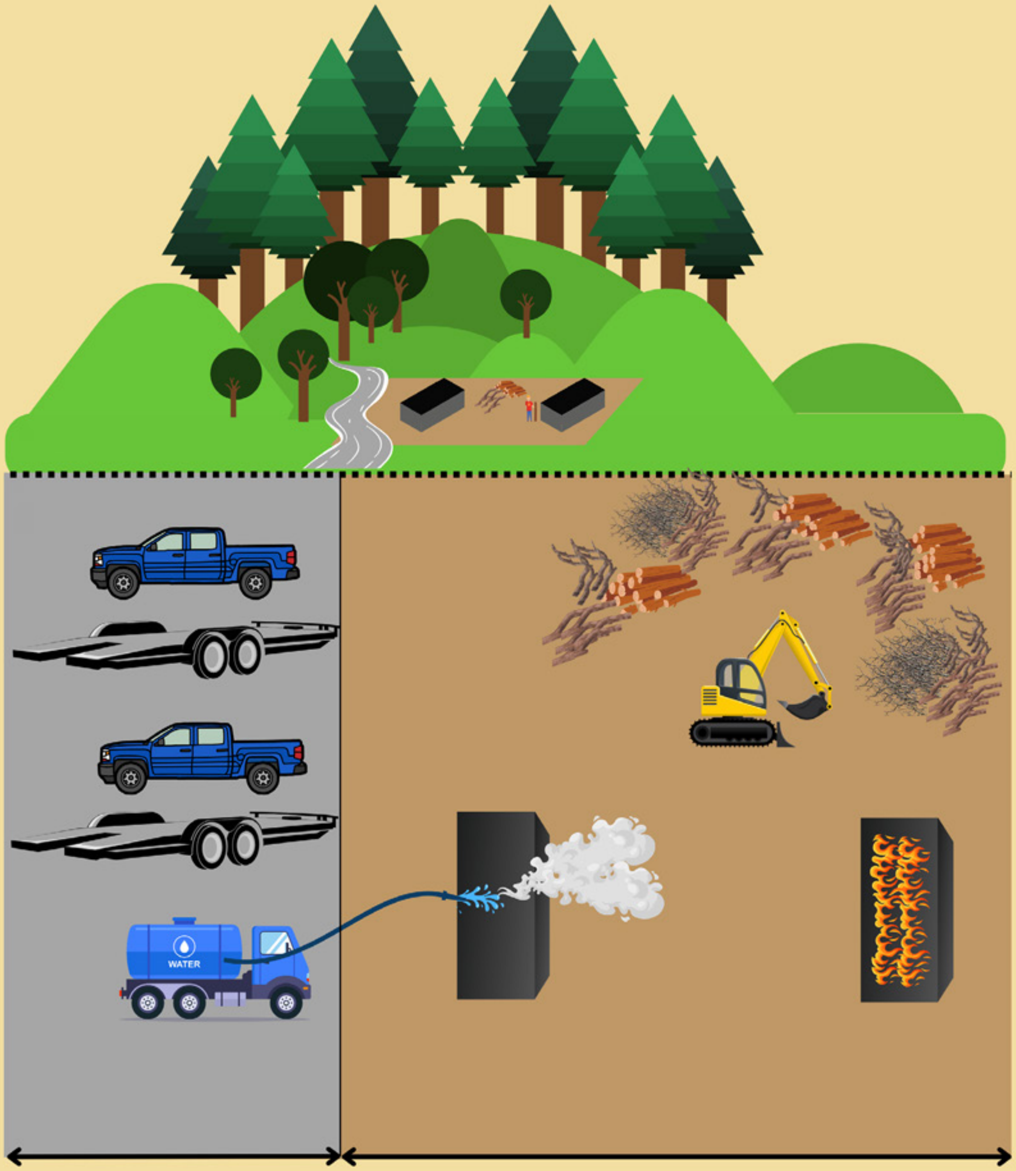
It is crucial to locate kilns close to the feedstock to minimize the LVM transport distances for hand crews or machinery. Both the Oregon Kiln and the Ring of Fire Kiln are generally loaded by hand, but mechanical assistance can reduce the amount of human labor it takes to move fuels scattered across the landscape to the kilns. For example, LVM can be moved to the kiln location by an ATV or a skid steer, leaving more time for the hand crews to carefully load and monitor the kilns. If whole tree yarding is used, it may be most efficient to employ a chainsaw crew to cut the material as it is loaded into kilns, rather than doing chainsaw work ahead of time and piling the material. Some operators have added more panels to the expandable Ring of Fire Kiln to make it larger to accommodate longer material. A mini-excavator or skid steer can be used to load the larger Ring of Fire Kiln, as in the Big Box Kiln. Machinery can also be used to load finished biochar into containers or a dump truck for transport.

Project planners must be able to visualize all the elements that need to come together to design an onsite biochar production project. In the next section, we present site plans for a typical job for each technology type, as an aid to project planning.

Site Plans for Each Technology

To assist land managers in planning a biochar project, the following site plans for each technology illustrate typical deployment scenarios and the volume of LVM that can be processed. These illustrative examples can also help project managers understand what kind and how much of various support resources are required to implement a biochar project using the different technologies.

TYPICAL SITE PLAN FOR BIG BOX KILN

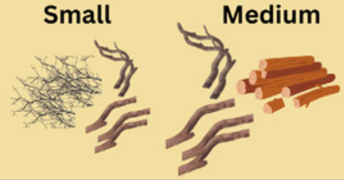


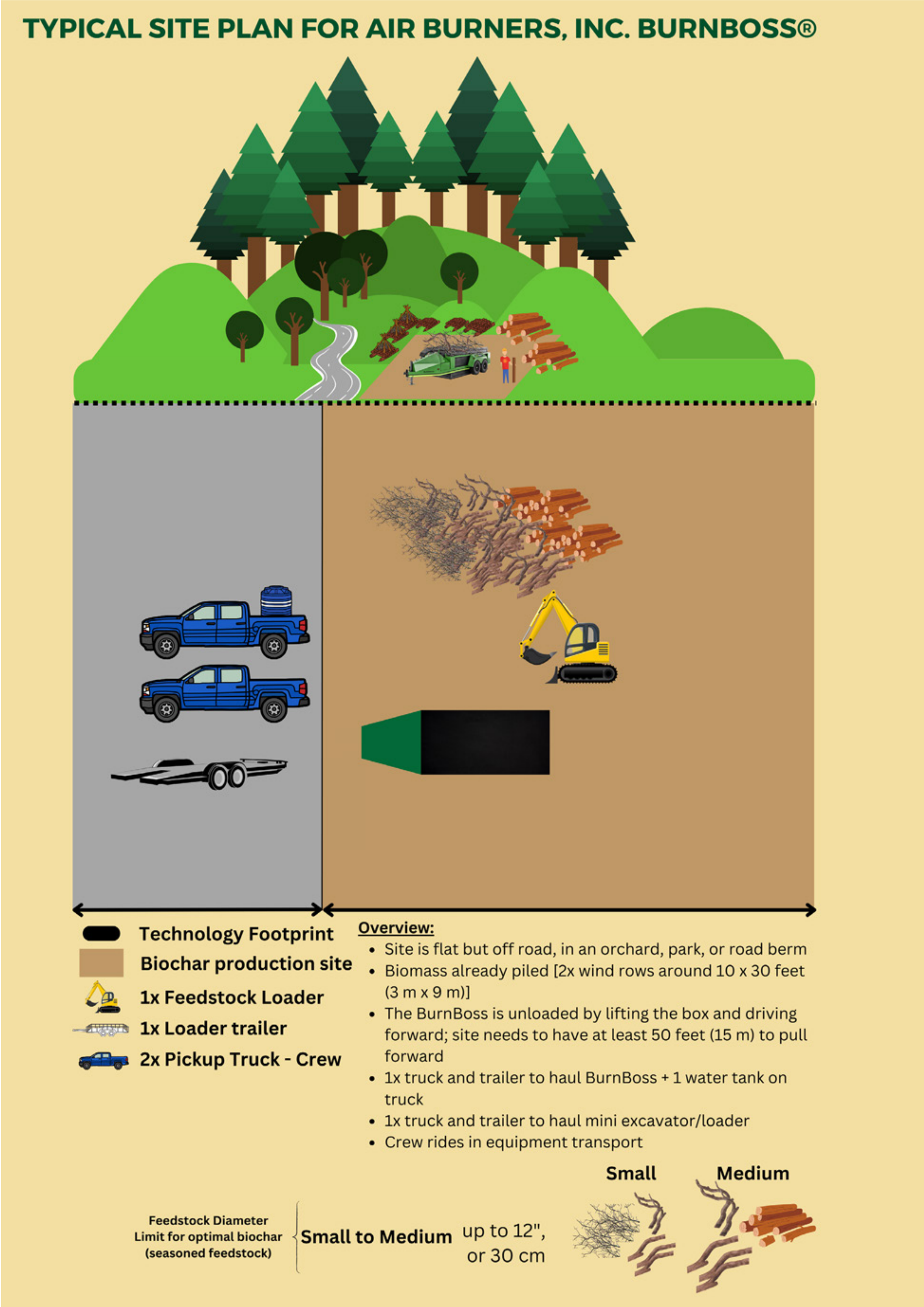
- Technology Footprint
- Biochar production site
- 1x Water tender
- 1x Feedstock Loader
- 2x Kiln trailer
- 2x Pickup Truck - Crew & kiln trailer

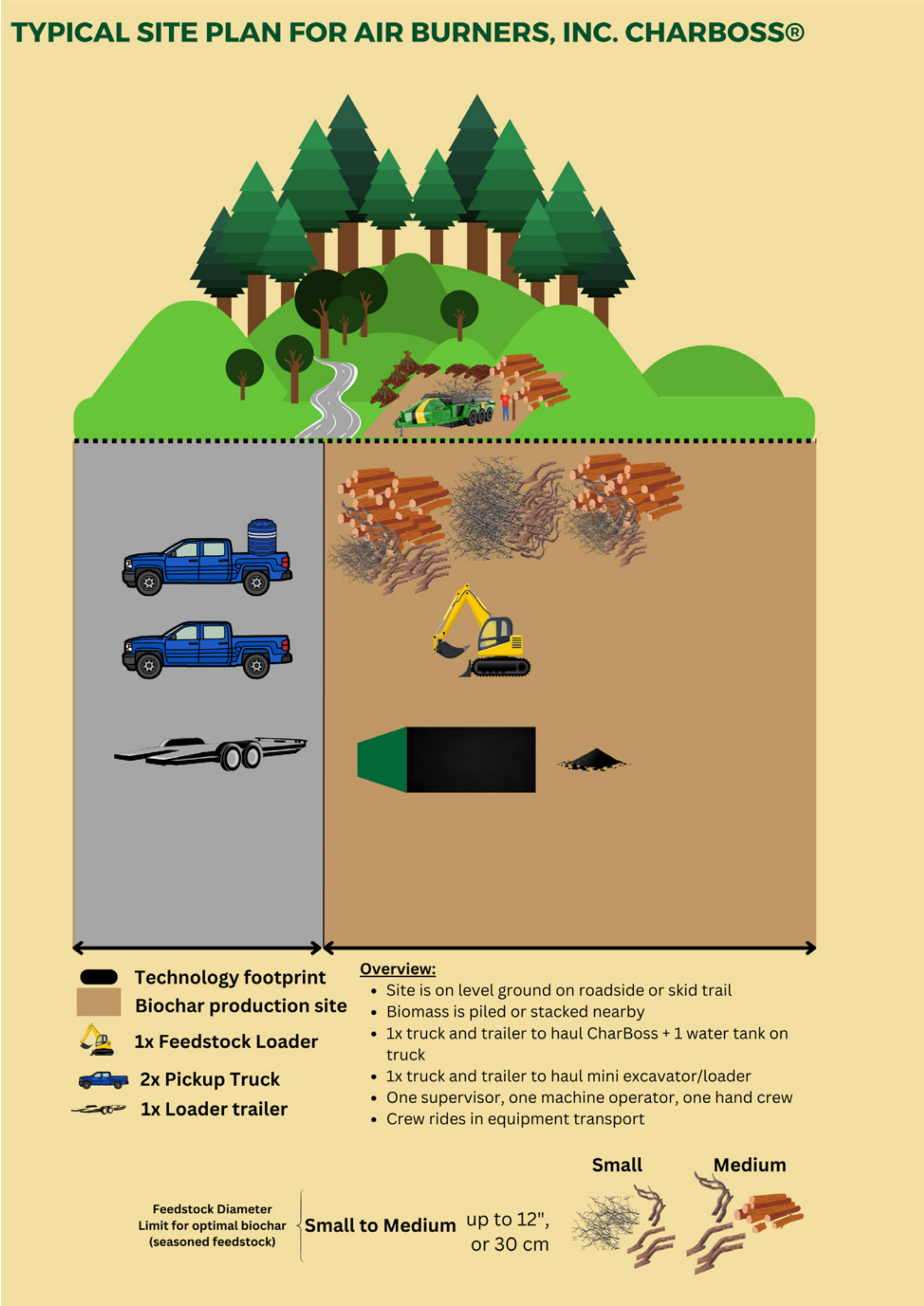
Overview:

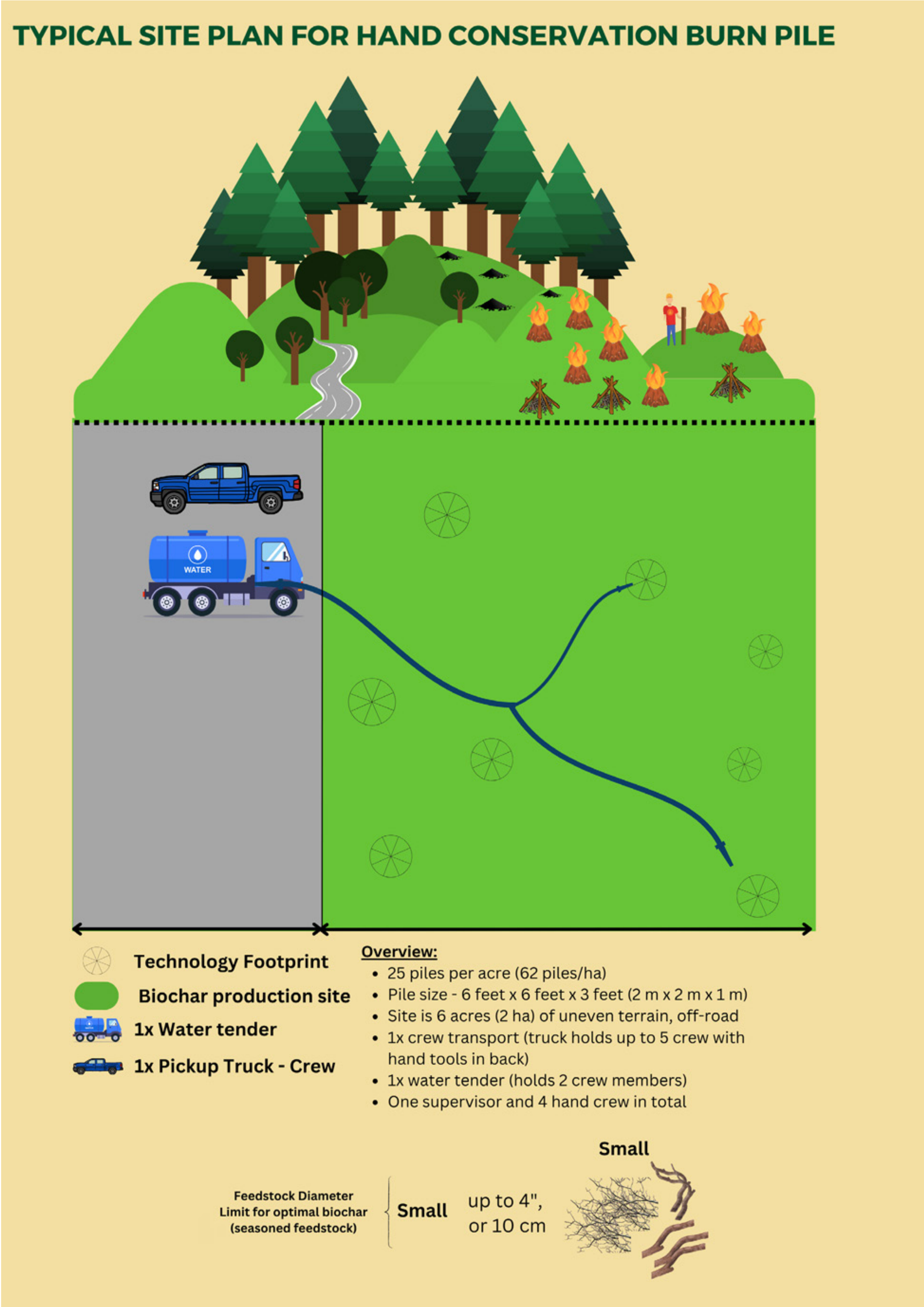
- 2 kilns deployed on about 3 acres (1.2 ha) about 100 feet (31 m) apart with cut material, unpiled, all around
- Site is uneven but not too steep - gentle topography. Kilns are within 300 feet (91 m) of the road
- Crew rides in equipment transport
- One machine operator per project and one hand crew per kiln
- 1x truck and trailer for kilns, 1x truck and trailer for loader
- 1x water tender

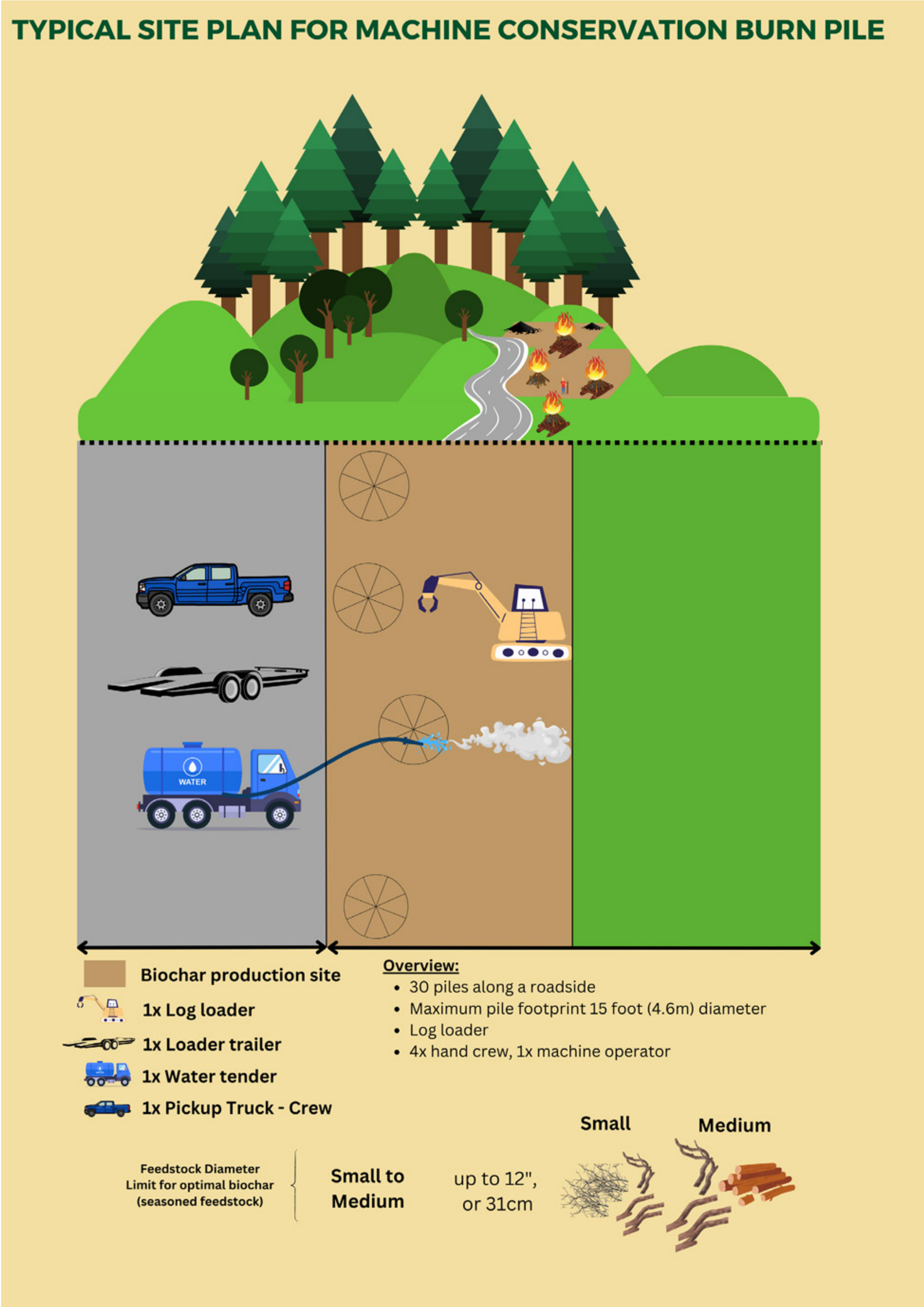
Feedstock Diameter Limit for optimal biochar (seasoned feedstock)	Small to Medium	up to 12", or 30 cm

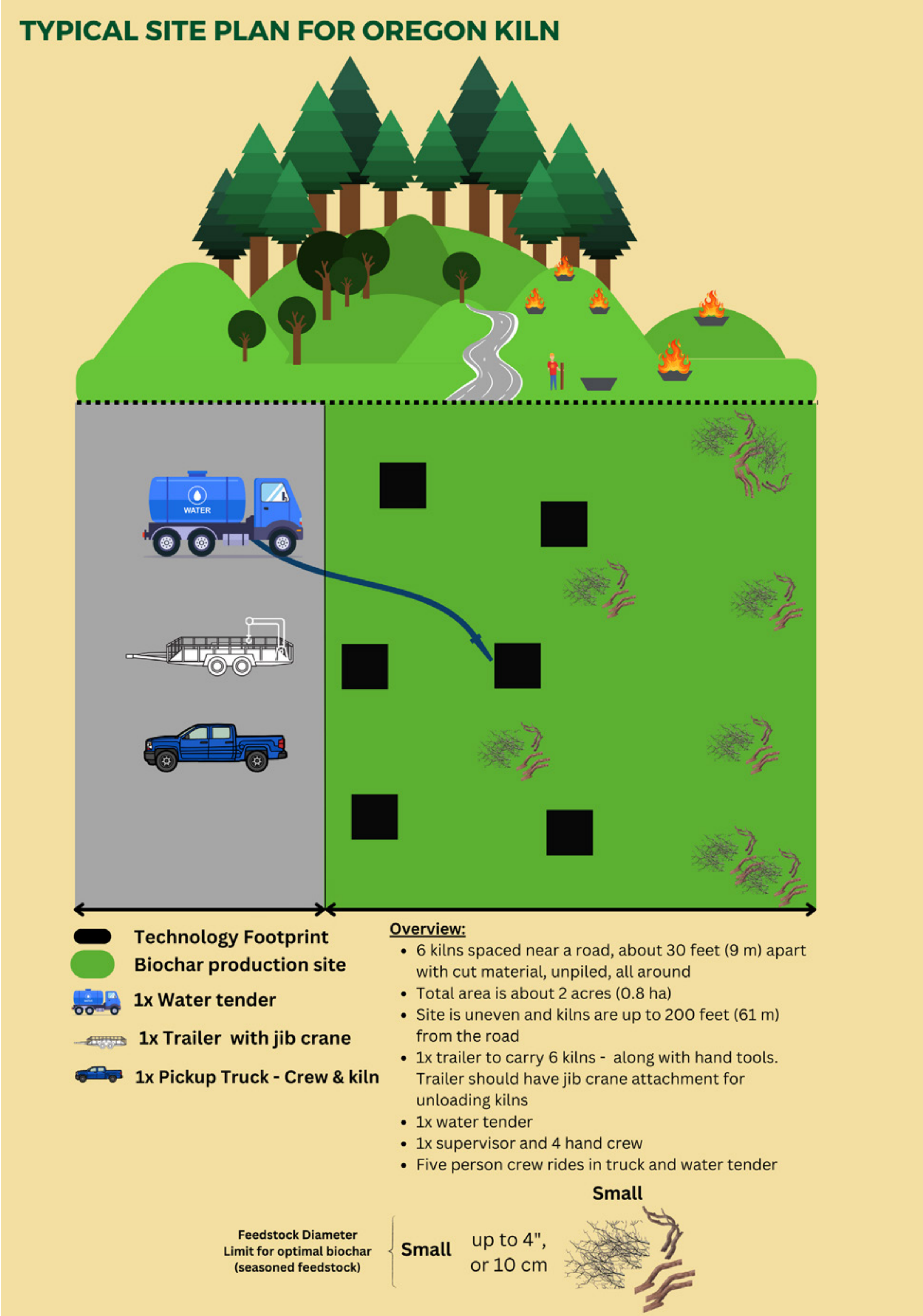


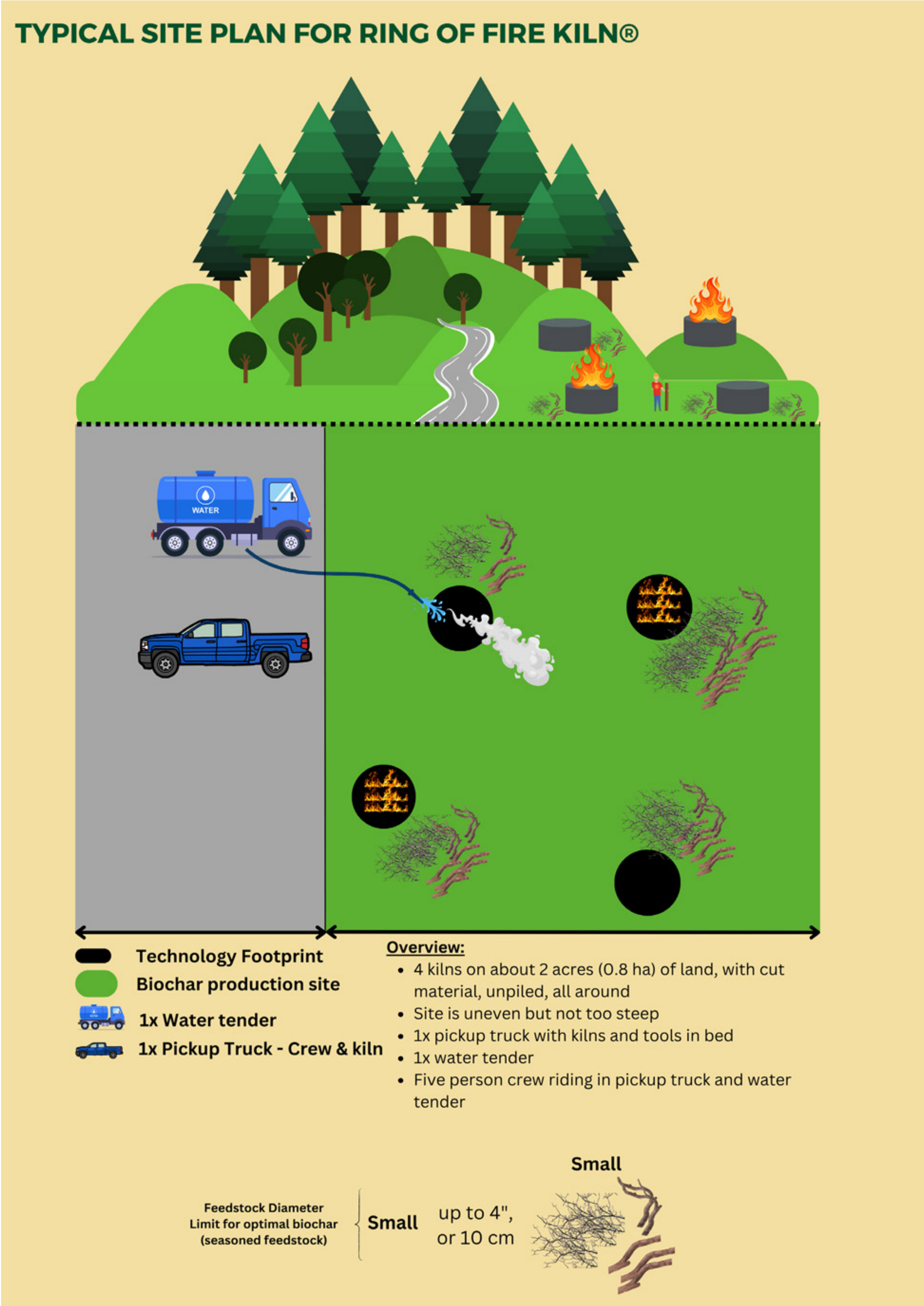

TYPICAL SITE PLAN FOR AIR BURNERS, INC. BURNBOSS®
Technology Footprint
Biochar production site
1x Feedstock Loader
1x Loader trailer
2x Pickup Truck - Crew
Overview:
• Site is flat but off road, in an orchard, park, or road berm
• Biomass already piled [2x wind rows around 10 x 30 feet (3 m x 9 m)]
• The BurnBoss is unloaded by lifting the box and driving forward; site needs to have at least 50 feet (15 m) to pull forward
• 1x truck and trailer to haul BurnBoss + 1 water tank on truck
• 1x truck and trailer to haul mini excavator/loader
• Crew rides in equipment transport
Small
Medium
Feedstock Diameter Limit for optimal biochar (seasoned feedstock)
Small to Medium
up to 12", or 30 cm

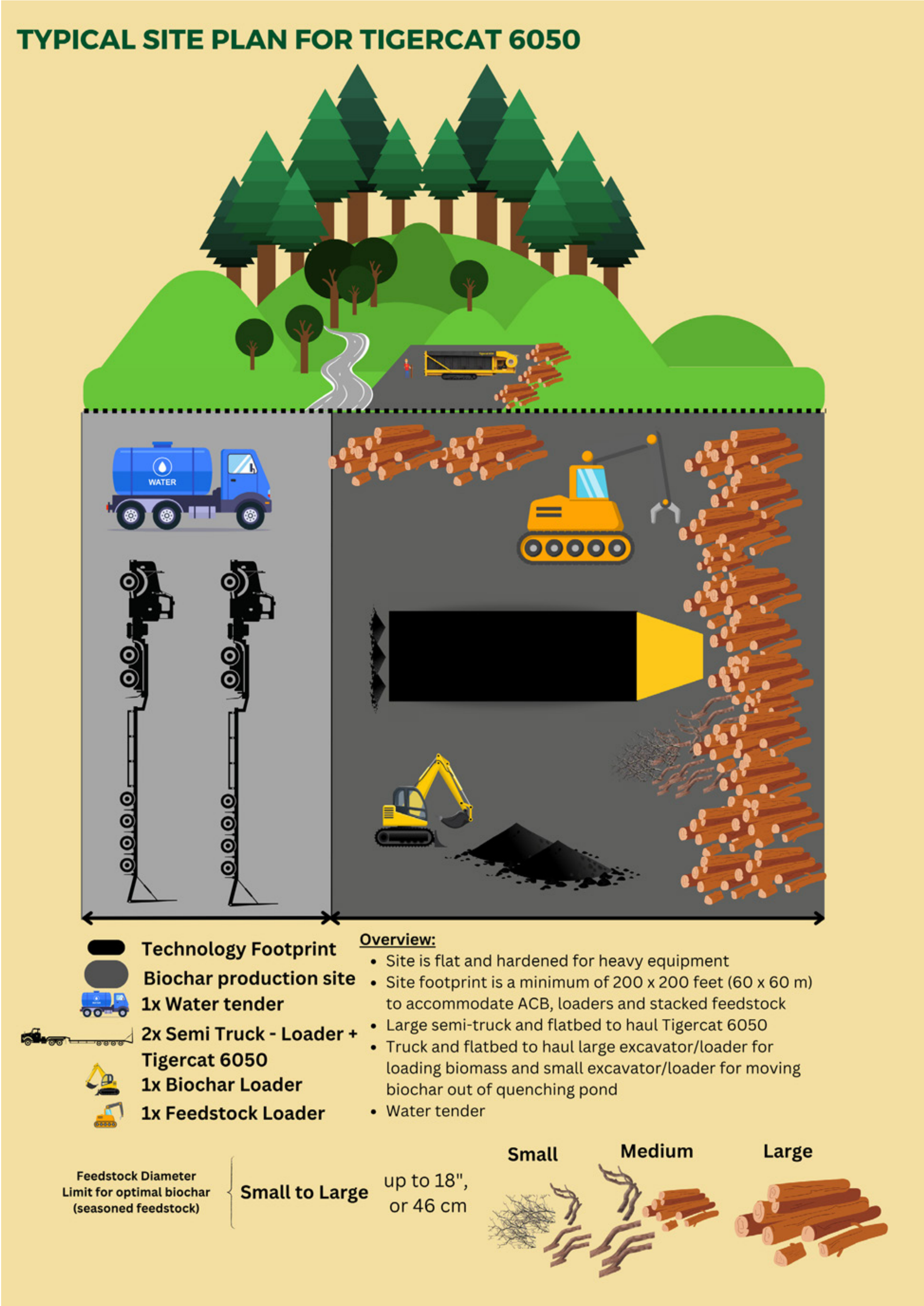

TYPICAL SITE PLAN FOR AIR BURNERS, INC. CHARBOSS®
Technology footprint
Biochar production site
1x Feedstock Loader
2x Pickup Truck
1x Loader trailer
Overview:
• Site is on level ground on roadside or skid trail
• Biomass is piled or stacked nearby
• 1x truck and trailer to haul CharBoss + 1 water tank on truck
• 1x truck and trailer to haul mini excavator/loader
• One supervisor, one machine operator, one hand crew
• Crew rides in equipment transport
Feedstock Diameter Limit for optimal biochar (seasoned feedstock)
Small to Medium
up to 12", or 30 cm
Small
Medium


TYPICAL SITE PLAN FOR HAND CONSERVATION BURN PILE
WATER
Technology Footprint
Biochar production site
1x Water tender
1x Pickup Truck - Crew
Overview:
• 25 piles per acre (62 piles/ha)
• Pile size - 6 feet x 6 feet x 3 feet (2 m x 2 m x 1 m)
• Site is 6 acres (2 ha) of uneven terrain, off-road
• 1x crew transport (truck holds up to 5 crew with hand tools in back)
• 1x water tender (holds 2 crew members)
• One supervisor and 4 hand crew in total
Feedstock Diameter Limit for optimal biochar (seasoned feedstock)
Small
up to 4", or 10 cm
Small


TYPICAL SITE PLAN FOR MACHINE CONSERVATION BURN PILE
WATER
Biochar production site
1x Log loader
1x Loader trailer
1x Water tender
1x Pickup Truck - Crew
Overview:
• 30 piles along a roadside
• Maximum pile footprint 15 foot (4.6m) diameter
• Log loader
• 4x hand crew, 1x machine operator
Small
Medium
Feedstock Diameter Limit for optimal biochar (seasoned feedstock)
Small to Medium
up to 12", or 31cm


TYPICAL SITE PLAN FOR OREGON KILN
WATER
Technology Footprint
Biochar production site
1x Water tender
1x Trailer with jib crane
1x Pickup Truck - Crew & kiln
Overview:
• 6 kilns spaced near a road, about 30 feet (9 m) apart with cut material, unpiled, all around
• Total area is about 2 acres (0.8 ha)
• Site is uneven and kilns are up to 200 feet (61 m) from the road
• 1x trailer to carry 6 kilns - along with hand tools. Trailer should have jib crane attachment for unloading kilns
• 1x water tender
• 1x supervisor and 4 hand crew
• Five person crew rides in truck and water tender
Small
Feedstock Diameter Limit for optimal biochar (seasoned feedstock)
Small
up to 4", or 10 cm


TYPICAL SITE PLAN FOR RING OF FIRE KILN®
WATER
Technology Footprint
Biochar production site
1x Water tender
1x Pickup Truck - Crew & kiln
Overview:
• 4 kilns on about 2 acres (0.8 ha) of land, with cut material, unpiled, all around
• Site is uneven but not too steep
• 1x pickup truck with kilns and tools in bed
• 1x water tender
• Five person crew riding in pickup truck and water tender
Feedstock Diameter Limit for optimal biochar (seasoned feedstock)
Small
up to 4", or 10 cm
Small


TYPICAL SITE PLAN FOR TIGERCAT 6050
WATER
Technology Footprint
Biochar production site
1x Water tender
2x Semi Truck - Loader + Tigercat 6050
1x Biochar Loader
1x Feedstock Loader
Overview:
• Site is flat and hardened for heavy equipment
• Site footprint is a minimum of 200 x 200 feet (60 x 60 m) to accommodate ACB, loaders and stacked feedstock
• Large semi-truck and flatbed to haul Tigercat 6050
• Truck and flatbed to haul large excavator/loader for loading biomass and small excavator/loader for moving biochar out of quenching pond
• Water tender
Feedstock Diameter Limit for optimal biochar (seasoned feedstock)
Small to Large
up to 18", or 46 cm
Small
Medium
Large

OPERATIONS, SAFETY, AND PERMITTING

Working with fire and heavy equipment requires a workforce that is well trained in safety procedures and equipped with appropriate personal protective equipment (PPE). More stringent procedures are required for jobs using heavy equipment than for jobs that use hand labor only. Permitting of biochar production jobs will depend on land ownership jurisdictions and will be concerned with fire risk, air emissions, and impacts to soil and water.

Protection of Workers and Equipment

For managing large piles and kilns, it is important to equip workers with standard fire safety equipment as detailed by the National Wildfire Coordinating Group (2023). The following are required PPE for firing devices:

- hardhat;
- flame-resistant pants;
- flame-resistant shirt, sleeves rolled down;
- leather gloves;
- approved boots; and
- eye protection.

Hand CBPs and small kilns (Oregon Kiln and Ring of Fire Kiln) can be managed safely by workers or volunteers who are equipped with sturdy boots, nonsynthetic clothing (cotton or wool), and leather gloves. Workers who are managing small piles and kilns with hand labor need to be well equipped with fire tools. Each worker should have a rake or a McCleod fire tool and a shovel. Water should be on-site before ignition takes place. It is sensible to fill several 5-gallon buckets around kilns to have water ready if needed.

Loading equipment (e.g., excavator, grappler) is generally not designed to work directly with flaming material. Equipment operators should take steps to protect their equipment from heat. Hydraulic control components are the most vulnerable. Occasionally test the boom of the excavator and associated hydraulic lines for overheating by first using the back of your hand (to prevent getting blisters on your palm) held a few inches away from the object and eventually placing your palm directly on the potentially overheated component of the machine; it should be cool enough to comfortably touch the components. Wrapping hydraulic lines in foil can help protect them. Operators should also minimize the time that tools are held near the flames.

Hazard Reduction

Making biochar in a combustion process depends on complete extinguishment of the coals at the end of the process. Flood quenching in bin kilns (Oregon Kiln, Big Box Kiln) is a more certain process than the method of spraying and raking the coals, but it is also possible that inadequate water in the kiln will leave behind hotspots that continue to burn, evaporating water and even igniting and burning additional material. On occasion, we have left what we thought was a fully quenched bin of biochar to return the next day and find it had reignited and burned to ash (fig. 19).

Figure 19—An Oregon Kiln was flood quenched and left overnight to be emptied the next day. A hotspot that escaped the flood quench dried out the wet biochar and reignited it. Over half the biochar was lost to ash (Courtesy photo by Kelpie Wilson, Wilson Biochar, used with permission).

“Cold trailing” is a good practice to ensure that all biochar is fully quenched. Start with a gloved hand or the back of your hand and run it through the quenched biochar. You should eventually be able to move bare hands through the entire pile of biochar and confirm it is cool to the touch. It is also important to separate out partially charred material from the finished biochar during the quenching process. Partially charred material still contains volatile fuels that are more difficult to extinguish and can potentially set the finished biochar on fire. Monitor these pieces until they are fully out and add them to a subsequent kiln burn or scatter them in the forest once they are completely cold. Partially charred wood contains nutrients that can contribute to forest soil health and plant growth (An et al. 2022).

Workers must also be vigilant in monitoring for spot fires during biochar production. Although the counterflow combustion regime in FKs and ACBs tends to minimize ember escape, it is still possible for embers or burning material to escape or fall out of the equipment and start spot fires. Continuously patrol around the work site, especially where there are heavy fuels (punky logs and stumps) that can smolder after the job site has been left, or where there are fine fuels like needles and dry grasses that can quickly turn a small spot fire into a larger blaze.

Raking to quench presents the possibility of raking embers onto stumps that can start fires in old root systems. This kind of fire can smolder for days or even months. Workers need to be aware of this potential and avoid creating this situation.

Seasonality of operations has a large impact on hazard risk reduction. Burning when snow is on the ground or during rain showers can be very helpful not only in reducing risk, but in quenching the biochar. Biochar raked over wet ground or snow will be quenched more easily with less risk of starting fires. Regardless of season, the crew supervisor needs to ensure that the area has been patrolled and any fire hazards are addressed before leaving a biochar production site at the end of a shift.

Operations Permitting

Biochar production operation permitting can be divided into three categories: impacts to land and water, fire hazards, and air emissions. Each of these areas is regulated by different agencies and permitting rules will vary by jurisdiction, location, site conditions, season, and local weather.

Soil impacts from heavy equipment are generally related to increased compaction or erosion. Understanding the allowed amounts of soil disturbance on Federal, State, or county lands associated with the operation is critical.

Wildland fire hazard permitting is generally determined at the State or county level on private and State lands. Federal lands have their own rules and permitting systems. Making biochar in hand or machine CBPs will almost always be treated by regulators as the same as conventional pile burning, and will be allowed under open burning laws for agriculture, forestry, and debris disposal on private land. Open burning permits are usually tied to the season (safe burn season). Some jurisdictions require additional daily permitting based on weather conditions such as relative humidity, wind, and air inversions.

Biochar production in FKs and the various types of ACBs has generally been permitted from the fire hazard perspective as safe to conduct during the normal open burn season. There are three factors common to all FKs and ACBs that increase the possibility of safe operations even outside of normal fire restrictions. First, the fire is contained, which reduces the possibility of wind spreading embers to ignite a wildfire. Contained fires should allow operations during slightly more windy conditions than otherwise allowed. Second, combustion air comes from above the flames in a counterflow, reducing embers transported out of the container. Fewer embers should allow for operations during lower humidity and higher temperature conditions, extending the allowable burn seasons in spring and fall. Third, water is always on-site and is used to fully extinguish the biochar, increasing operational safety. Biochar burns should never be left unattended, as they must be monitored and extinguished to efficiently create biochar. Even CBPs could be permitted outside the normal burn season if regulators are satisfied that water quenching mitigates fire risk on a particular site.

Air Quality Emissions

Air quality permitting is often a separate permit system from fire risk. Some urban or heavily populated areas may ban open burns, while others issue air quality permits for open burning daily in order to avoid adding more particulates during atmospheric inversions and on days with poor air quality. The ability of FKs and ACBs to burn smoke and reduce emissions would be expected to allow for expedited permitting, especially on days where air quality is marginal. However, some air quality regulators have been reluctant to permit FKs and ACBs due to lack of knowledge about their performance. As a result, cleaner methods of slash pile processing are excluded while open pile burning continues (Pierson et al. 2024).

Conservation burn piles are permitted the same as any open burn piles. In most cases, FKs are also permitted under open pile burning regulations. It is clear that CBPs, FKs, and ACBs managed for biochar production are less polluting than unmanaged piles for physical reasons: biochar production is optimized when using dry feedstocks and flaming combustion. When feedstocks are wet, the process takes longer and is less efficient, so on purely economic grounds, biochar production in CBPs, FKs, and ACBs will conform to best practices that result in minimal emissions. The difference is illustrated by the data in table 9 for wet vs. dry burn piles and flaming vs. smoldering burn piles (Aurell et al. 2017; Springsteen et al. 2011). These data indicate that both CBPs managed for dry, flaming combustion, and FKs, managed in the same way, have lower emissions than unmanaged burns that consist of wet, smoldering fuels.

Table 9—Emission factors (grams per kilogram dry biomass) for wildfires, burn piles, flame-cap kilns, and air curtain burners.

Type	PM10	PM2.5	Nitrous oxide (NOx)	Methane (CH4)	Carbon dioxide (CO2)	Carbon monoxide (CO)	Source
Wildland fire	—	23.2	2.00	7.3	1,600	135.0	Urbanski 2014
Burn pile, flaming	4.0	—	—	1.0	—	28.0	Springsteen et al. 2011
Burn pile, smoldering	7.0	—	—	8.5	—	116.0	Springsteen et al. 2011
Burn pile, dry	—	4.5	—	1.1	1,785	29.0	Aurell et al. 2017
Burn pile, wet	—	18.0	—	5.7	1,689	82.0	Aurell et al. 2017
Slash pile burn	4.4	3.9	2.50	4.5	1,690	65.3	Puettmann et al. 2020
Flame-cap kiln	1.3	—	0.14	2.6	780	2.6	Puettmann et al. 2020
Large air curtain burner	—	0.6	—	0.7	1,808	1.3	Susott et al. 2002
BurnBoss® air curtain burner	2.1	—	1.00	0.3	—	7.1	Montrose Air Quality Services 2023

— Indicates no data.

The FK emission factors are particularly interesting from the standpoint of CO2. Note that CO2 emissions from the FK used in biochar production are fewer than half the emissions of the other technologies that are managed for complete incineration (Puettman et al. 2020). This is an indication of the retention of carbon in the biochar and is consistent with biochar production efficiency measurements showing that biochar tends to retain about half of the carbon found in pyrolyzed wood, sequestering carbon and preventing it from entering the atmosphere.

Air curtain burners also have very low emissions as the excess air and high temperatures achieved in the firebox tend to burn smoke before it is emitted. The Forest Service tested emissions of the Air Burners, Inc. model 217 and reported the values found in table 9 (Susott et al. 2002). Some States are now evaluating a permitting structure for ACBs. Working with the appropriate agency to determine whether a permit is required is necessary before starting a project.

In May 2023, the Oregon Department of Environmental Quality (DEQ) conducted air emissions testing of a BurnBoss ACB belonging to Valley Environmental with the help of Montrose Air Quality Services (Portland, Oregon) (Montrose Air Quality Services 2023). The Oregon DEQ and the Oregon Department of Forestry have a vital interest in the technology for sanitizing debris from emerald ash borer-infested tree removals. Using an ACB allows this material to be treated on-site without having to move it and risk spread of the infestation. This option is especially important in air-quality-limited regions where open burning is not allowed. Testing of emissions collected during operation of the BurnBoss (fig. 20) showed that the operation was clean enough to satisfy permitting requirements (see table 9).

Figure 20—A special emissions collection hood was used by Montrose Air Quality Services for air emissions testing of a BurnBoss® air curtain burner (Courtesy photo by Ryan Ramage, Valley Environmental, used with permission).

VALUE AND APPLICATION OF BIOCHAR TO MEET MANAGEMENT NEEDS

Biochar is a form of charcoal that benefits soils, including forest soils. As a result of historical wildfires or prescribed burns in forested ecosystems, many forest soils include a large component of charcoal. Charcoal is less prominent in contemporary surface organic and mineral soil horizons, reflecting the history of fire suppression that reduced inputs of charcoal. New research indicates that returning charcoal in forest soils can help with nutrient cycling, soil water retention, and forest health (Rodriguez-Franco et al. 2022). Biochar left upon forest soils can mimic the effects of charcoal produced by natural fire and produce similar effects on soil carbon content and soil physical, chemical, and biological properties (Page-Dumroese et al. 2016b).

Restoring or enhancing soil properties on forest, range, mine, or agricultural soils is becoming increasingly important. In particular, threats to soil from drought, intense rain, flooding, heat, and wildfire can reduce the productive capacity of the soil and also reduce the ability to grow food and fiber or regulate carbon, water, or nutrients (Blanco-Canqui 2021). Biochar can help restore soil organic matter because it is a high-carbon (25–95 percent carbon) substrate and its addition to soil can rapidly increase soil carbon levels (Blanco-Canqui et al. 2020; Liu et al. 2016), depending on soil type, biochar feedstock, application rates, and conditions under which biochar is created. In addition, on many degraded sites (e.g., skid trails, log landings) biochar applications can increase soil cover, thereby reducing the potential for wind and water erosion. The key to successful deployment of biochar, however, is to understand the type of biochar, soil, and climatic regime. Usually, degraded soils show more response than soils with a high organic matter content, but most soils will benefit from biochar additions, and subsequent ecosystem benefits can be even greater (Blanco-Canqui 2021).

Impact of Biochar on Forest Ecosystems

Incorporating biochar into forest soils can enhance forest ecosystem services such as soil aggregation, nutrient retention, soil water availability, and carbon sequestration (Rodriquez-Franco et al. 2022). Several examples follow.

Climate and Carbon Sequestration

Making and using biochar within a project area or harvest unit can reduce greenhouse gas emissions as compared to open pile burning. Converting biomass to biochar can prevent as much as half of the biomass carbon from oxidizing into CO2. Biochar carbon is extremely slow to decompose and thus will reside in soil for hundreds to thousands of years, providing both climate mitigation and soil carbon benefits (Lehmann et al. 2006). Further, biochar can significantly improve soil structure, making it a compaction remediation treatment option. In many places, the climate has become warmer, and one impact of a warming climate is to increase the rate of soil organic matter decomposition, reducing the soil organic carbon stores that are essential for productive soils and increasing greenhouse gas emissions. Biochar can stabilize soil carbon and improve microbial metabolic efficiency, thereby helping to reduce a portion of greenhouse gas emissions from soil (Blanco-Canqui et al. 2020).

Aboveground biomass carbon density (carbon per unit area) is projected to increase by 17 to 25 percent between 2020 and 2070, while annual carbon stock change is projected to decrease, indicating carbon saturation in some U.S. forests. In addition, forest ecosystems are projected to become a net source of CO_2 by 2070 under future scenarios that include high roundwood demand and net forest loss (USDA FS 2023a). Using biochar on wildland or agricultural soils can be an important practice to bolster carbon sequestration under these changing conditions.

Soil Water Holding Capacity and Available Water

Biochar can improve infiltration, soil water holding capacity, hydraulic conductivity, and plant available water (Masiello et al. 2015). Retaining more water in soil not only improves vegetation success, but also helps the survival of native soil microbes, microfauna, mollusks, and insects. Soil disturbances and climate change reduce the amount of soil organic matter, thereby reducing ecosystem services (Lal 2020). Soil organic matter is a central component of soil water holding capacity. Depending on soil texture and clay mineralogy, a 1 percent increase in soil organic matter can increase available water by approximately 1.5 to 1.7 percent on a volumetric basis (Libohova et al. 2018). This increase is approximately equal to an additional 2,800 gallons (10,800 liters) of water in the top 6 inches (15 cm) of soil. Generally, coarse-textured soils have the greatest increase in available water, but since biochars and soils differ in their characteristics, the actual amount for a given soil will vary. The amount of biochar added to the soil will also influence how much additional water will be held. Biochar can improve soil health and resilience, especially in the context of drought, by increasing soil water holding capacity and available water.

Soil Disturbance

Despite all precautions, soil disturbances occur during timber harvesting. Biochar can be used to rehabilitate soil bulk density and reduce runoff while increasing water infiltration, thereby reducing flooding risk and erosion (Batey 2009). Application rates of at least 3 tons per acre (10 Mg per ha) are likely to be needed to substantially decrease compaction. Biochar can also be a long-term strategy for increasing soil aggregate stability, which improves soil resilience to additional impacts (Omondi et al. 2016).

Soil Microbes

Biochar has been found to significantly enhance microbial activity in forest soils, particularly in the short term (Gujre et al. 2021; Li et al. 2018). This enrichment is crucial, as microbes play a pivotal role in energy transfer and nutrient cycling within the soil ecosystem (Bauhus and Khanna 1999). A meta-analysis by Blanco-Canqui (2021) outlines multiple mechanisms through which biochar improves soil biological properties, such as the provision of labile carbon and nutrients, nutrient retention (i.e., by reducing runoff, leaching, nitrous oxide emissions), and the provision of microhabitats within its porous structure. Other advantages include refugia for microbes, increased water retention, soil acidity reduction, and the adsorption of toxic elements and compounds (Ameloot et al. 2013; Gul et al. 2015; Lehmann et al. 2011).

Mycorrhizal Fungi

Native mycorrhizal fungi boost restoration outcomes, ecosystem services, carbon sequestration, and climate adaptation (Markovchick et al. 2023). Biochar can have a positive effect on the abundance of mycorrhizal fungi, which are important in forest ecosystems. Further, biochar may help rhizosphere organisms to assist their host in resisting infection by plant pathogens (Kolton et al. 2016). However, their abundance can be affected by land management and biochar additions (Thies et al. 2015). Since biochar changes nutrient availability, it may result in changes in host plant growth and nutrient status and thus cause changes in mycorrhizal colonization rates. Biochar can also change the timing of mycorrhizal colonization (Herrmann et al. 2004).

Postwildfire Rehabilitation and Seedling Regeneration

High-severity wildfires cause significant changes to soil carbon and thermally alter soil organic matter. Wildfires are followed by rain events that lead to increased runoff and erosion. Sites at high risk for erosion after wildfire are mulched with straw, hydromulch, or other organic materials. However, it takes decades or longer for the soil organic matter to be rebuilt. Biochar coapplied with a mulch can replace some of the organic matter (Prats et al. 2021), which can increase plant survival in harsh postfire soils. After the Las Conchas Fire in New Mexico, biochar-treated soils improved planted tree seedling survival by 11 percent (Marsh et al. 2023). In another study, postwildfire use of biochar and woody residue mulches enhanced soil nitrogen, water dynamics, and plant recovery, leading to decreased erosion and offering an avenue to protect water supplies (Rhoades et al. 2017).

Invasive Species

A high carbon content makes biochar a food source for heterotrophic fungi, leading to greater microbial uptake and immobilization of nitrogen (Averett et al. 2004). Carbon additions, such as sucrose or sawdust, have resulted in a reduction in weedy plant biomass (Blumenthal et al. 2003) and an increase in desirable plant biomass, likely due to the reduction in available nitrate (Adams et al. 2013). However, other authors have noted no effect (Corbin and D’Antonio 2004) or reductions in desired species growth (Averett et al. 2004). As with other ecosystem services, the type of soil and biochar affect the outcomes of invasive species. Application of site-produced biochar could be used in areas most vulnerable to invasive species.

Biochar and Forest Health

Forests are important for food, fiber, medicine, water, biofuels, and other values. Forests also protect water and soil quality, host more than three-quarters of terrestrial biodiversity, and help combat climate change (FAO 2020). Therefore, it is critical to use an ecosystem services approach to sustainable forest management. Biochar can reduce the risk of wildfire and provide for long-term carbon sequestration (Rodriguez-Franco et al. 2022). Sustainable forest management provides the raw material (feedstock) for biochar production for use on contaminated or degraded soils and is an important tool to reduce the risk of wildfire. Further economic services can be enhanced through wildfire cost savings, improved watershed health, greater recreational opportunities, and production of a new forest product (biochar). Biochar can be used on-site. As noted, it can be used to reduce compaction or improve vegetative cover. It could also be used off-site to remediate abandoned mine sites or mixed with a compost to improve soil productivity. In this regard, biochar is often useful in tree nurseries (Dumroese et al. 2020) and for agricultural soils (Sessions et al. 2019).

Increasing soil health by using biochar can also improve forest health by making vegetation more resilient to drought and a changing climate. Increased soil health can also mean that trees are less susceptible to insect or disease attack, and better able to withstand infestations because of a greater soil water holding capacity and available water. In addition, because of the changes in carbon, nutrients, and microbial communities, biochar has been shown to reduce disease severity of several different pathogens. Although most of this research has been done on agricultural crops (e.g., Elad et al. 2011, Elmer and Pignatello 2011), the defense-enhancing mechanisms of biochar may also be important for forest vegetation. These sites are often low in organic matter and nutrients, and biochar can improve nutrient retention and water holding capacity. In addition, on many degraded sites (e.g., skid trails, log landings) biochar can increase soil cover, thereby reducing the potential for wind and water erosion.

Application Rates and Methods

Biochar can be applied at a variety of rates from 1 to 10 tons per acre (2.2–22 Mg per ha), depending on biochar and soil properties and project goals. As noted earlier, biochar made in CBPs or kilns can be raked out and left in place. Larger quantities produced in ACBs can be shoveled into buckets or wheelbarrows for wider distribution. A biochar spreader (Page-Dumroese et al. 2016a) has been developed and is pulled behind a log forwarder. The spreader is a modified salt spreader with clearance to go over stumps and traverse slopes up to 35 percent; it has an adjustable spread rate. Fertilizer or manure spreaders could also be used to apply biochar to large areas. If biochar is being applied to disturbed soil (no intact surface organic horizons), then it can be mixed into the mineral soil with a grappler or excavator. On small-scale projects, biochar can be added to a seedling planting hole. Application rates for this use should not exceed 25 percent of the planting hole volume and the biochar should be mixed with the mineral soil.

When biochar is applied on the surface of an intact forest soil, it will naturally be incorporated into the organic soil horizon over time. Biochar can be applied on the surface of the forest litter layer without needing incorporation into the soil profile, as needle and leaf fall from the overstory will accumulate on top of it (fig. 21).

Figure 21—Fungi and mosses grow 2 years after deployment of biochar from hand-built conservation burn piles, as the biochar is slowly buried under organic debris (Courtesy photo by Kelpie Wilson, Wilson Biochar, used with permission).

Integrating Biochar into Management Directives

Biochar presents many opportunities to change how we manage LVM, mitigate climate change, decrease wildfire risk, improve forest and soil health, and increase ecosystem services (e.g., erosion control). The pace and scale of biomass conversion to biochar will vary depending on the project type and the availability of equipment and personnel. Integrating harvest operations with biochar production is one hurdle to overcome, but onsite production methods make this easier than integrating transportation of LVM to a bioenergy facility or onsite chipping. The small-scale technologies discussed offer relatively inexpensive methods for biochar production. An important piece of this work is to engage the public and producers with biochar production activities. Biochar can be strategically employed for various land management practices, such as suppressing invasive species or mine soil restoration. Incompletely burned pieces of wood that contain more labile carbon can also be used for erosion control, hillslope stabilization, increasing soil permeability, or creating habitat for wildlife. Biochar could also be used to support seeding activities, providing extended moisture during dry months.

Wildfire Crisis Strategy

Integrating place-based biochar manufacturing offers multiple benefits. The most obvious is reduced smoke for forests in sensitive airsheds or near rural communities while also disposing of wildfire hazard fuels. Some mobile systems are flexible, offering methods to dispose of green wood waste or material with moisture content greater than 30 percent. Some less obvious benefits of biochar manufacturing and use include the following:

- Fuel moisture—Increased soil moisture improves live fuel moisture of fine fuels, resulting in reduced risk of wildfire ignition as more fine fuel stays green longer into late summer.
- Wildlife—Improved soil moisture increases forest and range forage for big game later in the year, benefiting pairs of cows and calves before winter.
- Fire risk to right-of-way easements—Place-based production could be used in easements for highways, rail, power line, and gas transmission lines to improve soil moisture and reduce wildfire risk to crucial infrastructure.
- Invasive plants—Biochar applications can help managers get ahead of invasive plant expansion by reducing pioneer conditions and improving native plant regeneration.

Climate Change

The Intergovernmental Panel on Climate Change (2021) models show a change in how precipitation is received across the United States. Using biochar to increase infiltration and water holding capacity can buffer some climate change impacts related to drought or excess rainfall.

Biochar for Abandoned Mine Soil Restoration

Abandoned mine sites across the United States pose environmental challenges, including soil erosion and water pollution. Biochar is a viable solution for restoring these lands. Applying biochar to mine soils can improve soil quality, thereby enhancing productivity and mitigating issues like erosion and leaching of contaminants. The use of biochar not only repurposes waste biomass, thereby reducing wildfire risks and air pollution, but also holds the potential to improve water quality and bind heavy metals in the soil (Ippolito et al. 2017). These applications contribute to forest health and long-term environmental sustainability.

Considerations for Biochar Markets and Alternative Funding Sources

Generally, place-based biochar production produces small amounts of biochar when compared to bioenergy plants that have a biochar co-product. However, some forest restoration projects may create large volumes of biochar. In this case, excess biochar can be transported off-site for uses in agriculture or other sectors. This approach could optimize resource utilization and open new avenues for revenue to subsidize the cost of the biochar production activities. There are many potential markets for offsite uses that could provide revenues to forest managers.

Product Labeling and Data Provision

For biochar intended for markets, standardized testing methodologies could be beneficial. Information such as the technology used to manufacture the biochar, feedstock species, date of production, distance transported, and the landscape where the feedstock was processed can be monitored and reported. These data would be valuable for labeling and traceability purposes. Meeting established standards can increase consumer confidence and, thus, market demand.

Value-added Biochar

Biochar can be left in a pile on-site for a period ranging from a few weeks to months, allowing for natural inoculation with forest microbes. This process could potentially be accelerated by adding small amounts of forest soils on top of biochar heaps, which would allow rainwater to filter the soil and embed microbes into the biochar. The resulting inoculated biochar could be sold as a premium product for soil restoration. Similarly, biochar can be moved off-site and added to a compost, resulting in a high-moisture content, nutrient-rich substrate.

Biochar Carbon Removal Certificates

When biochar is transported off-site, there is potential for issuing Biochar Carbon Removal Certificates. To uphold the integrity of these certificates, it would be necessary to calculate project leakage. This calculation would include factors such as the fuel used for transportation, the energy required for processing biochar to a consistent size, and the materials used for packaging.

Internal Carbon Removal Reporting

On private forest lands, if biochar production is monitored and measured, it can be incorporated into internal carbon removal reporting. This documentation would demonstrate how soil-level carbon stocks might be increased and emissions avoided from conventional pile burning methods.

Cost-sharing and Landowner Use

In wildland-urban interface areas, biochar production can be cost-shared with landowners, insurance companies, or local jurisdictions. The biochar can be given to these landowners for use on their property, or for mixing with compost.

Contributions from Insurance Companies or Municipalities

Insurance companies and municipalities could potentially contribute to the cost of managing fuel loads through biochar production. They could then include these biochar carbon removal activities in their sustainability reporting as “contributions towards carbon removals and fuel load reduction,” as carbon sequestration activities could fall within their mandate and sustainability commitments.

Public-Private Partnerships

Leveraging partnerships with private entities could help subsidize the cost of biochar production and expand its range of applications. These partnerships could be particularly valuable in areas where biochar has potential but is currently underutilized, such as nutrient runoff management, water treatment, and municipal composting.

CASE STUDY EXAMPLES

All place-based biochar production methods examined in this report are already in use. This section describes some of the projects that have been completed or are ongoing. These projects will illustrate potential use cases for each method, and will help managers understand how to choose the most appropriate biochar methods or combination of methods for a particular site or operation.

Hand Conservation Burn Piles: Islands Conservation Corps

The San Juan Islands Conservation District (Washington State) launched the Islands Conservation Corps (ICC) in 2020 to create and train an ecology workforce. The program addresses several conservation objectives including oak woodland restoration and community wildfire protection. Some support comes from the local electric utility to clear vegetation along utility corridors.

The crew is recruited from students at Western Washington University's College of the Environment (called Huxley College of the Environment until 2021). The 10 students who were selected from 70 applicants receive a stipend and 20 free college credits. "With this program, they are gaining many valuable skills in chainsaw work, burning practices, planting, riparian zone restoration, all in coordination with their academic coursework. We are bridging that gap between the university and the field" (Kai Hoffman Krull, Program Manager, Islands Conservation Corps, personal communication, March 15, 2024).

The work is done using the conservation burn technique. The crew makes standard size burn piles, about 5 feet in diameter. The piles are lit on the top to get a good flaming combustion going that reduces smoke. The ICC has a 1,300-gallon (4,921 liter) water truck for quenching and uses a combination of spraying water and raking. For very remote sites the ICC has 5-gallon backpack pumps. One backpack pump can extinguish two piles. Biochar yields can be as much as 35 gallons (133 liters) per pile.

By the end of 2023, the ICC had treated 32.3 acres (13 ha) and built and burned 843 CBPs (fig. 22). The corps also made 575 nurse-log analogues from material not used in the CBPs. Nurse-log analogues aggregate small diameter stems to simulate large coarse woody debris on the forest floor.

Figure 22—The Islands Conservation Corps has built and burned hundreds of hand-built conservation burn piles. The organization also makes nurse-log analogues to simulate coarse woody debris, as shown here between the burning piles (Courtesy photo by Maggie Long, Islands Conservation Corps, used with permission).

Machine Conservation Burn Piles: South Umpqua Rural Community Partnership

As part of the South Umpqua Rural Community Partnership program, the Umpqua Biochar Education Team built 26 piles with an excavator on a stewardship project in the Umpqua National Forest (Oregon) to test the machine CBP method (fig. 23). In November 2017, the piles were lit on top and burned until they formed a heap of glowing coals. A water tender was provided for quenching water. A crew of volunteers raked out the coals by hand while the water tender sprayed water. There was only enough water to quench about half the piles, so the rest of the piles were only raked to a thin layer to cool with no water, reducing the amount of char created. All the piles lit on top burned very cleanly, making this technique worthwhile, even with limited quenching water (Wilson 2018).

Figure 23—(a) A machine-built conservation burn pile processed slash from a stewardship contract on the Umpqua National Forest into (b) biochar that was left on-site (Courtesy photos by Kelpie Wilson, Wilson Biochar, used with permission).

Oregon Kiln and Ring of Fire Kiln: Bureau of Land Management

Flame-cap kilns were used in the Missouri Headwaters Habitat Restoration and Biomass Utilization project (Missouri Headwaters project) supported by the Montana Forest Action Plan (MFAP) that is under way in southwest Montana. The main goal is to implement landscape-scale restoration working across jurisdictional boundaries. Since its award in 2021, the MFAP project is directly responsible for over 3,000 acres (1,214 ha) of habitat work and its impact has allowed the Southwest Montana Sagebrush Partnership to leverage additional resources to complete nearly 30,000 acres (12,141 ha) of conifer expansion removal in the same period (Ashley Durham, U.S. Department of the Interior, Bureau of Land Management, personal communication, March 20, 2024).

One component of the Missouri Headwaters project is the Schwartz Creek Conifer Removal project, a partnership with the Bureau of Land Management (BLM), Dillon Field Office, the Montana Department of Natural Resources (DNRC), The Nature Conservancy, and the Restorative Forestry Sort-Yard. The silviculture prescription was to harvest all trees greater than 5 inches (13 cm) diameter at breast height. Every tree meeting this criterion was cut, processed, and hauled to a local sort-yard to be made into wood products including firewood, rails, sawtimber, and house logs. The dried slash piles from the DNRC harvest operation were ready to be made into biochar. With the help of BLM employees, the locally based Youth Employment Program, and the DNRC fire crew, 3 days of in-woods biochar production took place. Slash piles were pulled apart and sometimes cut to length to fit into the kilns. One Ring of Fire Kiln and three Oregon Kilns were used to make roughly 16 cubic yards (12 cubic meters) of biochar (fig. 24).

The biochar was then transported to the Ruby Habitat Foundation's Woodson Ranch. The foundation is a nonprofit support organization to the Montana Land Reliance, which promotes sustainable agriculture and thoughtful land stewardship through education programs and demonstration projects on the ranch. The biochar will be charged using local cow manure and, as the foundation practices no-till agriculture, the biochar will be top spread on an annual grain field and incorporated using a Truax seed drill (Truax Co., New Hope, Minnesota). Differences in aboveground biomass and changes in soil chemical and physical properties will be measured.

Figure 24—(a) Bureau of Land Management employees, firefighters, and a youth crew worked together (b) to make 16 cubic yards (12 cubic meters) of biochar from slash materials that will be used in sustainable agriculture. U.S. Department of the Interior, Bureau of Land Management photos by Ashley Durham. Photo illustration.

Ring of Fire Kiln: Watershed Consulting

Watershed Consulting in Missoula, Montana treated slash thinned from 21 acres (9 ha) of mixed conifer forest in western Montana using four small Ring of Fire biochar kilns, each with a volume of 3 cubic yards. Tree density throughout the unit averaged about 1,500 stems per acre (3,700 stems per ha).

Most stems were under 3 inches in diameter. The stand was thinned in 2020, and the slash was scattered and allowed to dry for 1 year before processing into biochar in spring and fall 2021. The project processed a total of 85 kiln batches over 55 days, with an average biochar yield of 1.3 cubic yards (1 cubic meter) per kiln for a total biochar yield of 112.5 cubic yards (86 cubic meters). The cost of producing the biochar was $42,302.00, or $376 per cubic yard ($492 per cubic meter).

Wilson Biochar, in association with ADTech (Cape Town, South Africa), estimated that the project sequestered 31.75 metric tonnes (34.99 tons) of CO2 at a cost of $1,332.35 per metric tonne ($1,209.03 per ton). This estimate was based on our own standard assumptions about biochar characteristics made in FKs. The alternative cost of piling and incinerating the material would have been $15,750.00, leaving a marginal cost of $26,552.00 for biochar production instead of incineration, or $836.28 per metric tonne ($758.87 per ton) of biochar produced. That marginal cost could be partially covered by carbon removal payments of $100 to $200 per metric tonne ($91–$181 per ton) of CO2.

To complete the economic picture of the project, it is important for financing authorities to acknowledge the ecosystem benefits of avoiding soil damage from burn pile scars, reduced greenhouse gas emissions and particulate air pollution compared to incineration, and returning char to forest soils for moisture retention, nutrient cycling, and soil health (Wilson et al. 2023).

Ring of Fire Kiln: Wisconsin Department of Natural Resources

Brian Zweifel, Forest Products Specialist with the Wisconsin Department of Natural Resources (WDNR), was looking for opportunities across the State to make biochar from sawmill residues and slash from forestry projects, including urban forestry. He purchased two Ring of Fire Biochar Kilns so the WDNR could experiment with producing biochar as a forest product. The WDNR's first project was to make biochar from hardwood brush cut around the Wilson State Nursery in Boscobel, Wisconsin. The nursery has been using peat in seedling beds to improve soil organic matter and build soil structure and water holding capacity. Peat is expensive and readily decomposes in the soil, but biochar could be a longer-lasting substitute for the peat. The nursery started a biochar field trial using eight different species of trees and shrubs to learn more about effective biochar uses (fig. 25). Eight species grown at the nursery were chosen, and biochar plot locations were randomized. Approximately 70 pounds (32 kg) of biochar were weighed out for each plot, which equates to roughly 3 tons per acre (7 metric tonnes per ha). In the growing seasons to come, nursery staff and Forest Service partners will monitor the effects of biochar on soil health, look for any effects or interactions with chemicals used to control pathogens (including fungal fumigants), and quantify effects on seedling root and stem biomass.

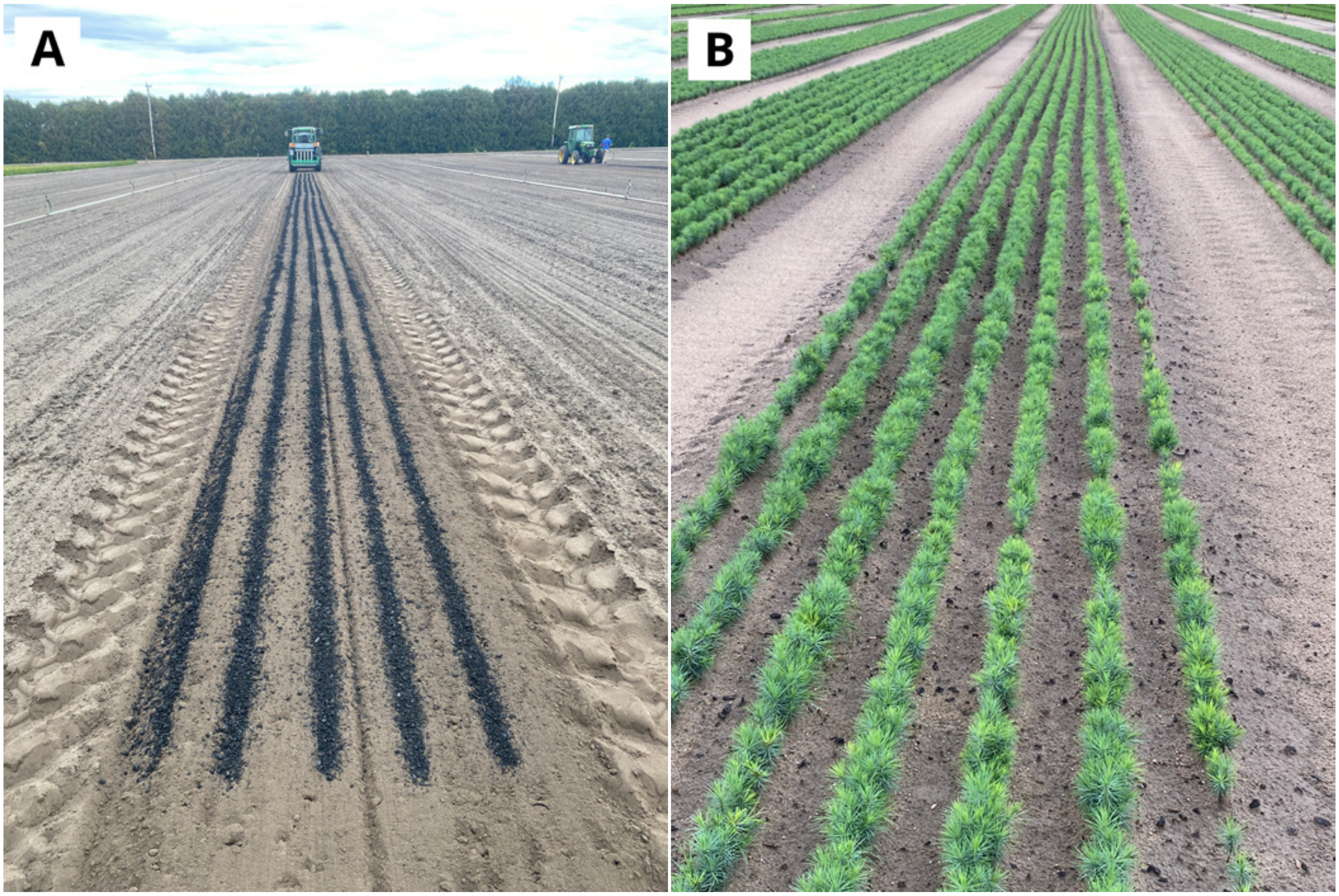


Figure 25—(a) Biochar is applied at Wilson State Nursery in Boscobel, Wisconsin. (b) Following application, the biochar was rototilled into the test beds (Courtesy photos by Brian Zweifel, Wisconsin Department of Natural Resources, used with permission).

Big Box Kiln: Hazardous Fuels Reduction

The Utah Biomass Resources Group (UBRG) and Utah State University Forestry Extension have utilized the Big Box Kilns for multiple projects on public and private lands since 2019. Some of the projects have involved collaborations with the Forest Service and the Utah Division of Forestry, Fire and State Lands. Projects have included slash from salvage harvest to remove spruce beetle-killed trees, juniper (*Juniperus* spp.), and invasive Russian olive (*Elaeagnus angustifolia*), and to reduce multispecies hazardous fuels (table 10). The biochar produced has mostly been used on-site to improve soils and help meet conservation objectives (fig. 26).

Figure 26—Big Box Kiln biochar is spread out and crushed on-site using a small excavator bucket (Courtesy photo by Darren McAvoy, Utah State University, used with permission).

BurnBoss: Valley Environmental

Valley Environmental in Canby, Oregon provides land clearing and waste disposal services throughout western Oregon and the surrounding Pacific Northwest. Ryan Ramage of Valley Environmental has been using a BurnBoss for the past several years to make biochar. He has produced biochar from land clearing, forestry, and orchard debris, working with city governments, private landowners, the Hood River Resource Conservation District (Oregon), and Oregon State University. Jobs in Oregon have included:

- Cleaning up storm-damaged trees at the Santiam Golf Club and leaving behind biochar for the golf greens, without impacting golfers with smoke emissions. The golf club is in an air-quality-limited area where open burning is otherwise not allowed.
- Work on the hazelnut orchards on the Oregon State University campus and providing biochar for research projects.
- Clearing multiple orchards of debris in the Hood River Soil and Water Conservation District, and leaving behind biochar for the farms (fig. 27).
- Clearing pine (*Pinus* spp.) trees from land that will become a vineyard and leaving behind biochar for the new vines.
- Processing slash from the poplar (*Populus* spp.) plantations used to treat municipal wastewater for the cities of Eugene and Springfield and leaving behind biochar for soil improvement in the plantations.

- Working with the Clackamas County Fire District community fuels reduction project, including a debris drop-off day where residents could bring yard debris to the fire station to be processed into biochar with no smoke emissions.
- Processing ash (*Fraxinus* spp.) trees infested with the emerald ash borer into biochar, effectively sanitizing the debris to stop the progress of this devastating pest.

Figure 27—A BurnBoss® processes orchard waste into biochar (Courtesy photo by Ryan Ramage, Valley Environmental, used with permission).

CharBoss: Testing a New Device

The prototype CharBoss was originally tested in Oregon on gorse (*Ulex europaeus*) and mixed conifer LVM. This equipment was then moved to the eastern United States, where it continues to work. The two beta-version CharBosses have been used at demonstration sites since 2020 in Florida, Utah, Arizona, Montana, Idaho, Oregon, Colorado, and California. The unit has processed many kinds of feedstocks, including mixed conifer LVM after wildfire, salvage logging, and fuels reduction projects. The biochar was used on-site or near-site for soil restoration projects to increase native forbs, grasses, and shrubs, but in all cases participants at the demonstrations took home much of the biochar for use in gardens or yards. Current work focuses on sharing this new technology and demonstrating where and when it should be used. In addition, each demonstration presents an opportunity to collect data on production rates and biochar quality.

Tigercat 6050: Removing Dead Trees

The East Bay Regional Park District needed to address extensive tree mortality affecting eucalyptus and other species that had resulted in more than 1,500 acres (607 ha) of standing dead and dying trees. The extensive mortality created hazardous wildfire conditions within the wildland-urban interface in the hills of the East San Francisco Bay Area. The park district contracted with Falk Forestry and Earth Foundries to operate the Tigercat 6050 and began processing mostly eucalyptus beginning in January 2023. The Tigercat 6050 was operated for 5 days a week until March, producing 88 tons (80 metric tonnes) of biochar. After stopping production for the summer, the Tigercat 6050 resumed production in fall 2023 and began operating 24 hours a day. Continuous operation is beneficial because it takes several hours from the start of ignition for the large firebox to come up to temperature. Running continuously, the machine produced 48 tons (44 metric tonnes) of biochar in November 2023. As of January 2024, the project has produced and delivered 165 tons (150 metric tonnes) of biochar and expects to deliver another 230 tons (209 metric tons) by the end of the project.

By choosing to make biochar in a large ACB, the park district avoided the truck traffic that would have been required to move the material for processing elsewhere. Park district officials estimated that it would have required continuous trafficking from seven semi-trucks driving on the narrow park roads, to remove the material. One other benefit of less truck traffic was the reduced emissions of carbon and particulates from the diesel-fueled trucks.

Most of the biochar produced from the project has been given to Ardenwood Historic Farm, where it is being utilized to improve soils and crop yields. The second largest user of biochar in the district has been Garin and Dry Creek Regional Parks, where the winter storms of January 2023 washed out the gardens, depositing 12 to 24 inches (30–61 cm) of silt. The biochar will be used to restore these soils. Several parks in the district have used biochar as a soil additive in native plant restoration projects, mixing it into the planting hole soil to aid with water retention during the dry months where irrigation was impractical.

The park district now has a biochar utilization committee, which is working to find beneficial uses for biochar within the park district. Going forward, the park district plans to convert up to half of the biomass removed from parks into biochar. The park ecologists have many ideas for using the biochar, including:

- inoculation with beneficial fungi,
- adding to apple orchards in the parks,
- use in native species and tree planting,
- use in wattles and bioswales for erosion control,
- use as a compost additive, and
- use to protect oak trees from sudden oak death.

MANAGEMENT IMPLICATIONS

Making place-based biochar is another tool in the toolbox to reduce the volume of LVM and wildfire risk. Adding biochar production using any of the described methods to the most common LVM disposal activities of creating and burning piles, masticating wood, or chipping and hauling material to a bioenergy facility can address the massive amounts of LVM while also creating a product that can improve forest and soil health.

Creating biochar from LVM engages the public in restoring healthy forest conditions, but it requires planning to use these tools. Place-based biochar production can create new jobs in the forest sector and provide training for the next cadre of natural resource workers who will need to help reduce hazardous fuels. In addition to reducing the volume of LVM, biochar promotes numerous ecosystem services such as clean water, soil cover, food, and fiber. Biochar has a high porosity and can ameliorate degraded soils to restore soil conditions and native plant abundance and diversity.

In particular, biochar is well suited for use in coarse-textured soils that have low organic matter and low fertility. Furthermore, biochar added at rates of up to 10 tons per acre (22 metric tonnes per ha) on numerous forest sites in Idaho, Montana, Oregon, and California has not been detrimental to plant or soil processes. Like all new technologies and processes, place-based biochar needs additional field trials and demonstrations to promote its production and use.

GLOSSARY

Air curtain burner (ACB)—An insulated box with a blower that projects a high-velocity curtain of air across the firebox to control air emissions during burning.

Airshed—The geographic area that produces a significant amount of the emissions that contribute to atmospheric deposition in a watershed (U.S. Environmental Protection Agency 2015).

Ash—A byproduct of biomass combustion. Ash can be used as a fertilizer.

Aromatic carbon—Carbon that is in the form of six-sided carbon molecules linked together in sheets or chains.

Biochar—A carbon-rich solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment that is suitable for many uses, especially in soils.

Biochar quality—Quality assessed according to the purpose of the biochar use. In the case of biochar used for carbon sequestration in soil, biochar quality is determined by the recalcitrance of the carbon in biochar.

Biomass—The biodegradable fraction of biological material derived from recently living beings, usually plants.

Carbonization—The conversion of an organic substance into a stable carbon residue through pyrolysis.

Charcoal—A solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment. All biochar is charcoal, but not all charcoal is biochar.

Charged biochar—Biochar that has been treated with nutrients or beneficial microbes (or both) to create a fertilizing soil amendment.

Conservation burn pile (CBP)—A method of open pile burning that manages the burn process to produce minimum smoke and ash and maximum biochar.

Devolatilization—Release of hydrocarbon gases from biomass through heat or drying.

Drivable dips—A common logging road maintenance feature as they are cheaper to install and maintain than relief culverts because they avoid plugging and road washout.

Feedstock—The material undergoing the thermochemical process to create biochar. Feedstock material for biochar is biomass from plants and other organisms.

Flame—Burning gas that emits heat and light.

Flame carbonization—A process for carbonizing biomass in the presence of an oxidizing flame that relies on stopping the combustion process before the material turns to ash.

Flame-cap kiln (FK) —A carbonizer that uses a cap of flame both to transfer heat to the feedstock and to prevent oxidation of the finished biochar by consuming all of the available oxygen.

Forest residues—Woody material not harvested and removed from logging sites in commercial operations, as well as material resulting from forest management operations such as clearcut harvesting, fuels reduction thinning, or salvage logging.

Gasifier—A thermochemical reactor optimized to produce gas from a fuel. The emphasis is on producing gas rather than biochar. In contrast, a carbonizer produces gas while optimizing biochar production.

Greenhouse gas (GHG) —Any of the gases whose absorption of solar radiation is responsible for the greenhouse effect, including carbon dioxide, methane, nitrous oxide, and the fluorocarbons.

Labile carbon—Carbon that can be more easily degraded by microorganisms than fixed carbon. Labile carbon includes active carbon.

Low-value material (LVM) —Woody biomass residuals with little or no commercial value that result from timber harvest and vegetation management.

Open burn pile—An ordinary burn pile or camp fire that does not take place inside a container of any kind.

PM2.5, PM10—Particulate matter in air is defined by the particle diameter in micrometers (microns) and used for air quality regulatory purposes. Fine particulate matter falls into the PM2.5 class though the larger PM10 is also inhalable.

Pyrolysis—The thermochemical decomposition of organic material in an oxygen-limited environment into biochar, gas, liquids, and ash.

Recalcitrant carbon—In soils, the recalcitrant carbon pool is that fraction of soil organic matter that is resistant to microbial decomposition.

Sequestered carbon—In the context of biochar, sequestered carbon is the recalcitrant carbon content of biochar that is added to soil.

Stable carbon—In biochar, stable carbon is another term to refer to recalcitrant or sequestered carbon that is not easily degradable by microbes.

Thermochemical conversion—Thermochemical conversion of biomass includes combustion, pyrolysis, and gasification. A thermochemical reaction may convert wood or other fuel into products such as heat, gas, oil, distilled liquids, char, and ash.

Thousand-hour fuels—Wood 3 to 8 inches (8–20 cm) in diameter, depending on location, that can take up to 1,000 hours to adjust to moisture conditions.

Volatile matter—In biomass, volatile matter is anything that burns, excluding mineral ash. In biochar, volatile matter refers to the labile carbon that is degradable by microbes.

Volatile organic compounds (VOCs)—Emissions from combustion that are harmful to health. VOC emissions from burning wood can include acetic acid, furfural, toluene, terpenes, PAH (polyaromatic hydrocarbons), and many other compounds.

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