The Financial Viability and Sustainability Benefits of Converting Slash Into Biochar Instead of Open-Burning Following Fuel Treatments in the White River National Forest

The Financial Viability and Sustainability Benefits of Converting Slash into Biochar Instead of Open-Burning Following Fuel Treatments in the White River National Forest

Timothy Robert Borden

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Abstract

The state of Colorado has 22.49 million acres of forestland, a growing proportion of which is under threat from disease, insects, drought and wildfire. The severity of these threats originates from a long history of misguided forest management practices that have decreased the overall health of Colorado forests. Federal, state, and local land management agencies have evolved to recognize and correct for past management mistakes, but a lot of damage has been done. These agencies need to continue with practices that will restore Colorado forests to a healthier state but are faced with financial and social barriers to doing so.

The aim of this study was to determine if the production of biochar from slash can be used to improve the health of Colorado's forests. Slash is the organic material left over following forestry projects. Biochar is the solid product leftover after combusting slash in an oxygen diminished environment and is used to improve soils and sequester carbon from the atmosphere. My main research question asked if the economic, environmental and social benefits of producing biochar are sufficient to induce the inclusion of a biochar industry within the state to assist with restoring forest health. I hypothesized that a cost-benefit analysis (CBA) model will show that a biochar industry when included with current practices will make forest management projects more financially viable than current methods.

Data to address the research question were obtained by contacting companies, individuals, government departments, trade associations and others. The data was input

into a CBA spreadsheet that linked operational, environmental and social costs to a set of independent and derived variables. The model was set up using a full-cost accounting framework to calculate key financial appraisals and valuations of social and environmental impacts of a commercial biochar operation operating in the Roaring Fork Valley of Colorado over a ten-year period (2021 – 2031).

The model was run to calculate changes in gross profit and net present value (NPV) under different operating conditions. Different scenarios were modeled by varying the values in the independent variables sub-set including tons of slash available, different equipment values, and price of finished biochar. Metrics evaluated included the financial, environmental and social impact of producing biochar for forest restoration; adding biochar to forest soils as an amendment, and long-term sequestration of carbon as biochar. Sensitivity analysis for variations of +/- 25% on baseline values was conducted in order to establish which variables have the greatest impact on gross profit and NPV.

The model indicated the importance of a stable price at or above $350 per US ton for finished biochar. Below that price a biochar operation could be profitable only with a subsidy for carbon emissions sequestered by the production of biochar. The model indicates profitability of the operation given the inclusion of a carbon subsidy based on medium estimates for the price of sequestered carbon.

The main implication of the thesis is that including biochar in forest restoration projects can reduce the cost of projects, improve the overall health of forest ecosystems, remove and sequester carbon from the carbon cycle, and provide a boost to local economies. All of these benefits suggest that biochar production should be encouraged on public lands and that financial incentives to do so may be very economical

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Definition of Terms

Autothermal Process: A thermochemical reaction that creates synthesis gas from organic materials using only the heat produced by the reaction itself.

Biochar: Charcoal produced from plant matter by pyrolysis and is suitable for incorporation into soils as a form of soil amendment.

BLM: Bureau of Land Management. A land management agency of the United States Government that manages 247 million acres in the United States. BLM lands are mostly brush and grass and are managed under multi-use strategies.

Carbonization: The conversion of an organic substance into carbon or a carbon-containing residue through pyrolysis.

Clear Cutting: The removal of all or most trees from a given landscape.

CSFS: Colorado State Forest Service

Charcoal: A solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment that is suitable for use as a fuel.

Fixed Carbon: Fixed carbon is another term for recalcitrant carbon.

Flame Cap Kiln: A flame cap kiln is a carbonizer that uses a cap of flame both to transfer heat to the feedstock and to prevent oxidation of the finished biochar.

Forest Residues: Woody material not harvested or removed from logging sites in commercial operations as well as material resulting from forest management operations such as pre-commercial thinning and removal of dead and dying trees.

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

Global warming potential (GWP): Greenhouse emissions factored to represent CO2 equivalents.

Life cycle assessment (LCA): Method for the environmental assessment of products covering their lifecycle from raw material extraction to waste treatment.

Life cycle inventory (LCI): LCA study that goes as far as an inventory analysis but does not include impact assessment.

Life cycle impact assessment (LCIA): Phase of an LCA study during which the environmental impacts of the product are assessed and evaluated.

Mechanical Thinning: Thinning of forested areas conducted by mechanical equipment such as chainsaws, feller buncher, or other heavy equipment.

Pyrolysis: The thermochemical decomposition of organic material in an oxygen-limited environment.

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

SMH: Scheduled Machine Hour.

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

Slash: The biomass remnants left over from the removal of trees and other large woody material after fuel treatment projects.

USFS: United States Forest Service. A land management agency of the United States Government that manages 193 million acres in the United States.

Chapter I

Introduction

According to the United States Forest Service (2018), Colorado’s forestland has been under an accelerated amount of stress. More than a century of misguided management practices has resulted in excessive tree stand densities. There are three times as many trees in Colorado today as there were in 1900, but no discernable increases in water and nutrients. Colorado trees have become ‘stressed’ in their competition for these finite resources, leaving them increasingly vulnerable to events such as drought, insects, wildfire, and climate change. Of the 24.4 million acres of forestland in Colorado, 8.5 million acres have experienced abnormally high rates of tree mortality over the past three decades from these events, an increase of nearly 150% from the three decades prior (USFS, 2017).

Maintaining the health of these forests has been a critical concern within the state. Colorado’s forests provide immeasurable social, economic, and ecological benefits. They provide a diversity of wood products, support wildlife, provide freshwater to millions, and support a tourism and recreation industry that brings in $1.2 billion dollars per year (Worthington, 2017). Land managers understand that if Colorado’s forests remain in a state of decline, the negative impacts on these benefits can have far reaching consequences.

Solutions to improving forest health have taken many forms. These solutions, referred to as ‘fuel treatments,’ include mechanical thinning, manual thinning, clear cutting, chemical applications, and prescribed fire. All solutions are centered around some method to remove woody material from the forest. Any woody material that cannot be sold into existing markets is deemed 'slash' and except for uses of prescribed fire, are piled and burned in a 'slash pile.' Slash represents 60 and 80% of all material removed from the forests during these fuel treatments (Ter-Mikaelian, Colombo, & Chen, 2016).

The burning of these slash piles is effective at disposing of the slash but is not immune to negative consequences. This negatively impacts local air quality and contributes to greenhouse gas buildup in the atmosphere. Additionally, due to the intense heat generated by the pile, and the long duration at which they can continue to burn, slash pile burning can significantly change soil processes, plant establishment, and adjacent vegetation (Evans, 2011). The impacts to soil can last decades (Page-Dumrose, 2012),

It is important that fuel treatment projects continue, but the burning of slash piles needs to be rethought. Researchers at the US Forest Service's Rocky Mountain Research Station believe the answer is to turn slash into biochar. This would eliminate impacts on local air quality, soils, and adjacent vegetation. It would also trap the carbon from the slash in a solid form, which is the product called biochar (McElligott, Page-Dumroese, & Coleman, 2011). The long-term impacts of trapping the carbon in a solid form rather than releasing it into the atmosphere through open burning can help to mitigate elevated levels of carbon in the atmosphere, which are directly related to climate change (IPCC, 2018). The biochar can then be returned to the soil in the area where the slash originated from to improve local soil health, can be sold as an agricultural amendment or for other uses, or a combination (Wilson, 2013).

This idea has been tested on smaller scales in Utah (Page-Dumroese, Busse, Archuleta, McAvoy, & Roussel, 2017) and Oregon (Wilson, 2016). Both of these studies indicate strong support for the benefits of choosing biochar production over slash pile burning. However, neither of these studies explored the long-term financial, social, and environmental benefits of doing so. The long-term benefits are certain to compound in coming years as Colorado forests are projected to continue to be stressed by overgrowth, insects, drought, and wildfire. Additionally, the Utah and Oregon studies were conducted in different forest ecosystems which may produce different results then Colorado.

Research Significance and Objectives

Using the Roaring Fork Watershed as an example, my research evaluated the cost of 'business as usual' (BAU) and compared that with the economic, environmental and social benefits of replacing slash burning with biochar production in fuel treatment projects. The environmental benefits were calculated in terms of restoring forests to healthier carrying capacities, reduced risk of mortality from natural events, reduced direct impacts from slash burning, reduction of local air pollution, reduced greenhouse gas emissions, and long-term sequestration of carbon. The economic benefits were calculated in terms of difference in cost of slash burning and producing biochar, and related job creation. The social benefits were calculated in terms of changes in quantity or quality of ecosystem services.

If shown to be feasible, my research could compel land managers to incorporate biochar into fuel treatments projects, could contribute to healthier forests in Colorado, and may lead to reductions in atmospheric carbon.

My objectives were:

- To evaluate the financial feasibility of converting slash to biochar, and to identify the conditions under which this could be achieved
- To compare the costs of slash burning with the costs of biochar conversion
- To determine whether the social and environmental benefits produced by biochar conversion would be sufficient to induce land managers to alter practices that would make that happen
- To enable policymakers to make informed decisions about the benefits of biochar production over slash burning

Background

The publication of the IPCC Special Report on Climate Change and Land (IPCC, 2019) makes it clear that changes in land management will have to play a major role in implementing policies and practices that reduce carbon emissions. Multiple IPCC reports (2018; 2019) specifically mention biochar as a viable Negative Emissions Technology (NET) for carbon removal from the atmosphere and one that most needs to implemented to undertake the "rapid and far-reaching" transitions required if global warming is to be limited to an increase of 1.5ºC.

Current Conditions of Forestland in Colorado

Of the 22.9 million acres of forestland in Colorado, about one-third is owned by private landowners. The remaining two-thirds are public lands and are managed by the U.S. Department of Agriculture (USDA) Forest Service, the U.S. Department of the Interior (USDI) Bureau of Land Management, the USDI National Park Service, and the

State of Colorado.

The lowest elevations of Colorado support grasslands. As elevation increases along the Front Range, grasslands became mixed with Ponderosa Pine (*Pinus ponderosa* Dougl. ex C. Laws.) trees in open savannahs. Mixed conifers species can become interspersed with Ponderosa. In central and western Colorado, the transition from grassland to forest includes areas with substantial shrublands and low-density woodlands with Junipers (*Juniperus* spp.) and Pinyon Pines (*Pinus edulis* Engelm.) (Romme et al., 2009).

In the eastern mountains of Colorado, Lodgepole Pines (*Pinus contorta* Dougl.) dominate mid-elevation landscapes, characterized by substantial winter snowpack, and large, intense fires with return intervals of one to a few centuries. In western Colorado, Aspen (*Populus* spp.) forests dominate landscapes that would tend to have Lodgepole Pine farther east. In some areas, Aspen forests remain essentially monoculture forests with little establishment of understory conifers. The highest elevation forests consist of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine Fir (*Abies lasiocarpa* (Hook.) Nutt.). These general patterns apply to most of the landscapes, but not to high mountain valleys that contain meadows, Willow (*Salix* spp.) shrub communities, and wetlands.

Insects and Pests

Colorado forests have always been susceptible to outbreaks from numerous different insects and pests on small and localized scales. Since 1996 Colorado forests have been hit by numerous waves of severe infestations from the Mountain Pine Beetle, Spruce Beetle, Round headed Pine Beetle, Western Spruce Budworm and others, but the scale of this had not been seen before. The United States Forest Service (2019) estimated 5.4 million acres of Colorado forests were severely impacted between 1996 and 2018, leading to excessively high rates of tree mortality (Figure 1). Part of the reason for the outbreaks is contributed to a decrease in the overall health of Colorado's forests. Overcrowding and over competition for nutrients and water has weekend many trees, leaving them less able to fight off infestations (DeLuca, MacKenzie, & Gundale, 2009). Causes for the increased severity and scale of the outbreaks have also been linked to climate change.

Figure 1. Large stand of beetle killed trees in Colorado (Kaufmann et al., 2016).

The massive rates of mortality from insects since 1996 has left areas of Colorado's forests choked with standing dead trees and a buildup of dead woody debris. More dead trees fall to the ground every year, further contributing to the buildup of dead biomass and creating hazardous conditions for recreation and other industries (Kaufmann et al., 2016).

Wildfire

Colorado forests are inherently designed to burn. Every ecosystem in the state requires fire at some level of frequency in order to maintain long-term health. This is evident from historical studies of fire frequency prior to widespread settlement of the state by European descendants (Lebere, 2011).

The occurrence of fires across Colorado depends strongly on drought periods. Seasonal droughts are often enough to dry fuels at low elevations, but fuels at high elevations only dry enough to carry fire during severe droughts that historically occurred at intervals of 50 years or more. The large impact of fires depends on the severity of droughts (McAvoy & Peltz, 2015).

Ponderosa Pine forests at low elevations historically experienced frequent fire regimes, with fires recurring every decade or so, minimizing the long-term establishment of new trees and maintaining open forests. Lodgepole Pine forests are characterized by intense fires with return intervals of one to a few centuries. Archeological data indicates few if any forests of Lodgepole Pine went more than three centuries without stand-replacing fires. Aspen forests do not burn as readily as pine forests, but fires are still important in the long-term development of Aspen-dominated landscapes. Aspen trees develop rapidly after fires, sprouting from surviving root systems. Engelmann Spruce and Subalpine Fir also experienced occasional intense, stand-replacing fires, recurring after several centuries. However, some old forests (>500 years) do not record any evidence of any fires, so some spruce–fir forests may have burned only very rarely (and very intensely) (Bates & Draper, 2019).

Following the widespread settlement of Colorado's forests by European descendants in the latter half of the 19th century, land managers adopted fire suppression policies that disrupted these natural fire regimes. For most of the 20th century any and all wildfires were immediately suppressed. These policies lead to overgrowth in Colorado's forest and fundamentally changed the character of its landscapes. Trees that normally would have been culled by wildfire were able to establish themselves and the amount of combustible material in the forests has continued to increase (McAvoy, 2013). This deficiency in natural wildfires, along with the increased loads of combustible material, has reached a breaking point. Since 2000 Colorado has seen increases in large and severe wildfires, with the twenty biggest in the state's history all having occurred since then (National Interagency Fire Center, 2019). Increases in wildfire intensity and severity can have lasting negative impacts on forests landscapes and on crucial ecosystem services.

Fuel Treatment Projects

In 1995, the Federal Wildland Fire Management Policy and its update in 2001 set the stage for the federal land management agencies (as well as other jurisdictions) to take action to reduce fuel accumulation in order to avoid larger and more damaging fires (McAvoy, 2015). Implementation of the recommendations of the National Fire Plan and the Healthy Forest Restoration Act of 2003 created the expectations that fuel reduction treatments (sometimes synonymously referred to as fuel treatments) would alleviate the problem of landscape-scale wildfire, help reduce the need and cost for suppression, and restore forests to healthier states. The federal land agencies had $620 million at their disposal for fuel treatment projects in 2018 (USFS, 2018) (USDI, 2018).

Fuel treatments projects typically take the shape of one or more of the following; prescribed fire, mechanical thinning, manual thinning, mastication, or slash removal. The goal of all of these techniques is to reduce the amount of combustible material from forests. Research from the USDA (2018) shows that fuel treatments have been effective in reducing fire behavior about 80% of the time. Research on the overall improvement of forest health from fuel treatment projects has been inconclusive due to the short duration of which fuel projects have been conducted with that intent (Huffman, 2013).

Slash

A byproduct of thinning projects is 'slash' (Figure 2). Slash is any organic material removed from the forest that is deemed to have little to no value and is not worth physically removing from the forest. It typically consists of litter, branches, pinecones, and small diameter trees. The amount of slash created by thinning projects is usually too much to leave dispersed on the forest floor for decomposition. The semi-arid conditions that can exist in some parts of the forest mean that decomposition of the material can take an exceptionally long time. The buildup of slash on the forest floor can hinder the movement of larger animal species, change the dynamics of forest development, and greatly increases the risk of high severity wildfire (Ter-Mikaelian, 2016). Due to these consequences, standard protocol is to create 'slash piles' that eventually get burned during times of low wildfire risk.

Slash piles cannot be left on site in the forest because they would take an excessively long time to discompose and would defeat some of the goals of conducting fuel treatment projects. Instead they are disposed of by open burning, usually during

Figure 2. Un-piled slash on ground. (McAvoy, 2015).

wet conditions. When the piles are burned in these conditions, they emit harmful chemicals including carbon into the atmosphere, contribute to poor local air quality, and impact surrounding soils and vegetation (Korb, 2004). Slash-pile burning is also expensive, costing an average of $10 per ton to dispose of (Evans, 2011). The high cost of disposal restricts the amount of public land acres that can be treated every year.

Biochar

Biochar has been around for thousands of years, dating back to the pre-Columbian Amazonian natives between 450 BC to AD 950. Modern day researchers were fascinated by the dark, nutrient-rich soil that these Amazonian natives left behind. This Amazonian soil has since been referenced to as “Terra Preta,” which translates to black earth (Thomas & Gale, 2015). Centuries of agricultural operations has caused detrimental effects to the world’s soil quality – the majority of the world’s soil is considered degraded, very degraded or without vegetation. Biochar (Figure 3) – with its ability to retain nutrients – can be a solution to this agricultural problem.

Figure 3. Biochar (Wilson, 2013).

Biochar is produced using a technique called pyrolysis, in which biomass is heated in the absence of oxygen to temperatures between 300-800 degrees C (Baranick et al., 2011) (Figure 4). The chamber in which the pyrolysis process occurs is referred to as a kiln. There are three major outputs produced from the pyrolysis process: a solid (biochar), a liquid (oil) and a gas (syngas). The quantity of each output is determined by four key variables of the pyrolysis process: input material, water content, operating temperature and process time. Biomass that is heated between temperatures of 300-600 deg C typically is referred to as a "slow" pyrolysis product, as the process time can take many hours. The benefit of the slow pyrolysis process is that up to 40% of the biomass input can be converted to biochar. The "fast" pyrolysis process occurs at temperatures above 600 deg C and can be completed in minutes; however, this process produces higher ratios of oil and syngas and less biochar (Thomas & Gale, 2015).

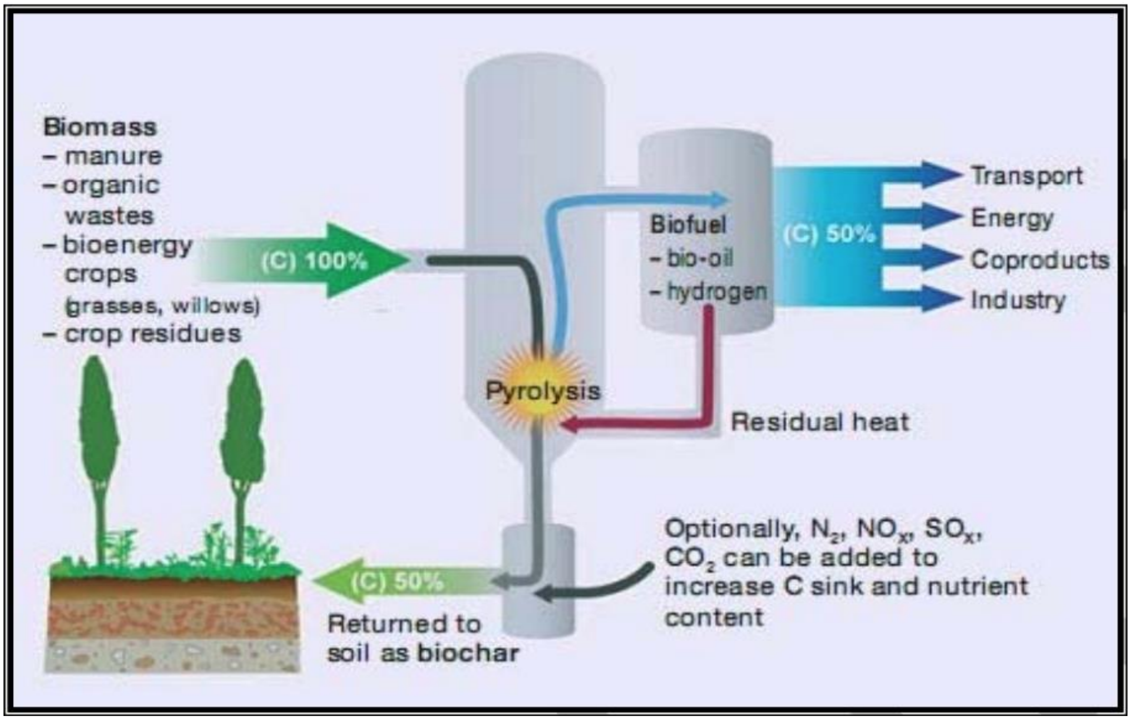

Figure 4. An overview of the pyrolysis process (Baranick et al., 2011).

Pyrolysis of biomass produces two additional byproducts: syngas and bio oil. Both byproducts can be used as fuel, providing clean, renewable energy. Syngas is a mixture of hydrogen, carbon dioxide, carbon monoxide, and hydrocarbons. The primary application of syngas is as an input in the pyrolysis process, either as a heating source in the drying process or in the kiln itself. Depending on the climate and geographical location, biomass typically has to be dried in order to reduce the water content, as biomass with greater than 20% water content is difficult to create biochar (Glover, 2009).

Therefore, this syngas byproduct can become an essential piece of the pyrolysis process. Furthermore, syngas does not have to be processed or refined before reusing, thus creating yet another advantage of this byproduct. Many kilns are able to capture the syngas and immediately reuse the byproduct as an input into the process, and as a result the production of biochar is a closed-loop process. Excess syngas that is not reused in the pyrolysis process can be sold, which can be used to generate electricity or as a low-grade fuel in boilers or cooking stoves.

The production of bio oil is not as beneficial as syngas, as the oil must be refined before using. The oil can be used as a standalone product; however, the emissions can be heavy in particulates and black carbon. Therefore, it is best practice to upgrade the oil to biodiesel, which can then be used as a fuel for transportation (Glover, 2009). This application can be very beneficial, especially when the biochar production process requires delivering the feedstock to a central processing plant or if the biomass product is exported. This oil byproduct contains approximately 55% of the energy content by volume as diesel fuel (Sorenson, 2010).

Biochar can also be pelletized, in which the primary application is to be used as residential or commercial energy production. This pelletized biochar can be used as either a direct heat source or as an input to produce steam for electricity. Biochar pellets are advantageous in that the overall density is increased, thereby reducing transportation costs (Blackwell et al., 2009). The pelleting process takes place after pyrolysis and requires a pellet mill or press, along with a series of steps depending upon the size and amount of substrate (Pellet mill, 2009). Before a mill can be used, woody substrates should pass through a woodchipper and a "hammer mill" in order to create smaller pieces.

Pellet mills are varied in their design and size, with larger engines necessary for commercial processes (Pellet mill, 2009).

Production Technologies

Technology allowing for up-scaling and creation of commercial biochar production has been developed over the last few decades, but up until recently biochar production has been confined to small-scale production, as the market for biochar has been small and slow to grow. Most current users of biochar have been proponents of sustainable agriculture, who tend to favor locally sourced inputs and purchase on small scales (Sorenson, 2010).

Trade organizations such as the International Biochar Initiative, the U.S. Biochar Initiative, and others have been critical in paving the way for increases in the use of biochar through collaboration, legislation, and education. Land agencies such as the U.S. Forest Service and Bureau of Land Management have begun to explore this potential as a way to help manage forested lands (Page-Dumrose & Anderson, 2012). Finally, a larger emphasis on forest health and carbon sequestration as a way to combat climate change has caused biochar to be viewed as a powerful tool in that fight (DeLuca & Aplet, 2008).

Soil Amendment

The current primary application of biochar is use as a soil amendment in agriculture. Biochar can either be applied directly to agricultural crops or used as a supplement in fertilizer or compost (Laird, 2009). When used as a supplement to fertilizer or compost, biochar can reduce the inputs of these products by 30% (Blackwell et al., 2009). Biochar does not have to be limited to conventional agriculture. It can serve just as well of a purpose being applied back to the forests and landscapes that the organic material is initially taken from (Wilson, 2013).

Biochar has an extremely high surface area – a gram of biochar can have approximately 25 square meters of surface area (Figure 5) (Masiello et al., 2015). As a result of this high surface area, biochar acts as a “carrier” that can hold and retrain nutrients within its porous structure. Therefore, when biochar is mixed with a fertilizer or compost it has the ability to store nutrients in the ground for longer periods of time, thus reducing the future annual applications of fertilizer or compost (DeLuca, 2009). Reducing the quantity of fertilizer used in agricultural operations has enormous benefits as the fertilizer emissions can often produce detrimental effects of the surrounding ecosystem (Page-Dumrose, 2015).

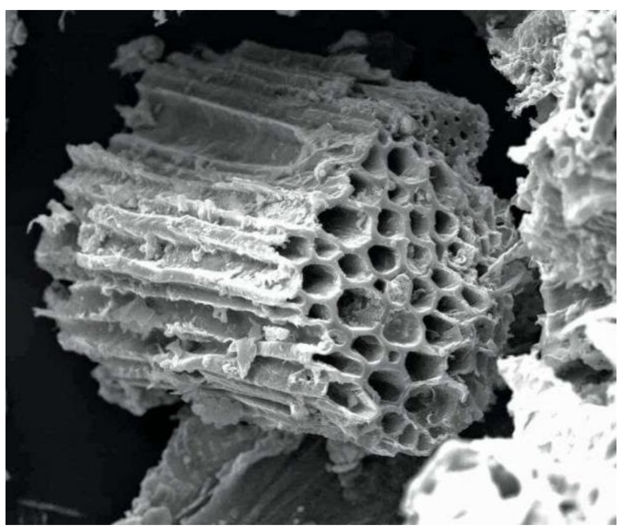

Figure 5. Porous structure of biochar (Farrell, 2013).

Another benefit of biochar when used in the agricultural industry is its ability to capture nitrogen and methane. High levels of nitrogen in the ground are problematic in that it can leach into nearby groundwater. With regard to methane, one of the leading causes of global warming, biochar is able to sequester this gas and restrict its ability to enter the atmosphere (DeLuca & Aplet, 2008). Additionally, biochar is also able to stimulate mycorrhizal fungi colonization, which has the capacity to deliver nutrients, especially phosphorus, to plants for increased nutrient uptake and root growth (Blackwell, Collins, & Riethmuller, 2009).

Finally, biochar used as a soil amendment can also increase water retention. Like nutrients, water is attracted to biochar's high surface area and porous structure. Biochar can therefore offer protection from extreme precipitation events, which have become more prevalent and likely to increase due to climate change (Farrell, Kuhn, Macdonald, Maddern, & Murphy, 2013). Biochar can absorb more water and can do it faster during high-volume precipitation events. During these events, depleted soils often lack the ability to absorb the rain as fast as it falls, leaving most of it to drain to nearby creeks, streams, and rivers taking vital soil and nutrients with it (Gomez, Denel, Stewart, Zheng, & Cotrufo, 2013). Soils with biochar incorporated into them will be able to absorb more of the moisture during these events.

On the other hand, biochar can offer protection during drought conditions by reducing the amount of water needed for agricultural lands, and by increasing retention of moisture (Masiello, 2015). With rising costs and demand of water – a direct result of the world's diminishing supply of freshwater resources – amending biochar in soils can reduce utility costs for agricultural operations. Lastly, when irrigation systems are used during drier periods, many farmers tend to overwater their fields, which can cause nutrients and fertilizers to leave the soil, contributing to agricultural runoff (Lehman et al., 2011). When using biochar as a soil amendment, it is best to incorporate the char using mechanical machinery, as the biochar is most effective when applied at plant root depths. Alternatively, the biochar can be placed in pre-tilled soil; however, this incorporation method is less desirable as it may increase soil disturbance and decrease the overall biochar coverage (Blackwell, 2009). The amount of biochar that is necessary to significantly alter the soil density and nutrient levels is dependent upon the existing soil condition, and researchers have yet to agree on a set of standards regarding soil types. However, experiments have shown that there is a positive correlation between the amount of biochar applied and the resulting increase in the nutritional and water retention characteristics of the soil. For instance, in an experiment on plots of savannah terra preta soils in Columbia, biochar was added by varying amounts per hectare of soil (0, 8 and 20 tons), with the most significant increases in nutrient retention occurring at the 20-tons/hectare scenario (Major, 2009). Furthermore, in an experiment with typical midwestern soils from the U.S., biochar was tested in an isolated container in the amounts of 0, 5, 10 and 20 grams per one kg of soil (Laird, 2009). The results indicated that the 20 g biochar scenario raised the soil's pH by 1 unit, while also increasing its water retention potential by 15% (Laird, 2009).

Carbon Credits

Biochar also has the potential for participating in the very lucrative carbon offset market in the future. The carbon-offset market is divided into two distinct segments: a compliance market and a voluntary market. A compliance market is utilized by companies that purchase carbon credits in order to comply with mandatory emissions caps. Conversely, carbon offsets in a voluntary market are typically purchased by governments, NGOs, individuals, or even environmentally conscious businesses that do so in order to reduce carbon emissions (Sorenson, 2010). Biochar is currently not recognized as an official method of producing carbon credits, although many researchers believe its entry into the carbon credit market is imminent (Wilson, 2013). For this reason, the selling of carbon credits from biochar production will not be further explored in this feasibility study but may have an impact on future viability.

Roaring Fork Valley Watershed

The Roaring Fork Valley watershed is located in Western Colorado, approximately 150 miles west of Denver, and 80 miles east of Grand Junction, Colorado (Figure 6). Located North and East of the Elk Mountains, and West of the Sawatch Mountains, the watershed has a population of approximately 32,000 and includes the cities and towns of Aspen, Snowmass Village, Basalt, Carbondale, Glenwood Springs, Marble, and Redstone. The watershed ranges in elevation from 14,200 feet at the top of Castle Peak near Aspen to 5,500 feet in downtown Glenwood Springs (US Census Bureau, 2019).

The watershed is made up of three rivers; the Roaring Fork, the Fryingpan, and the Crystal and is located within parts of Pitkin, Eagle, Garfield, and Gunnison counties (Figure 7). The Roaring Fork River is the larger river in the watershed, traversing the entire length of the valley, it drains into the Colorado River in Glenwood Springs. The Fryingpan River and Crystal River are both tributaries of the Roaring Fork. All three rivers start at high elevations in federally protected wilderness areas. The valley floor

Figure 6. Location of Roaring Fork Valley in Colorado (Google, n.d.).

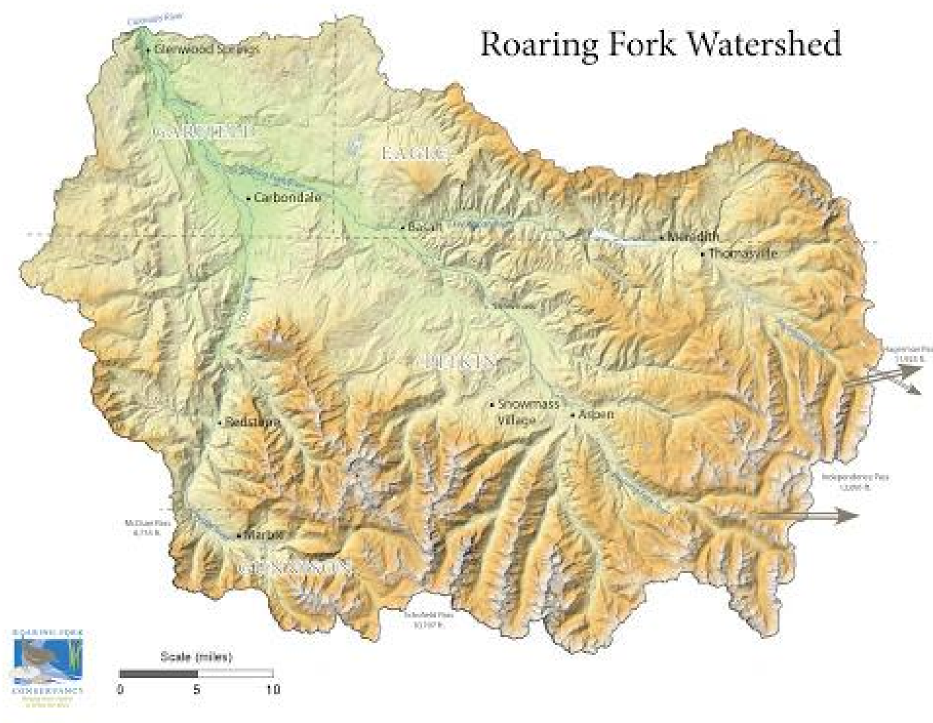

Figure 7. The Roaring Fork Watershed (Roaring Fork Conservancy, 2019).

is largely privately owned, while the surrounding areas are forested public lands mostly managed by either the USFS or the BLM. 80% of the valley is rural. The primary industry is recreation and tourism, while agriculture and ranching still predominate in lower elevations of the watershed, and in the surrounding watersheds (US Census Bureau, 2019).

The Roaring Fork Watershed has an abundance of feedstock sources available and a high degree of sustainably oriented agriculture operations that could potentially be interested in biochar, making this valley an ideal location for this research. This can help answer long term questions surrounding biochar such as the impact on soil runoff from agriculture. The Colorado River, of which the Roaring Fork River is a tributary, suffers from runoff that hampers downstream ecosystems. Using biochar as a soil amendment in the Roaring Fork Valley may be able to decrease the amount of agricultural runoff in the watershed.

Furthermore, Ponderosa Pine, Douglas Fir, Blue Spruce, and Engelmann Spruce trees, all abundant feedstock within the Roaring Fork Watershed, can produce relatively high pH biochar (Gundale & DeLuca, 2006). Biochar with higher pH levels increases the char's electrical charge and can therefore attract even more nutrients, greatly improving the soil's health (DeLuca, 2009).

Research Questions and Hypotheses

My primary research questions were: Can biochar be incorporated with existing fuel treatment projects to help improve forest health, sequester carbon, and eliminate negative consequences that currently exist with the disposal of slash? And further, is the incorporation of biochar production in fuel treatment projects in Colorado forests a financially viable alternative to disposing of slash in slash pile burning, if evaluated as an investment over time?

In addressing these questions, I examined these specific hypotheses:

- A social appraisal of the use of biochar to dispose of slash instead of open burning produces significantly greater sustainability benefits, including a measurable reduction in greenhouse gas contributions.
- An enterprise financial appraisal will show that the conversion of slash to biochar is more financially viable than open burning.
- Commercial biochar can be an important tool in combating rising carbon dioxide levels in the atmosphere.

Specific Aims

My specific aims for completing this research were to:

1. Develop a business spreadsheet appraisal to differentiate fuel treatment projects, over time
2. Estimate variables and construct scenarios to make comparisons based on relevant data sources
3. Establish the conditions (the numeric values for specific variables) under which slash conversion to biochar is more financially viable than open burning of slash
4. Use a financial spreadsheet model to identify the environmental impacts made by slash pile burning and compare them with those made by slash conversion to biochar

5. Quantify, if possible, the relative impact of slash pile burning and biochar conversion on forest health, ecosystem services, and human health
6. Evaluate the overall sustainability benefits of using converting slash to biochar instead of open burning of slash piles.

Chapter II

Methods

An initial technical analysis estimated the operational logistics, market prices, and production costs that would determine the profitability of a biochar conversion operation that employs the conversion of existing slash. This information informed a financial appraisal of a hypothetical biochar business. Sensitivity studies were conducted for optimal firm size and the effect of price and transport distance on profitability. A final economic analysis was performed in order to determine the overall benefit of generating biochar toward the goal of improving forest health and reducing greenhouse gas emissions.

Operational Logistics

Fuel treatment and forest management projects that create slash would not change due to the inclusion of biochar production. As is, most fuel treatment projects are contracted out to private companies. These contracts stipulate that upon completion of a project leftover slash needs to be piled. Disposal of slash is not part of these contracts and is instead conducted by USFS employees. Freshly cut slash has a high moisture content that prevents it from burning efficiently. Therefore, slash is left to dry in piles for anywhere between three and twenty-four months before it is burned (Figure 8). Since the only variables relevant to my analysis are what occurs to the slash after it has dried I did not examine the process of how fuel treatments are conducted, only the difference in how to dispose of the slash.

Figure 8. Typical slash piles (Evans, 2011).

Due to the mountainous landscape, sensitive habitats, and the small diameter of the majority of slash, I determined that the ideal hypothetical chipping operation would utilize heavy equipment and hand labor. The preferred operation consists of ground crews gathering slash by hand and delivering them to the chipper, which would be located on a road as close to the pile as possible. Ground crews of three individuals would be organized into work teams where the team members pull, haul and deliver the slash to the chipper. Wheeled skid-steer loaders would help transport the slash from the piles to the chipper and may be able to access the piles directly depending on the site (Figure 9).

A set out truck, operated by a frontline supervisor, stages the chipper and chip trailers so that slash chipping may continue with minimal interruptions. When full, the set out truck would move the chipped slash to the biochar kiln, which would be centrally

Figure 9. Wheeled skid steer (Caterpillar, 2019).

located relative to the slash in an area large enough for its size. Chipped slash is then processed through a drying machine where excess moisture will be removed. If the chipped material has too high of a moisture content, it will decrease the efficiency of the kiln.

The energy for the dryer would be generated by the kiln through capture of heat energy by a genset. The purpose of a genset is to capture heat capacity into mechanical energy, which it then converts into electrical energy (Figure 10).

Figure 10. Heat capacity to electric genset (Caterpillar, 2019) .

The conversion process is a self-contained energy loop. The biochar kiln must be ignited by a propane torch at the beginning of each day, but once lit it would produce the heat that would be used by the genset to generate electricity. The electricity would power the dryer and provide auxiliary power to the kiln.

The biochar kiln, designed and manufactured by Biochar Solutions Inc. (BSI), would combust the dried slash chips, burning away any remaining moisture and chemicals. At this point the remaining solid material would be about 80% carbon and classified as biochar. The biochar would be removed from the kiln by a conveyer belt and can be deposited directly into a trailer (Figure 11).

Figure 11. Biochar Solutions Inc. kiln (Biochar Solutions, 2019).

Once full, the tractor unit would pull the trailer to either a delivery location, or a centralized holding area where the biochar can go into short-term storage until buyers are ready for delivery.

The conversion operation will occasionally need to be moved to different locations based on the availability of slash. The tractor and trailer would be used to move the operation.

Chipping, conversion, and transport operations were considered as separate production systems in order to identify the critical functions and bottlenecks in productivity (Table 1).

Table 1. Production systems, personnel, and their associated equipment types.

Chipping System		Conversion System		Transport System	
Equipment	Personnel	Equipment	Personnel	Equipment	Personnel
Set out truck	1	BSI kiln	1	Tractor unit	1
Chipper	3	Genset	1	Trailer	0
Skidder	1	Dryer	0		

Market Price Considerations

Existing markets for bulk quantities of biochar are few and under-developed. Most current uses for biochar involve the agriculture industry. When used as an additive for soils, bulk quantities of biochar, which reduce to one-inch length or less during the conversion process, can be applied directly to soils without further processing.

Universal standards for biochar are still in development, and because the market is highly fragmented, the price of biochar has wide fluctuations. Biochar price was estimated by crowdsourcing other producers of bulk biochar throughout the United

States. The price of bulk biochar ranged from $300 ($/US t) to $5,000 ($/US t). Most models were estimated to sell at the median price of $5000 ($/US t) (USBI, 2019). Prices are recorded in US dollars per US ton (US t) (Timmons, Lema-Driscoll, & Uddin, 2017). When necessary, biochar commodity price ($/US t) was multiplied by the constant 1.10231 to convert to U.S. dollars per metric ton ($/M t).

Production System Costs

The ideal organizational structure for a biochar operation reflected typical crew sizes and equipment utilized in woody biomass harvest operations for fuel or bioenergy applications (Keefe, Anderson, Hogland, & Muhlenfeld, 2014). Production costs were determined according to the "machine rate" method for cost estimation of logging operations (USFS, 2017; Miyata, 1980). Separate machine rates (MR) were calculated for each equipment type as the sum of fixed, variable and labor costs described as a dollar value cost per hour of equipment operation. Fixed costs, or ownership costs, accumulate with the passage of time, rather than rate of work (FAO, 1992). Operating costs are the variable costs associated with running each piece of equipment. Labor costs are additional variable costs that describe the costs required to keep machine operators on the job (Miyata, 1980). Once determined, equipment machine rates were totaled for each system and divided by the system production rate (US t/PMH) to determine the cost of production ($/US t) for each type of equipment (USFS, 2017). The summary table outlines the comprehensive production system cost calculations (Table 2).

Table 2. Comprehensive production system costs.

Preliminary Data	Conversion System			Chipping System			Transport System	
Equipment Variables	BSI kiln	Dryer	Genset	Setout truck	Skidder	Chipper	Tractor	Trailer
Scheduled Machine Hour (SMH)	2000	2000	2000	2000	2000	2000	2000	2000
Utilization Rate	50%	50%	50%	75%	80%	80%	75%	100%
Productive Machine Hour (PMH)	1000	1000	1000	1500	1600	1600	1500	2000
Retail Price	$340,000	$45,000	$35,000	$40,305	$70,000	$50,000	$125,000	$4,738
Sales Tax	7.75%	7.75%	7.75%	7.75%	7.75%	7.75%	7.75%	7.75%
Salvage Value	$73,270	$9,697	$7,542	$8,724	$15,128	$10,804	$27,166	$6,769
Economic Life (yr)	10	25	18	8	10	10	15	10
Initial Equipment Investment	$366,350	$48,487	$37,712	$43,624	$75,641	$54,021	$135,831	$33,845
Average Annual Investment	$51,289	$5,624	$4,609	$6,543	$10,589	$7,562	$17,205	$4,738
Depreciation	$29,308	$1,551	$1,676	$4,362	$6,051	$4,321	$7,244	$2,707
Interest	$4,103	$449	$368	$523	$847	$605	$1,376	$379
Insurance & Property Tax	$3,590	$393	$322	$458	$741	$529	$1,204	$331
Yearly Ownership Cost	$37,001	$2,395	$2,367	$5,344	$7,639	$5,456	$9,825	$3,418
Tire Cost ($)				$196	$216	$146	$1,144	$915
M&R Rate	75%	75%	75%	75%	100%	100%	75%	25%
M&R Cost	$21.98	$1.16	$1.26	$2.18	$3.78	$2.70	$3.62	$0.34
Consumption Rate (gal/hr)				0.65	2.8	2	6.7	
Consumption Rate (mpg)				15.5			15.5	
Average Speed (mph)				10			40	
Fuel Cost			$2,946	$14,873	$10,624	$33,366		
Lubricant Cost			$1,090	$5,503	$3,930	$12,345		
Operating Cost $/SMH	$117.67	$49.01	$1.26	$54.75	$50.57	$101.51	$72.20	$0.34
Crew Size	2	1	0	1	1	3	1	0
Wages & Benefits	$23.92	$23.92		$37.41	$27.24	$23.92	$28.58	
Operating Cost ($/PMH)	$154.67	$51.40	$3.62	$58.31	$55.35	$104.92	$78.75	$2.05

Preliminary Data

Specific determinations and assumptions were made about the hypothetical biochar production systems in order to calculate equipment and labor costs. Annual work time, referred to as scheduled machine hours (SMH), was determined by calculating the total number of working hours outside of winter conditions that would prevent access to the work sites (Table 3).

Table 3. Presumed snow free access to work sites from May 1st – December 15th. Federal holidays. (U.S. Postal Service, 2019).

	Calendar days	Weekend days	Holidays	Work days
May	31	8	1	22
June	30	10	0	20
July	31	8	1	22
August	31	9	0	22
September	30	9	1	20
October	31	8	1	22
November	30	9	2	19
December	15	5	0	10
Total				157

All operations worked standard 8-hour days. Work hours (SMH) were further divided into productive and nonproductive time (Wenger, 1984). Productive machine hours (PMH) are defined as the time spent by a machine performing its primary task as well as time spent on support activities, such as refueling or loading and unloading trailers. Nonproductive time was assumed to include delays such as scheduled and unscheduled maintenance or a halt in production due to management issues such as bottlenecks in production caused by mismatched equipment processing speeds (Wegner, 1984). The ratio of productive time to scheduled time is utilization. Average utilization rates (UR) were taken from Brinker, Kinard, Rummer, & Lanford (2002) for the chipping systems. The transport system UR was set at 50%, determined by dividing the drive hours per day into the total transport shift length. Equipment UR was multiplied by the annual SMH in order to determine the annual productive machine hours for each equipment type (Table 4).

Table 4. Annual maximum productive machine hours (PMH) per equipment type.

Equipment	SMH	UR	PMH
BSI kiln	2500	50%	1250
Dryer	2500	50%	1250
Genset	2500	50%	1250
Set out truck	2500	75%	1875
Skidder	2500	65%	1625
Chipper	2500	80%	2000
Truck	1250	50%	625
Trailer	2500	100%	2500

The initial investment for each piece of equipment was calculated as the retail price plus sales tax, minus the cost of tires (Table 5). Equipment list prices were obtained from dealers and manufacturers during the fall of 2019. All equipment was assumed to be purchased within the study area in Colorado. Sales tax was estimated as 8.25%: the

Table 5. Initial investment per unit by equipment type (Caterpillar 2019; Kelly Blue Book 2019; Jackson et al., 2010).

Equipment	Retail Price	Sales Tax	Tire Cost	Total
BSI kiln	$340,000	$26,350	-	$366,350
Dryer	$45,000	$3,487	-	$48,487
Genset	$35,000	$2,712	-	$37,712
Set out truck	$37,305	$2,891	$49	$40,245
Skidder	$175,000	$13,562	$216	$188,778
Chipper	$250,000	$19,375	$146	$269,521
Truck	$125,000	$9,687	$1,144	$135,831
Trailer	$30,561	$2,601	$915	$34,077

average sales tax rate among all counties within the study area (Walczak & Drenkard, 2019). Annual tire costs are variable, dependent upon use of equipment, and were therefore subtracted from the initial investment. Initial equipment investment costs ranged from $30,561 for a trailer up to $340,000 for a BSI biochar kiln.

The preliminary estimates required to determine equipment costs included the initial investment, salvage values, equipment life, and average annual investment (Table 6). Salvage values were described as the dollar amount that equipment can be sold for at the time of disposal (Miyata, 1980). All salvages values were estimated as 20% of purchase price (Brinker, Kinard, Rummer, & Lanford, 2002). Economic life estimates, in years, were determined by dividing useful life hours specified by the manufacturer by the annual scheduled machine hours (SMH) for the entire operation (Caterpillar, 2019). An average annual investment value (AAI) was determined for each equipment type in order to estimate insurance and taxes (Bushman, 1988). AAI was calculated as follows:

$$AAI = \frac{(P - S)(N + 1)}{(2N) + S}$$

where P = initial investment; S = salvage value; & N = economic life in years.

Table 6. Preliminary data for equipment machine rate estimation.

Equipment	Initial Investment	Salvage Value	Economic Life (yrs)	AAI
BSI kiln	$366,350	$146,540	10	$21,981
Dryer	$48,487	$19,395	25	$1,163
Genset	$37,712	$15,085	18	$1,257
Set out truck	$40,245	$8,049	8	$4,024
Skidder	$188,778	$37,755	5	$30,204
Chipper	$269,521	$53,904	5	$43,123
Truck	$135,831	$27,166	15	$7,244
Trailer	$30,077	$6,769	10	$2,966

Ownership Costs

Fixed ownership costs were calculated as the sum of interest, insurance, taxes, and depreciation (Table 7). Interest is defined as the rental amount charged by a lender for the use of money (Thuesen, Fabrycky, & Thuesen, 1977). An interest rate of 4%, annual percentage rate (APR) was selected as an estimate based upon the current average interest rate on a 30-year fixed mortgage (Bankrate, 2019). Equipment liability and comprehensive insurance coverage costs vary by locality, equipment type, and size of operation, but a standard 2.5% of AAI was used for estimation purposes (Miyata, 1980). An additional property tax rate of 2.5% of AAI was charged on heavy equipment, excluding pickup trucks (Miyata, 1980). Depreciation, defined as the reduction in value of a piece of equipment over time, was computed using a straight line methodology that assumes equipment value reduces at a constant rate for each year over its economic life (Miyata, 1980). This decline in value is not an "out-of-pocket" cost in the sense that a cash payment is made. It simply reflects a loss in value over time. Straight-line depreciation was calculated as follows:

$$\text{Depreciation } (D) = \frac{P - S}{N}$$

where P = initial investment; S = salvage value; and N = economic life in years.

Table 7. Annual ownership costs per unit by equipment type.

Equipment	Type	Interest	Insurance	Property Tax	Depreciation	Total
BSI kiln	Heavy	$4,103	$3,590	$3,590	$29,308	$40,591
Dryer	Heavy	$449	$393	$393	$1,551	$2,786
Genset	Heavy	$368	$322	$322	$1,676	$2,688
Set out truck	Light	$482	$422	-	$4,024	$4,928
Skidder	Heavy	$2,718	$1,189	$1,189	$30,204	$35,300
Chipper	Heavy	$3,881	$1,697	$1,697	$43,123	$50,398
Tractor	Heavy	$1,376	$602	$602	$7,244	$9,824
Trailer	Heavy	$415	$181	$181	$2,966	$3,743

Operating Costs

Equipment operating costs are variable costs that typically change in direct proportion to hours of operation or use (Miyata, 1980). Some operating costs, however, such as fuel consumption, can be within the control of the operator or owner. Total operating costs were determined as the sum of the costs of tires, fuel, lubricants and oil, and maintenance and repair. Annual tire costs, initially subtracted from initial equipment investment, were calculated as follows:

$$\textit{Tire Cost} = \frac{P_t \times Q \times PMH}{N_t}$$

where P_t = tire unit price; Q = tire quantity; PMH = productive machine hour; and N_t = tire life (Table 8).

Table 8. Tire costs per unit by equipment type.

Equipment	PMH	Unit Price	Quantity	Life (hrs)	Tire Cost
BSI kiln	1,250	-	-	-	-
Dryer	1,250	-	-	-	-
Genset	1,250	-	-	-	-
Set out truck	1,875	$175	4	3,000	$437
Skidder	1,625	$300	4	3,000	$648
Chipper	2,000	$175	4	3,000	$462
Tractor	625	$500	10	5,000	$625
Trailer	2,500	$500	8	5,000	$2,000

Fuel costs were determined by multiplying fuel price per gallon, fuel consumption rate and productive machine hours (Table 9). Light equipment was priced using gasoline while heavy equipment utilized diesel fuel. Fuel prices were taken from values published by the U.S. Energy Information Administration (2019) for the state of Colorado. Fuel consumption rate estimates were provided by equipment manufacturers (Caterpillar, 2019; Kelly Blue Book, 2019; Jackson et al., 2010). For the transportation system, fuel costs are a significant part of the machine rate, each tractor unit requiring roughly five times greater annual fuel expenses than every other piece of equipment. Lubricant costs included the cost of engine oil, hydraulic oil, and other lubricants and was estimated using a standard 36.8% percent of annual fuel costs (Brinker et al., 2002).

Table 9. Fuel costs per unit by equipment type.

Equipment	Fuel Type	Price ($/gal)	Consumption (gal/hr)	PMH	Fuel Cost	L & O Cost
Set out truck	Gasoline	$3.05	0.6	1,875	$3,683	$1,362
Skidder	Diesel	$3.32	2.8	1,625	$15,106	$5,589
Chipper	Diesel	$3.32	2.3	2,000	$15,272	$5,650
Tractor	Diesel	$3.32	6.7	625	$13,902	$5,143

Maintenance and repair (M&R) estimates were taken from Wenger (1984) as percentages of equipment depreciation (Table 10). Trailers were not assigned a value for maintenance and repair. All other equipment types ranged from 75% to 100% of depreciation for M&R costs.

Table 10. Annual maintenance and repair (M&R) costs per unit by equipment type.

Equipment	Depreciation	M&R (%)	M&R Cost
BSI kiln	$2,930	75%	$43,962
Dryer	$62	75%	$2,325
Genset	$93	75%	$2,512
Set out truck	$503	75%	$3,018
Skidder	$6,040	90%	$30,208
Chipper	$8,624	100%	$43,120
Tractor	$482	100%	$5,431
Trailer	$296	0%	$750

The trailer, lacking an engine, was not assigned estimates for fuel or lubricants. Only tire replacement costs of $915 per year were accounted for trailer operating costs. Total annual operating costs per equipment type were calculated as the sum of all aforementioned operating costs (Table 11).

Table 11. Annual operating costs per unit by equipment type.

Equipment	Tires	Fuel	L&O	M&R	Total
BSI kiln	-	-	-	$43,962	$43,962
Dryer	-	-	-	$2,325	$2,325
Genset	-	-	-	$2,512	$2,512
Set out truck	$437	$3,683	$1,362	$3,018	$8,500
Skidder	$648	$15,106	$5,589	$30,208	$51,551
Chipper	$462	$15,272	$5,650	$43,120	$64,504
Tractor	$625	$13,902	$5,143	$5,431	$25,101
Trailer	$2,000	-	-	$750	$2,750

Labor Costs

Labor costs are variable costs that were accounted separately from operating costs because employees were assumed to be paid for an entire workday regardless of whether or not specific pieces of equipment were operating at a given time. Employee wages, benefits, and labor burden were multiplied by the annual working hours (SMH) to calculate equipment labor costs (Table 12). Position title and wages were determined for each equipment type as described by the Bureau of Labor Statistics (2015) for the state of Colorado. Benefits and labor burden percentage were calculated as 48% of hourly wages (Stone, 2008).

Ground crew workers, operating chippers, moving biomass, and feeding the chipper, were given an hourly wage and benefit rate of $26.23. Equipment operators operating skid steers and performing in-field equipment troubleshooting received $29.87 in hourly wages and benefits. First-line supervisors, operating set out trucks and overseeing crew operations, earned $41.01 in hourly wages and benefits. Driver wages and benefits were $31.33 per hour (Bureau of Labor Statistics, 2015).

Table 12. Annual labor costs per unit by equipment type.

Equipment	Position	Wage	Benefits	Quantity	SMH	Total ($/yr)
BSI kiln	Equipment operator	$20.18	$9.69	1	2500	$74,675
Dryer	-	-	-	-	2500	-
Genset	-	-	-	-	2500	-
Set out truck	First-line supervisor	$27.71	$13.30	1	2500	$102,525
Skidder	Equipment operator	$20.18	$9.69	1	2500	$74,675
Chipper	Ground crew worker	$17.72	$8.51	2	2500	$131,150
Tractor	Driver	$21.17	$10.16	1	1250	$39,162
Trailer	-	-	-	-	2500	-

Total annual equipment costs per unit type were determined as the sum of ownership, labor, and operating costs (Table 13). An additional 10% indirect cost was added to each piece of equipment to account for miscellaneous expenses (USFS, 2017). The chipper, with two ground crew workers, had the highest annual per unit equipment cost at $131,150. The chipper, skidder, and set out truck had annual equipment costs of roughly $90,000, $60,000 and $45,000, respectively.

Table 13. Total annual equipment costs per unit by equipment type.

Equipment	Ownership	Operating	Labor	Indirect	Total
BSI kiln	$40,591	$43,962	$74,675	$21,981	$181,209
Dryer	$2,786	$2,325	-	$1,163	$6,274
Genset	$2,688	$2,512	-	$1,257	$6,457
Set out truck	$4,928	$8,500	$102,525	$4,024	$119,977
Skidder	$35,300	$51,551	$74,675	$30,204	$191,730
Chipper	$50,398	$64,504	$131,150	$43,123	$298,175
Tractor	$9,824	$25,101	$39,162	$7,244	$81,331
Trailer	$3,743	$2,750	-	$2,966	$9,459

Machine rates, describing the hourly costs of operating each type of equipment ($/hr), were calculated by dividing total annual equipment costs by annual productive machine hours (Table 14). The set-out truck, skidder, and chipper machine rates were

$224, $112, and $142 dollars per hour respectively.

Table 14. Machine rates for all equipment types in all production systems.

Equipment	Annual Cost	PMH	Machine Rate
BSI kiln	$181,209	1250	$144
Dryer	$6,274	1250	$5
Genset	$6,457	1250	$5
Set out truck	$119,977	1875	$63
Skidder	$191,730	1625	$117
Chipper	$298,175	2000	$149
Truck	$81,331	625	$130
Trailer	$9,459	2500	$3

Transport System Logistics

The optimum configuration for the transportation of bulk biochar is to use a flat bed trailer where the sacks of biochar can easily be loaded onto the trailer (Figure 6). The skidder will do loading of the trailer during downtime in the chipping process. Once full, the tractor connects to the trailer and delivers the biochar to its intended destinations.

Figure 12. Sacks of biochar loaded onto a flatbed trailer (Biochar Solutions, 2019).

Transport systems cost estimates were influenced by payload and cycle time. Payload was defined as the maximum amount of slash biomass that could be physically and legally hauled in a single trip. The cycle time was the total time it takes for a trailer to load at the kiln, drive to the intended destination, unload the biochar, and return to the kiln location.

Total transportation costs were determined by multiplying the available payloads by the cycle time to calculate the total required PMH for the area. Total PMH was then multiplied by the transportation system machine rate ($/PMH) to derive the total transportation cost. The profitable haul (PH) distance from the study area to the biochar kiln was calculated in order to determine the break-even point at which direct sale of biomass becomes profitable.

Maximum Payload

Colorado road transport laws limit the maximum size and weight of trucks (Table 15). The goal for the biomass transport system is to carry the maximum possible payload, either by weight or by volume, in order to minimize costs (Scion, 2009).

Table 15. Colorado legal weight and size limits (Colorado Vehicle Code, 1982).

Gross Vehicle Weight (lb)	80,000
Width (in)	102
Height (ft)	13
Straight truck (ft)	40
Tractor & Semi-Trailer (ft)	65

A transport vehicle is full when it either “bulks out” or “weighs out”. Bulking out is when the transport vehicle runs out of volume before maximum payload is reached.

Weighing out is when the vehicle reaches maximum payload before the truck is full (Scion, 2009). Whether a truck reaches maximum weight or maximum volume first depends on the bulk density of the material being transported. Maximum payload was determined by calculating the maximum payload by weight and maximum payload by volume and selecting the lesser of the two values. Parameters were defined in a set of relevant equations (Table 16).

Table 16. Parameters for determining transportation system maximum payload.

Item	Parameter
Maximum payload	MP
Maximum payload by weight	MP_W
Gross vehicle weight	GVW
Vehicle tare weight	W_T
Maximum payload by volume	MP_V
Volume of chip container	V
Bulk density of biochar	BMB

The maximum payload by weight (MPw) was calculated as follows. The legal maximum gross vehicle weight (GVW) in the state of Colorado is 40 US t (Colorado Vehicle Code, 1982). The estimated vehicle tare weight is 17.09 US t (Scion, 2009). Total maximum payload by weight was 22.91 US t. Maximum payload volume (MPv) was calculated as follows: The maximum trailer volume was estimated at 132 cubic yards (yd3) (Scion, 2009) (Table 17).

The payload also depended on the weight of biochar within a given volume, its bulk density. As a physical property, bulk density depends on many factors, including material composition, particle shape, particle size distribution, and moisture content

Table 17. Load space dimensions for possible truck configurations.

Truck Type	Truck				Trailer				Total V (yd^3)
	L (yd)	W (yd)	H (yd)	V (yd^3)	L (yd)	W (yd)	H (yd)	V (yd^3)	
Chip Small	6.3	2.5	2.5	40.2	10.4	2.5	2.5	65.8	106
Chip Large	6.3	2.6	3.1	49.9	10.4	2.6	3.1	81.8	132
Bin Small	6.1	2.5	2.5	38.8	9.1	2.5	2.5	57.5	96
Bin Large	6.1	2.5	3.0	45.5	9.1	2.5	3.0	67.5	113

L = length, W = width, H = height, & V = volume (Scion, 2009).

(Sokhanhanj et al., 2008). Maximum weight and maximum volume values were compared to determine maximum payload (MP):

$$MP_w = 22.91\ US\ t > 22.23\ US\ t = MP_v$$

The maximum chip van payload was limited by the lesser value of the maximum payload by volume, so was set at 22.23 US t per truck.

Distance to Biochar Kiln and to Consumers

Biochar kilns have a degree of portability that allows them to be set up in remote locations. Finished biochar is about 30% of the total mass processed, meaning finished biochar is more cost effective to move then slash chips based on volume alone. Biochar kilns should be centrally located in relation to where the source material is and should be set up within a 15-minute drive of the currently processed slash piles. Potential locations sites for mobile biochar kilns in the Roaring Fork Valley were identified using public data from the U.S. Forest Service (USFS, 2005).

Potential final destinations of bulk biochar were determined by picking areas with high concentrations of agricultural activity within a 550-mile round trip radius of the

Roaring Fork Valley, seeing as how these areas are current and future markets of biochar. Glenwood Springs, CO, the largest city in the Valley, and centrally located along transportation corridors, was considered to be the origin point for transportation systems. Estimated distances from hypothetical slash pile locations to possible kiln sites were determined using data from Google Maps (Google, n.d.) (Table 18).

Table 18. Estimated distances and cost of delivery to selected agricultural areas.

City	Round Trip Distance from Glenwood Springs, CO (Miles)	Cycle Time (PMH)	Cost of Delivery ($/Full Load)
Carbondale, CO	20	1	$ 174.17
Rifle, CO	54	2	$ 413.71
Meeker, CO	136	4	$ 958.14
Paonia, CO	142	4	$ 986.15
Fruita, CO	196	5	$ 1,319.06
Craig, CO	234	6	$ 1,577.27
Delta, CO	240	6	$ 1,605.28
Montrose, CO	280	7	$ 1,872.83
Vernal, UT	344	9	$ 2,333.23
Green River, UT	374	10	$ 2,554.09
Gunnison, CO	408	11	$ 2,793.62
Greeley, CO	432	11	$ 2,905.67
Alamosa, CO	444	12	$ 3,042.49
Rawlins, WY	468	12	$ 3,154.54
Pueblo, CO	490	13	$ 3,338.05
Cortez, CO	550	14	$ 3,698.97

Cycle Time

Transportation cycle time was calculated as the sum of loading, hauling, unloading, and return times. Parameters for cycle time calculations are listed in Table 19. Cycle time was expressed with the following equation:

$$t_C = 2(D/S) + t_L + t_U = 2(D/40) + 1.98$$

Haul and return times were determined by dividing distance to the biochar kiln by average travel speed (Assakkaf, 2003). Average travel speed for a loaded tractor-trailer was estimated at 40 mph (Ford Torrey & Murray, 2014).

Table 19. Parameters for transport system cycle time calculations.

Item	Parameter
Cycle time	t_C
Distance	D
Speed	S
Loading time	t_L
Chipper production rate	PR_C
Maximum payload	MP
Trailer hitch time	t_h
Unloading time	t_U
Dump time	t_D
Waiting time	t_W

Loading time was calculated as:

$$t_L = PR_C / MP + t_H = 34/22.23 + 0.17 = 1.70\ hrs$$

Unloading time was calculated as:

$$t_U = t_D \text{ x } t_W = 0.03 + 0.25 = 0.28\ hrs$$

The number of payloads of biochar was calculated by dividing total biomass by the maximum payload. Total transportation costs for each area were determined by multiplying the available payloads by the cycle time to derive the total required PMH for the area.

Optimum Firm Size

The optimal firm size of a company in a given industry is that which results in the lowest production costs per unit of output (Canbäck, 2002). The optimum firm size is achieved when the benefits from internal economies of scale, such as specialized equipment, are fully enjoyed without the negative aspects of company size, such as reduction in output and duplication of effort, yet beginning to accrue. The production rate for a forestry system composed of several machines is limited to the least productive function in the system (Stokes & Hartsough, 1993). Either increasing the quantity, the productivity, or the scheduled machine hours of the limiting function usually balance functions within the system. Balanced systems typically have the lowest cost (Stokes & Hartsough, 1993).

For a biochar production system, the production rate increases in a positive correlation with the ground crew size. If the slash feedstock is available, small increases in productivity could occur easily with additional crew members and large increases could occur with additional equipment. Conversion and transportation systems could meet the increased production through expansion of operating hours rather than increases in crew or equipment sizes.

A sensitivity analysis was conducted in order to determine the optimum firm size for slash conversion to biochar. Annual SMH was dictated by the maximum working days outside of the winter months when access to slash piles can occur and could not reliably be increased. The quantity of ground crewmembers in the chipping system was reduced as the total number of chipping teams increased (Table 20).

The chipper utilization rate was adjusted to the nearest 0.25% in order to most closely match the chipping system production rate. Production rates were estimated in US tons per hour (US t/PMH) according to various sources (Caterpillar, 2019; Pitts Enterprises, Inc., 2013; Smidt & Mitchell, 2014).

The chipper productivity was estimated at 30 metric tons per PMH with an annual maximum production of 19,246 mt (Smidt & Mitchell, 2014). Chipping system machine rates were calculated as the equipment and labor costs for each firm size. The chipping system machine rate was calculated as the sum of the costs for all chippers and set-out trucks, added together along with a single skidder. The chipping system contained a single chipper at variable utilization rates added to the machine rate for a single setout truck.

Table 20. Annual production (US t) of Biochar at variable firm sizes.

Chipper Quantity	1	2	3
Work Crew Size	5	4	3
Chipper UR	11%	22%	32%
Annual Slash Processing	40,000	80,000	120,000

The transport system cost per metric ton of output was determined by configuring the annual transport cost at the various biochar output rates for the three variable firm sizes. Each tractor-unit had a maximum annual PMH of 1,144 hours. The number of trucks required to transport the annual harvest was determined by subtracting an individual tractor-unit PMH from the available annual PMH in each county. The remainder determined the extent to which additional trucks would be required to haul the harvested biomass in each county. Annual transport cost was calculated as the tractor-unit machine rate multiplied by the number of tractor-units required for biomass transport as:

$$Annual\ Transport\ Cost = (T_{MR} \text{ x } Q_T) \text{ x } (P \text{ x } t_C)$$

where T_{MR} = Tractor-unit machine rate; Q_T = required tractor quantity; P = payloads; and t_c = transport cycle time.

Transport costs were calculated assuming biochar outputs for each of the three variable firm sizes($/mt). Finally, the production rates of the chipping and transport systems were added to determine the overall optimal firm size.

Economic Appraisal

An economic appraisal for different transport distances within the study area was performed in order to determine the profitability of converting slash into biochar for sale. The cost-effectiveness analysis (CEA) approach was followed in order to determine the distances within the study area where biochar output per dollar spent is maximized. Total costs were the sum of chipping, conversion, and transport system costs at the respective optimal firm size for various distances. These costs were added to business-as-usual calculations of carbon dioxide (CO2) emissions.

Business-as-usual CO2 emission costs were estimated with the US Environmental Protection Agency (EPA) (2018) figure of 80% carbon release for every metric ton burned. The recalcitrant portion of biochar carbon was estimate at 97%. When carbon (C) needed to be converted to CO2 it was multiplied by a factor of 3.6667 to compensate for the addition of oxygen molecules. CO2 emissions were priced using the Intergovernmental Panel on Climate Change (2019) median figure of $40 per metric ton of CO2 ($/mt CO2) (Table 21).

Slash chipping, conversion, and biochar transportation system machine rates were not included in business-as-usual, since those actions are not taken in that scenario.

Table 21. Environmental appraisal of slash burning and biochar conversion.

Slash Burning		Biochar Conversion	
Annual slash production	20,000	Annual slash production	20,000
Biochar yield	-		30%
Biochar production, US tons	-		6,000
Carbon content of biochar	-		79%
Recalcitrant portion biochar carbon			97%
Long-run carbon release, US tons	20,000		4,597
Long-run carbon sequestration, metric tons CO_2	73,334		16,858
Economic cost of released/sequestered CO_2	$2,933,360		-$674,350

Direct benefits were considered as the gross profit generated from the sale of biochar. Net profit for three hypothetical firms was calculated by subtracting system costs from gross profit. The three firms were a fully integrated field-to-char operation, a fully integrated system including carbon payment, and business-as-usual slash pile burning. Net profit for each firm was divided by total carbon emissions in order to derive a dollar value profit per ton of carbon removed.

The Effect of Distance on Profit Potential

A simple sensitivity analysis was conducted in order to determine the profitability of selling bulk biochar at variable prices and over different transport distances. Biochar price and transport distance variables were constrained by the maximum transport distance in the study area, 550 miles, and the subsequent range of chip prices required to generate a positive net profit. Net profit for each delivered payload was calculated 100 times as a partial derivative of ten hypothetical chip prices and 10 distance values. Chip price ranged from \$250 – \$2000 per US t of biochar and distance values ranged from 0 – 450 miles from the study area. Net profit was calculated according to specific parameters and equations (Table 22).

The formula for determining net profit was calculated as:

$$P_N = P_G - C_T$$

Gross profit was determined as:

$$P_G = B \text{ x } P_C$$

Total production cost was calculated as:

$$C_T = PC_H + PC_C + PC_T$$

Harvest system production rate was calculated as:

$$PC_H = B \times PR_H$$

Chipping system production rate was calculated as:

$$PC_C = B \times PR_C$$

Transport system production rate was calculated as:

$$PC_T = 2(D/40) + 1.98 \times PR_T$$

Table 22. Parameters for calculating profitability at variable stand densities and distances to biochar consumers (Nelson & McAvoy, 2013).

Parameter	Variable
Net Profit	P_N
Gross Profit	P_G
Payload (US t)	B
Biochar price ($/US t)	P_C
Total production cost	C_T
Conversion system production cost	PC_H
Conversion system average production rate	PR_H
Chipping system production cost	PC_C
Chipping system average production rate	PR_H
Transport system production cost	PC_T
Transport distance	D
Transport system average production rate	PR_T

Chapter III

Results

The main variable in profitability of a biochar enterprise using slash from the White River National Forest depends mostly on the market rate for finished biochar. Lesser limiting factors to profitability included the amount of slash material available, the firm size, and the transportation distance for moving finished biochar.

Hypothetical enterprises showed a high chance of profitability within the study area when potential taxes and subsidies on carbon were considered.

Biochar Market Price

If a stable price of $330 per oven dry US ton of finished biochar or higher can be attained, the business will be profitable in its third year of operation and will have positive cash flow upon completion of the ten-year projection (Table 23). This is true regardless of the firm size.

Table 23. Sensitivity of biochar pricing on cash flow.

Market Rate of Biochar	Cash flow in year 3 of operation.
$290	-$837,000
$300	-$593,000
$310	-$350,000
$320	-$106,000
$330	$136,000
$340	$380,000
$350	$624,000

Optimum Firm Size

Annual slash production on the White River National Forest is about 40,000 US/tons per year. Any changes to that would most likely be related to changes in the federal budget and not how efficient the biochar enterprise would be. Therefore, the best firm size for the study area was the one tailored to the current rate of 40,000 tons of slash, however hypothetical firm sizes that could accommodate 80,000 and 120,000 tons were also considered. If annual slash production increases, the largest firm size would be most profitable (Table 24).

Table 24. Benefits and costs of different firm sizes.

Firm Size (Tons of slash processed)	40,000	80,000	120,000
Direct Benefits	$2,801,000	$5,603,000	$8,405,000
Direct Costs	$2,476,000	$4,952,000	$7,428,000
10-year net revenue (Benefits – Costs)	$325,000	$651,000	$977,000

The optimal biochar enterprise consisted of a business that operated at the lowest cost per US tons of slash chipped, converted, and biochar transported. Chipping operations demonstrated the lowest cost at the firm size that most closely matched the chipper production rate. The smallest firm size, consisting four ground crew laborers, one skidder, one chipper, and a set-out truck had an annual cost of $188,000. The largest firm size, three separate chipping teams, had an annual cost of $298,000. The chipping system annual cost increased from $103,000 to $145,000 as the utilization rate for the chipper increased from 11% at the smallest firm size to 32% at the three-team firm size. The cumulative cost per ton of slash converted, however, decreased as the firm size increased. Chipping and conversion costs were lowest at the three-team firm size.

Transport system costs increased as the firm size, annual converted slash, and distance to consumers increased. The current processing rate of 40,000 tons per year requires only a single tractor-unit to haul the entire year's production of biochar. Processing rates of 80,000 tons or above, however, required increased numbers of trucks as annual biochar production increased with firm size. At the largest firm size, 120,000 tons per year, three tractor units would be needed.

Transport system production rates were lowest at the largest firm size. This is because a three-team system could harvest and process biomass at the lowest cost but only produced enough biomass to require a single tractor-unit. In the larger firm size where annual biochar production was largest, multiple tractor-units are needed to transport to the consumers, the lowest production rates were at the smallest firm size.

Cost Effectiveness of Biochar Conversion

Business-as-usual costs for slash burning were assumed to be $50 per US ton and includes the piling and burning of the material and all related personnel and equipment. At that cost, business-as-usual disposal of slash by pile burning in the study area is estimated at $2,000,000 annually.

When converting 40,000 tons of slash to biochar, the costs of conversion and transportation of finished biochar can be aggregated to a cost of $58 per ton of slash material, or $2,320,000 annually. There was no instance, utilizing the Wilson (2016) conversion cost estimate, where net benefit was positive compared to slash burning. In other words, biochar conversion and transportation more often cost more money per ton of slash disposed then slash burning. The net positive for biochar conversion occurs from the sale of finished biochar, carbon subsidies, or both. The least amount of financial risk for biochar operation exists when carbon subsidies are in place. If the same price for sequestering carbon were applied to releasing carbon from slash burning, there becomes a very clear financial incentive to prioritize biochar conversion over slash burning, netting $1,159,000 on 20,392 t/$CO_2$ sequestered emissions (Table 25).

Table 25. Net positives for biochar with and without subsidies.

	Direct Benefits without Carbon Subsidy (Annually)	Direct Benefits with Carbon Subsidy (Annually)	Direct Cost of Slash Burning with Carbon Tax (Annually)
Emissions Sequestered (Mt/CO_2)	20,392	20,392	-
Emissions Released (Mt/CO_2)	-	-	133,000
Value of carbon sequestered/emitted	-	$816,000	-$5,322,000
Benefits - Costs	$344,000	$1,159,000	-$5,322,000

The profitability of hypothetical enterprises revealed that biochar conversion displays true profit potential, especially compared to business-as-usual. Three configurations were used to determine cost of fuel treatments: business as usual, biochar conversion, and biochar conversion with carbon subsidy. Biochar conversion, regardless of firm size were profitable when supported by a high enough price for biochar. Biochar conversion with carbon subsidy needed a much smaller amount of guaranteed price for finished biochar. Finally, when a monetary amount is attached to the amount of carbon released from slash burning,

The Effect of Commodity Price and Distance on Transport Profitability

The profitable haul (PH) distance, the distance under which transporting biomass generates a profit, was found to be directly influenced by the market price of finished biochar (Table 26). At the biochar price of $350/US t, the PH distance is 545 miles. At the biochar price of $310/US t, the PH distance is 125 miles.

Table 26. Cost of delivery in sensitivity to distance.

City	Round Trip Distance from Glenwood Springs, CO (Miles)	Cycle Time (PMH)	Cost of Delivery ($/Full Load)
Carbondale, CO	20	1	$174
Rifle, CO	54	2	$413
Meeker, CO	136	4	$958
Paonia, CO	142	4	$986
Fruita, CO	196	5	$1,319
Craig, CO	234	6	$1,577
Delta, CO	240	6	$1,605
Montrose, CO	280	7	$1,872
Vernal, UT	344	9	$2,333
Green River, UT	374	10	$2,554
Gunnison, CO	408	11	$2,793
Greeley, CO	432	11	$2,905
Alamosa, CO	444	12	$3,042
Rawlins, WY	468	12	$3,151
Pueblo, CO	490	13	$3,338
Cortez, CO	550	14	$3,698

Chapter IV

Discussion

This study proposes optimized logistics and profitability of converting forestry slash to biochar to offset the costs of fuel treatments on the White River National Forest in Colorado. The $344,000 potential revenue generated by biochar conversion could be used to offset fuel treatment costs for the 40,000 acres modeled, leading to more treatments and an overall decrease in the amount of carbon released into the atmosphere. Although it is not expected to be as profitable, best management practices for operational logistics can be taken from other woody biomass harvesting operations within the forestry sector. The results indicated that the profit generated from biochar sales was usually enough to cover the cost of transport and conversion costs, and financial benefits could be used to offset fuel treatment costs to varying degrees. Utilizing machine rate and cost effectiveness analysis methodologies, similar studies could be conducted for other forest types.

Several assumptions in this study might lead to different results in real world situations. Business-as-usual disposal costs of $50 per ton were estimated utilizing rates from Wilson (2016). This figure was calculated as the mean value from previous biochar conversion projects. Due to the high variability in project sizes, costs, and scope, a wide variety of other estimates may occur.

A second set of critical assumptions has to do with the sale of biochar. First, although it is technically feasible to deliver entire loads of biochar to one location, there may likely be other barriers to delivering biochar, such as having multiple deliveries in each tractor load that may require more time for delivery.

Second, the international index price for biochar was used as the direct sale price for biochar. Consumers of biochar, however, could be unwilling to pay this price. Competition with forestry operations, which often harvest woody biomass residues as a secondary income to high-value logging, may reduce the dollar value per ton of biomass delivered to the mill (Keefe et al., 2014). An amendment in the 2018 Farm Bill, allocating for up to $144 per cubic yard of biochar applied to soils, may help subsidize biochar sales on the consumer end. The USDA's Natural Resource Conservation Service is still deliberating how to execute this amendment (Harrigan & Charney, 2019).

Further study would benefit from auditing real-world restoration projects to compare time standards. For instance, there are several variations of mechanized and ground labor work crews, each typically being specific to the site, the available funding, and contractor preference. Trials could compare the costs and productivity of several types of harvest operations to determine the optimal arrangement for a given set of parameters as well as providing more accurate machine rate estimates for future cost estimating.

There are also numerous different biochar kilns available that could meet the needs of this project with more being commercially produced every year. Different biochar kilns will have slightly different production rates and using different kilns could lead to better margins of profitability.

The very concept of creating a market out of forestry waste from national forests could draw criticism from conservation organizations. Opposition has existed in the past towards efforts by the USFS to encourage biochar production from its forests because of an idea that it would promote excessive removal of woody biomass from National Forest land more than what is needed.

This concern, while valid, is less of a threat than it may seem upon first consideration. Currently, private contractors are mostly used to remove woody biomass as part of fuel treatment projects and USFS employees are used for disposal of the slash piles. Should biochar conversion be considered, it would be most likely be conducted by an additional private contractor then who conducted the original fuel treatment, and there would be no direct benefit for the original contractor to remove more woody biomass then normal.

Conclusions

The White River National Forest needs active management to help build resiliency from insects, drought, and wildfire risk. Money for fuel treatments from the federal government helps, but the availability of money for these purposes is stagnant, not currently projected to increase, and is in not enough to keep up with the increasing demand for fuel management projects. This shortage negatively impacts biodiversity and threatens human infrastructure with increased fire risk and flood damage. Although a positive cost benefit ratio has been identified with biochar conversion under the right conditions, high variability in the market price for biochar currently prohibits biochar conversion of slash material on a commercial scale.

Subsidies to promote biochar through a credit on sequestered carbon would substantially reduce the current financial risks of biochar production. Subsidizing biochar could sequester a great deal of carbon in the ground for an extended amount of time. The expected benefits would be a decrease in the amount of GHG emissions in the atmosphere, an overall improvement of soil health, and the improvement of local and regional air quality.

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