

THESIS

OPTIMIZING BRUSH PILE DISPOSAL ON WESTERN USFS LAND

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Caleb E. Axlund

Department of Agricultural and Resource Economics

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Master's Committee:

Advisor: Jordan Suter

Daniel W. McCollum

Jude Bayham

Yu Wei

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ABSTRACT

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This research evaluates the social costs of burning piled biomass and the economic trade-offs of alternative removal strategies. Timber harvesting and forest thinning often leave behind branches and other tree parts, which are piled and burned, resulting in what are known as brush or slash piles. These piles pose significant costs to nearby communities and have global environmental impacts, including greenhouse gas (GHG) emissions and reduced local air quality (Wiedinmyer et al., 2006; Ganguly et al., 2018; Pierobon et al., 2022). The United States Forest Service (USFS) is testing a new device called the ‘Charboss’ that removes excess brush and repurposes it as biochar, a substance with potential environmental and agricultural benefits. Analyzing the external social costs of burning brush piles is crucial for assessing the economic viability of future brush removal strategies. By using social costs as a gauge, this study employs an optimization model to maximize benefits while minimizing the associated costs of this new forest management technology. Private investment and social planners’ perspectives are considered when determining optimal deployment strategies. This study examines various scenarios for deploying the USFS device cost-effectively and concludes that, under certain assumptions, it can significantly benefit local communities and global environmental health.

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Chapter 1

Introduction

Forests play a vital role in our ecosystem, serving as a source of lumber and a crucial component of environmental sustainability. Forest thinning is a silvicultural treatment that reduces biomass density to improve tree growth, enhance forest health, and provide economic benefits for wood products (Verschuyl et al., 2011; Helms, 1998). Forest thinning practices implemented by forest managers aid in mitigating drought stress (Sohn et al., 2016) and wildfire intensity (Banerjee, 2020), as well as enhancing overall forest health. Through these activities, large piles of excess brush form from the unwanted parts of the timber. Brush piles, which populate U.S. forests by the thousands, are a source of local and global externalities due to the long-standing practice of burning them.

Burning brush piles, also known as slash piles, can fuel wildfires, impact soil and water quality, and contribute to greenhouse gas (GHG) emissions and intense burn scars (Pierobon et al., 2022; Halpern et al., 2014). In addition to its contribution to climate change, smoke from biomass burning has the potential to impact local and regional air quality with distinct negative impacts on human health (Anenberg et al., 2012; Ganguly et al., 2018; Pierobon et al., 2018; Reisen et al., 2015).

As wildfires have become more prevalent and intensified in the past decade (Pausas and Keeley, 2021), wildfire mitigation strategies will need to be proactive in addressing the source of wildfire catalysts, and in many cases, this will require additional forest thinning. Producing wood products from forest thinning is possible; however, up to 60% of the harvested material remains on site (Parikka, 2004). Therefore, the societal costs of these slash-pile burns are critical considerations for future policymakers, forest managers, and timber manufacturers.

Wildfires are one of the most substantial sources of biomass burning and have been a point of focus in determining the impacts of smoke pollution on human health, (Reid et al., 2016). Although some papers attempt to identify the impact of brush pile burning on human health (Pierobon et al., 2022), no known literature attempts to quantify these damages as a social cost to society. Under-

standing these social costs can help policymakers determine appropriate resource allocation to the problem of slash disposal.

Brush piles remain on site for burning primarily due to the high cost of any other disposal method. The primary cost that limits alternative brush removal is the high cost of hauling and transporting biomass to processing facilities. Other costs include chipping and manufacturing the brush to create a viable product for the market, which can be done at a low-profit margin (Pierobon et al., 2022). There has yet to be a viable market mechanism for disposing of this additional slash economically. This lack of a market mechanism forces timber manufacturers and forest managers to absorb the cost of this disposal.

These issues have led the United States Forest Service (USFS) to cooperatively design, develop, and test a new device to consume the leftover brush. This device labeled the 'Charboss,' can consume brush and apply pyrolysis and 'air curtain' techniques to produce biochar, a lighter, more market-viable product. Biochar is a substance that has significant capabilities in carbon sequestration, soil replenishment, bioenergy, and fertilizing properties, as well as many other uses (Han et al., 2018; Galinato et al., 2011; Yadav and Ramakrishna, 2023).

Biochar is a product that has been used in history, with regions of the Amazon being treated with biochar more than 8000 years ago (Sohi et al., 2010). These Amazon sites still have dark soil due to high char content even after thousands of years, which results in these areas containing some of the most fertile soil in the world for various cash crops (Sohi et al., 2010). Yang et al. (2021) found that as much as 0.50 Pg of CO₂ ($1Pg = 1 \times 10^9t$) can be sequestered using biochar made just from crop residues, providing insight into the potential for using biochar as a carbon sequestration tactic. This allows biochar to combine carbon dioxide removal technology with significant agronomic and environmental co-benefits (Schmidt et al., 2021). Additionally, biochar could be an important component in the evolving 'carbon-sink' economy, potentially creating an economically feasible venture into biochar production (Yadav and Ramakrishna, 2023).

The 'Charboss' is a portable metal furnace designed to be deployed directly at timber harvest and forest thinning sites where brush piles accumulate. Its ability to consume multiple tons of

biomass on-site significantly reduces the volume and weight of material that needs to be transported afterward. This innovative device addresses many cost challenges forest managers and timber manufacturers face, potentially facilitating more efficient and cost-effective forest management. Understanding the trade-offs amongst different brush pile removal scenarios is a predominant concern when addressing optimal ‘Charboss’ deployment.



Figure 1.1: The ‘Charboss’ in action at a forest site

The social costs associated with brush pile burning must be estimated to determine where biochar production is most beneficial from a society’s perspective. Determining the social costs of slash pile burning in as many aspects as feasible is paramount to ensure a comprehensive analysis is applied for ‘Charboss’ deployment. This paper focuses on global costs in the form of GHG emissions and local costs in the form of PM_{2.5} air emissions. Examining brush pile data and the associated emissions profile of each pile helps establish the social costs of these pile burns for benefit-cost analysis of ‘Charboss’ usage.

This paper uses a case study on a specific forest, the Deschutes National Forest in Oregon, to comprehensively assess the impacts of brush pile burning on a local and global scale. This choice

was made due to the Forest's large number of piles and significant population nearby, which offer an ideal setting to assess the local and global costs associated with pile burning. Using a single year in a single forest, we investigate the entire profile of impacts resulting from the pile burns that took place that year and the populations affected.

This research aims to quantify the magnitude of the social costs derived from brush pile burning through GHG emissions and local air quality impairment. These measures are then used to determine where alternative slash disposal provides the most significant societal benefit. The revelation of these social costs leads to the penultimate research questions of this paper: What factors govern the viability of 'Charboss' utilization, what is the optimal number of 'Charboss' devices to deploy, and where does their deployment provide the most significant net social benefit?

Additional analyses are applied to determine what biochar pricing warrants private 'Charboss' investment under different deployment scenarios only when considering the profit potential of biochar sales. Similarly, if biochar is applied directly after being produced, what is the optimal 'Charboss' deployment decision when including both biochar's carbon sequestration potential and social cost mitigation as benefits? This research optimizes 'Charboss' deployment using methods similar to the well-known optimization scenario, the 'Traveling Salesman Problem¹.' Three central factors are considered: the spatial distribution and size of the brush piles, the feasibility of reaching the pile, and, most importantly, the social costs mitigated by deploying the 'Charboss.'

¹The traveling salesman problem considers a salesman whose goal is to use the shortest possible route that visits each city in a set of cities exactly once. Here, we are trying to determine a route that minimizes the travel distance and cost of deploying additional 'Charbosses'

Chapter 2

Background

Modern approaches to mitigate wildfires include forest thinning and timber harvesting to reduce fuel loads, resulting in additional brush piles (Agee and Johnson, 1988). Following this thinning or harvest, the excess slash is then piled, either by hand or machine, contributing to the varying composition of each pile of different fuel types and soil content. Mechanical piling typically leads to a greater soil level in each pile and is typical of timber harvesting. Hand piling, on the other hand, results in lower soil content of the pile and is typically the result of forest thinning practices (Hardy, 1996). These different compositions of brush and soil influence the volume of smoke and chemicals released (Sifford et al., 2016).

Brush pile burning contributes to making biomass burning the largest source of primary fine carbonaceous particles and the second largest source of trace gasses² in the global atmosphere (Akagi et al., 2011). As the global climate worsens, removing excess sources of greenhouse gas emissions and trace gasses is a chief concern in tackling these environmental threats.

To prevent more destructive wildfires, we must employ forest thinning to reduce fuel loads, remove understory ladder fuels, and reduce tree crowding and competition for water and nutrients (Agee and Skinner, 2005; Agee, 1993). This process requires sizeable workloads and offers little financial return besides reducing the risk of catastrophic wildfire (Sifford et al., 2016). This process provides the benefit of increased forest health and wildfire prevention strategies at the cost of increased brush production and subsequent brush pile burning. As wildfires continue to dominate the behavior of forest management practices and budgets, we must be conscious of the increased prevalence of brush pile burns alongside those practices.

The major challenge in alternative brush disposal methods is the economic and operational barriers, which include the costs of collecting, processing, and transporting a product with little

²Trace gases are gases in the Earth's atmosphere other than nitrogen, oxygen, and argon, which make up more than 99.9% of the global atmosphere.

market value (Han et al., 2002). Most timber production occurs in hard-to-reach areas, such as mountainous or deeply forested areas. Thus, transportation creates a significant barrier to efficient slash removal, resulting in forest managers and timber harvesters burning most piles. In a 2016 study, Bisson et al. found that the costs of collection of biomass can reach as much as \$31.25 per bone dry ton, with an additional \$13.91 per bone dry ton for transportation (Bisson et al., 2016).

In a U.S. Department of Energy-funded series of studies, researchers evaluated a composite analysis of the effects of slash pile production and subsequent burning and the feasibility of implementing biomass conversion technologies (Han et al., 2018). A critical finding of this research is that prescribed burning of woody biomass in forests is a significant source of air pollution (Sifford et al., 2016). While pile burning can be a controlled process and reduce larger-scale wildfires, the burning of piled biomass releases chemicals and particulate matter into the atmosphere, which can negatively impact local and regional air quality and further impact human health in local areas (Sifford et al., 2016; Schwartz, 1993; Dockery and Pope, 1994). These impacts can be of substantial cost to vulnerable or sensitive populations in the short term, such as those with asthma, the elderly, pregnant women, and children, and in the long term, can even increase hospital visits and premature death (Sifford et al., 2016).

Han et al. (2002) have found that un-merchantable brush and small-diameter trees can produce renewable bioenergy and bioproducts. The high transportation costs of forest residues hinder the effectuation of most attempts to convert biomass into marketable products. The four-year Department of Energy project provides a structural foundation for this research as they analyze various strategies to combat growing brush disposal issues. Their research concludes that among all the various biomass conversion technologies, the ones that produce biochar are the most likely candidates for transportable conversion, given their low power consumption, a wide range of acceptable feedstock size specifications, and low product transportation costs (Han et al., 2018). As an extension to Han et al. (2018), we examine the specific biomass conversion technology, the 'Charboss,' and assess its feasibility in a realistic implementation.

Despite the literature identifying several problems with slash pile burns, including greenhouse gas emissions and local air pollution (Pierobon et al., 2022; Halpern et al., 2014; Akagi et al., 2011), research monetizing the societal costs remains limited. This is a vital characteristic we consider in this research, as converting smoke emissions and their interactions with the population to a dollar amount allows for a benefit-cost analysis of integrating ‘Charboss’ deployment into brush pile management.

Chapter 3

Data and Methods

A central objective of this research is to understand the social costs of brush pile burning. This analysis leverages the brush pile database maintained by the USFS, which logs all brush piles formed by purchasers of National Forest timber. The dataset contains detailed information about the location, size, and characteristics of thousands of brush piles, including the exact harvest area, disposal method, date of pile creation and removal, and other relevant aspects.

In conjunction with this dataset, we utilize the BlueSky modeling framework (Larkin et al., 2009) to provide emission profiles and air quality measurements for each brush pile burn. Developed by the USFS and the University of Washington, the BlueSky Playground model estimates emissions ranging from GHGs such as carbon dioxide (CO_2) and methane (CH_4) to particulate matter generated from a prescribed burn or biomass combustion. The model also integrates the VSmoke model, which calculates the peak 24-hour concentration dispersion of $\text{PM}_{2.5}$ based on average wind speed and direction.

It is essential to incorporate all aspects contributing to pile emissions to comprehensively measure the social costs associated with an individual pile burn. This involves quantifying emissions and dispersion from the pile burns using the BlueSky model, determining air quality changes with the VSmoke framework, and assessing the interaction of these emissions dispersed with people using population data. These steps allow for estimating global costs from GHG emissions and local costs from shorter-lived emissions and smoke particulates.

The first step in assessing the social costs of a brush pile burn is to identify the emissions generated. Each data point in the brush pile dataset is assigned various attributes to uniquely identify each pile created, including a use code that categorizes the final method of pile removal. Only piles with use code 1130 are included in these calculations, as this code confirms that a burn has occurred. Emissions profiles are simulated using the BlueSky model by inputting the harvested acreage and the latitude and longitude of each pile location. Similar factors ensure consistency

across the data for fuel type, fuel moisture, consumption rate, and burn timing. Based on these characteristics, the model outputs an emission profile relative to the harvest size.

Following this, the VSmoke framework within BlueSky derives $PM_{2.5}$ concentrations based on given wind speed and direction. This model outputs peak hourly concentrations of specific gasses and particulate matter in a Google Earth file format. These output concentrations are then converted into shapefiles to be compatible with population analysis, enabling the determination of the affected populations associated with specific changes in $PM_{2.5}$ levels.

Finally, using the 'Gridded Population of the World' dataset (CIESIN - Columbia University, 2018), we estimate the number of people affected by $PM_{2.5}$ concentrations to infer further damages from these brush pile burns. This comprehensive approach provides both global costs from GHG emissions and local costs from particulate matter, allowing for the optimal integration of the 'Charboss' into brush pile management practices.

3.1 USFS - Brush Disposal Funded Activities

The USFS brush pile dataset is a free, regularly managed dataset provided by the USFS. It documents the location and characteristics of brush piles formed by all purchasers of National Forest timber. Due to this criteria, the data do not contain all brush disposal activities, notably missing information on piles formed in the eastern and southern parts of the U.S. The lack of data in the East is because most forest land on the eastern side of the U.S. is privately owned (Butler et al., 2016) and is therefore not tracked by the USFS. Similarly, these data will not include brush piles formed via mechanical thinning since forest managers would not be considered timber purchasers. However, this dataset does provide high-quality spatial data on the locations of each pile, its size in acres, and the date of disposal, all of which are used extensively in this analysis.

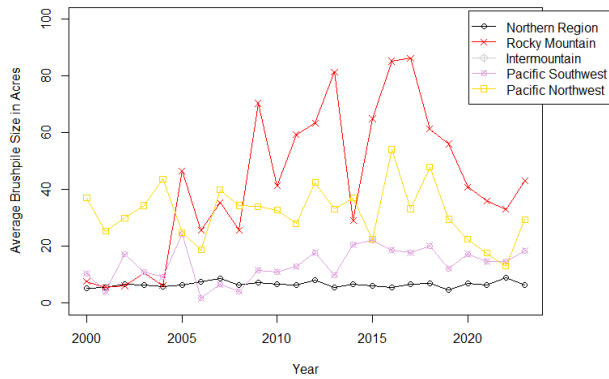
The USFS separates the U.S. into nine administrative regions for their internal analyses (no region 7). The dataset contains most piles in the U.S.'s Northern, Rocky Mountain, Intermountain, Pacific Southwest, and Pacific Northwestern regions. Since 2000, over 42,000 brush piles have been characterized with code 1130 in these various sections, with thousands more in other use

code categories. The size of the piles ranges from 0.2 acres to 5020 acres in Black Hills Forest, South Dakota.

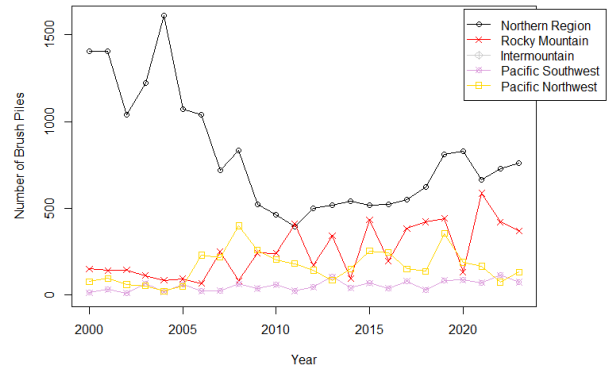
Table 3.1: The locations of burned brush piles within the USFS Brush Pile Dataset. Locations of the regional boundaries are provided in Appendix A.

Region Name	Number of Brush Piles Burned 2000-2023
1: Northern Region	18,506
2: Rocky Mountain Region	5,671
3: Southwestern Region	79
4: Intermountain Region	1,227
5: Pacific Southwest Region	3,825
6: Pacific Northwest Region	13,100
8: Southern Region	0
9: Eastern Region	114
10: Alaska Region	0

When the data describes a pile, it is not to be inferred as one singular mass of brush but instead a representation of the area where harvesting or thinning occurred. This would mean that a ‘pile’ labeled as having 50 acres is a collection of piles formed from the harvest across those 50 acres. The collection of piles is typically consolidated before burning or processing, but this is not considered for the emission calculation. Across the Western U.S., the Pacific Southwest has been stable regarding pile number and size. On the other hand, the Pacific Northwest has seen an uptick in the number of brush piles formed, from around 500 in 2005 to 1500 in 2022.



(a) Average brush pile size burned in USFS regions



(b) number of brush piles burned in USFS regions

Figure 3.1: Distribution of burned brush piles 2000 - 2023

The average pile size in 2022 for our forest of interest, the Deschutes National Forest, is 49.2 acres, with a minimum harvest area of 4 acres and a maximum of 246 acres. These piles are most dense on the eastern side of the forest, nearest to the city of Bend, which has a population of over 100,000 and is the highest-populated city in central Oregon (U.S. Census Bureau, 2020). This provides the opportunity to examine how brush pile burns impact an affected population due to their proximity to the burn sites. This proximity to a city also supplies the necessary scenario to see how the trade-off between global and local costs determines optimization strategies.

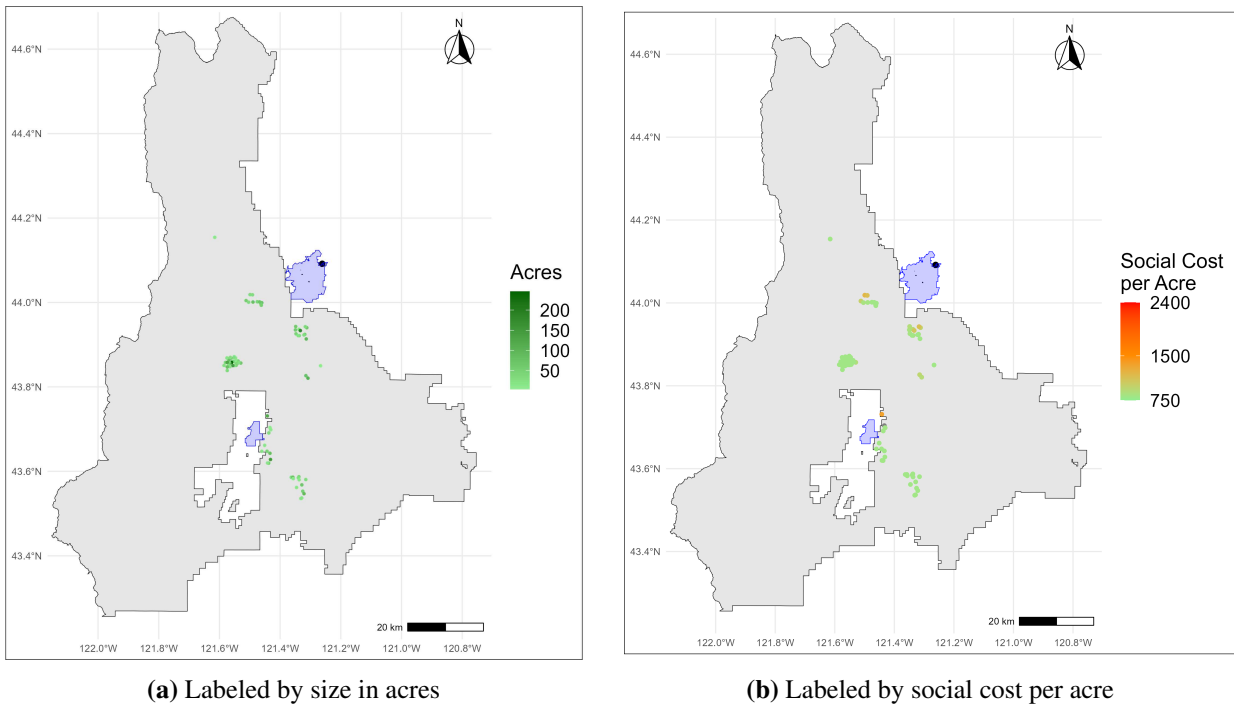


Figure 3.2: Burned brush piles locations in Deschutes National Forest in 2022

Figure 3.2 above shows the locations of all brush piles burned in Deschutes National Forest in 2022, sorted by both size in acres and the amount of social cost associated with that pile’s burn on a per-acre basis³. The blue areas represent the two major population centers surrounding the forest, with Bend to the northeast of the forest and La Pine on the southern side. The black dot in Bend represents the USFS station, which is assumed to be the deployment location for all ‘Charbosses’ used in brush management. Figure 3.2a shows the size of each pile in acres by different shades of green, while Figure 3.2b shows each pile colored by the social cost per acre that would result from that pile being burned. The largest pile shown in Figure 3.2a is 246 acres, and the smallest pile is 4 acres. The highest social cost per acre, reaching \$2,537, is attributed to a small 6-acre pile. This is primarily due to the significant local costs associated with the burn and the pile’s small size, which yield a greater social cost per acre.

³Zoomed versions of these images are provided in the appendices.

3.2 BlueSky and VSmoke Modeling

The BlueSky model allows for calculating various emissions based on the geographic location of each pile (Larkin et al., 2009). The USFS and the University of Washington developed this model to simulate emissions output across the United States. The model also considers the size and composition of each pile to allow for greater accuracy in its estimations.

This model has been used in a variety of applications, including developing wildland fire emissions (Jaffe et al., 2020), balancing public health and land management goals (Oakley, 2022), and other analyses of air quality impacts of slash pile burns in Washington State (Pierobon et al., 2022). The model's accuracy was reviewed against observed fire events by Pan et al. (2020), who concluded that although there were issues in identifying a small number of fire cases, the BlueSky model observed most fire signals reviewed. Because of its extensive use in the fire literature, the BlueSky model is suitable for the research goal of modeling the emission profiles of pile burns.

The BlueSky program outputs emission levels in tons of $PM_{2.5}$, PM_{10} , carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_x), volatile organic compounds (VOC), ammonia (NH_3), and sulfur dioxide (SO_2). The emission levels depend on the parameters inputted into the model, such as the fuel type, fuel moisture, amount of consumption, and timing of the burns. To ensure consistency across all estimations, the fuel type is set to ponderosa pine savanna based on the forest's geographic location, fuel moisture is set to moist to replicate ideal brush pile burn timing, consumption is set to 5% shrub and canopy consumption, and timing is set to 1 day for each burn. These emission factors allow for social costs to be computed directly from the various greenhouse gasses and local air emissions calculations from the associated levels of $PM_{2.5}$, which are known to be harmful to human health (Anenberg et al., 2012; Ganguly et al., 2018; Pierobon et al., 2018; Reisen et al., 2015).

The other important aspect that the BlueSky model can handle is how wind impacts the distance these particles travel. BlueSky can use the VSmoke model to predict emissions from each simulated burn in November. The wind speed and direction used are based on the average values for November since this is the month that most prescribed burns occur (Sifford et al., 2016; Pier-

obon et al., 2022). These predicted emissions, along with an estimated wind speed of 7 mph and a wind direction from the southwest, are inputted into VSmoke to determine the smoke's trajectory⁴.

Estimated wind speed and direction for Deschutes National Forest are retrieved from weatherspark.com, which acquires its weather information from NASA's Modern-Era Retrospective Analysis (MERRA-2)(Deschutes River Woods Climate, Weather By Month, Average Temperature (United States) - Weather Spark, 2022) and identifies the average wind speed and average direction for November. This feature allows for greater accuracy in figuring out how many people are impacted by the traveling smoke. These two models are essential in computing the social costs associated with local and global air emissions.

3.3 Global Social Costs of Brush Pile Burns

Global social costs are calculated by normalizing all possible emissions to a CO₂ equivalent based on their global warming potential. The US EPA defines Global warming potential as the amount of energy a gas will absorb over a specified period relative to the energy absorbed by the emission of 1 ton of CO₂ U.S. Environmental Protection Agency (2024). This allows for direct social cost calculation using the social cost of carbon (SCC). However, of the emissions that BlueSky outputs, only CO₂ and methane (CH₄) are considered to have a significant global warming potential (U.S. Environmental Protection Agency, 2024) The global warming potential value for methane is 27-30 times that of CO₂ over a 100-year horizon and 81-83 times that of CO₂ over a 20-year horizon. This research draws conclusions using the 100-year time horizon, with methane having 27 times the global warming potential of CO₂. While other emissions from the BlueSky outputs likely have associated global social costs, these costs cannot be standardized with global warming potentials and are more challenging to quantify. They are, therefore, beyond the scope of this research.

Since BlueSky provides the tonnage of CO₂ and CH₄ from each pile burn, it enables a straightforward calculation of the global social cost of these emissions. This can be done by using the SCC

⁴Justification for using this wind speed and wind direction is located in the Appendix.

multiplied by the tonnage of CO₂ and adding the product of 27 times the tonnage of CH₄ times the SCC. The SCC is a vital characteristic that will significantly influence any calculations. The SCC has changed drastically in the U.S. over the last ten years, going from \$43 per ton under the Obama Administration to \$5 per ton under the Trump Administration to the Biden Administration's value of \$51 per ton (Rennert and Prest, 2023). Other countries use a much higher value, with Germany citing a range from \$235 to \$820 per ton and the United Kingdom citing a range of \$20-\$100 per ton (Wagner et al., 2021). In November of 2022, the U.S. EPA proposed a near fourfold increase to \$190 per ton, further citing the instability in the consensus of what this value should be (Rennert and Prest, 2023). Due to this instability, sensitivity analysis of varying social costs of carbon levels is used to comprehensively understand this factor's impact on the optimization of brush pile disposal.

3.4 Local Social Costs of Brush Pile Burns

Deriving the social cost of a change in air quality is less straightforward than determining the social cost of global emissions. This is due to the complex nature of air quality and its interaction with weather and populations, from wind speed to the amount of human health impact associated with a change in PM_{2.5} concentrations. To accommodate this variability, average impact measurements are used wherever possible to ensure a consistent benchmark across all piles and their associated air quality impacts. As mentioned, most piles are burned far enough away from population centers to have a relatively low impact. Still, some large piles are burned, which could substantially impact the air quality of surrounding populations.

To measure the costs associated with these changes in air quality, 24-hour peak PM_{2.5} concentrations are acquired from BlueSky's VSmoke model using the area's average wind speed and direction. These outputs provide five separate tiers of air quality based on the proximity of the fire's location. These tiers are moderate (38-88 $\mu\text{g}/\text{m}^3$), unhealthy for sensitive groups (88-138 $\mu\text{g}/\text{m}^3$), unhealthy (138-351 $\mu\text{g}/\text{m}^3$), very unhealthy (351-526 $\mu\text{g}/\text{m}^3$), and hazardous (526+ $\mu\text{g}/\text{m}^3$). To measure the amount of damage these air quality changes cause relative to baseline air quality, each tier

of exposure uses the midpoint of each range to provide a consistent measure of $PM_{2.5}$ damages. Similarly, research that measures the response to a change in $PM_{2.5}$ concentrations is measured by changes of $10\mu g/m^3$ at a time; therefore, each tier of exposure will be rounded to the nearest ten for ease of calculation. This implies that for the moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous levels, the assumed exposure concentrations will be $60\mu g/m^3$, $110\mu g/m^3$, $250\mu g/m^3$, $440\mu g/m^3$, and $530\mu g/m^3$ respectively.

With the air quality benchmarks in place, the number of people in each affected area is determined using a dataset containing the 1-km gridded population of the region (CIESIN - Columbia University, 2018). Since the air quality surfaces are irregularly shaped over some grid cells, the percent coverage of the air quality surface and each population grid cell is measured and then summed and rounded to the nearest person to reveal the affected populations by each brush pile burn's air quality impacts. Figure 3.3 below shows an example of this calculation. The red outlined shape represents the movement of the moderate air quality surface from a pile burn over 24 hours, while the blue shape represents the location of the burn. We then overlap the air quality surface with the population raster, as shown by the colored rectangles ranging from black to white.

The pile in figure 3.3 is located directly south of Bend, where most air quality changes interact with nearby populations. The cell outlined in green is an example where, since around 50% of the purple cell overlaps with the red air quality surface, it is assumed that 50% of the population within that cell is being impacted by the change in air quality. This proportion of coverage is calculated precisely for all five air quality concentration surfaces for every pile burn in the data. As a result, there will be some people within each of the five $PM_{2.5}$ concentration tiers.

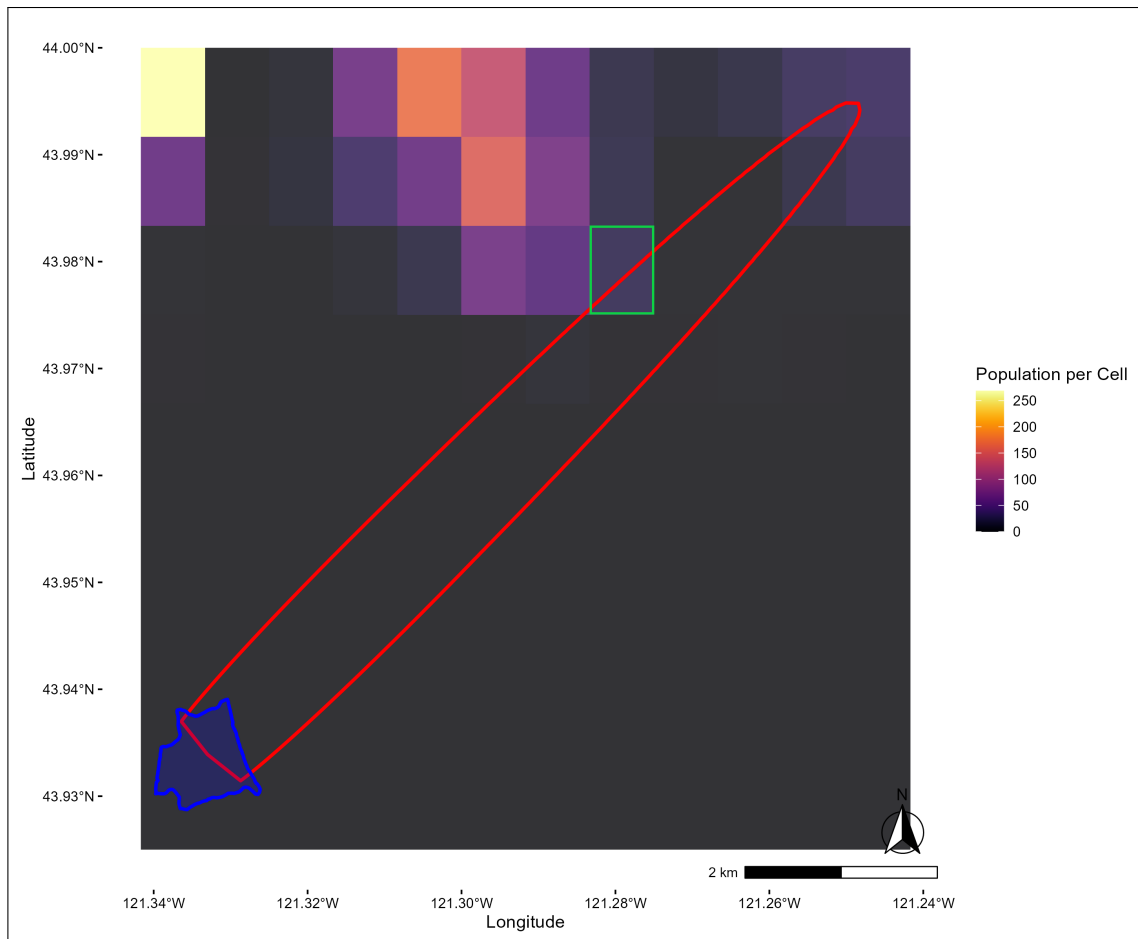


Figure 3.3: Illustrating population exposure within air quality zones: A weighted average approach

With an affected population associated with each $PM_{2.5}$ concentration tier and an assumed level of exposure within each, health impacts can be estimated. The estimated health impacts of $PM_{2.5}$ are derived from the US EPA 2019 Integrated Science Assessment for Particulate Matter (U.S. EPA, 2019). The EPA’s analysis is a review of literature that attempts to determine a correlation between a $10\mu g/m^3$ increase in $PM_{2.5}$ concentrations and the associated health impacts of that change. For short-term exposure, the report concludes that an increase in $PM_{2.5}$ concentration is ‘likely to be causal’ for respiratory effects. At the same time, cardiovascular impacts and changes in mortality are deemed to be causally influenced by higher increases in concentrations of $PM_{2.5}$ (U.S. EPA, 2019).

A $10\mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$ concentrations raises asthma hospital admissions by 1.3% to 6.8%, cardiovascular hospital admissions by 0.5% to 3.6%, cardiovascular mortality by 0.47% to 0.94%, and total non-accidental mortality by 0.25% to 1.6%⁵. Similar findings from (Delfino et al., 2009) state that average increases of $70\mu\text{g}/\text{m}^3$ during heavy smoke conditions were associated with a 34% increase in asthma admissions. In comparison, (deSouza et al., 2021) found a 0.9% increase in cardiovascular hospital admission rates per $10\mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$ concentrations. The EPA report indicates that the concentration-response relationships for $\text{PM}_{2.5}$ are linear and have no threshold, meaning that the effects scale proportionally across different concentrations. Therefore, a $50\mu\text{g}/\text{m}^3$ increase would result in these impacts being five times greater (U.S. EPA, 2019).

Since each of these impacts has a range, each range's lower, midpoint, and upper bound values will be evaluated to ensure a comprehensive assessment of the effects under different assumptions. These additional analyses are provided in the Appendix. The findings shown in this paper will be based on the midpoint of impacts on asthma, cardiovascular health, and cardiovascular mortality. This selection was made to prevent the double counting of mortality and to focus more on the potential healthcare costs.

The increases outlined in the 2019 EPA report are based on an increase in respiratory, cardiovascular, and mortality cases as an increase from the baseline levels of each. Respiratory baseline levels are obtained from a 2020 study that found 5% of workers had at least one asthma-related medical event between 2011 and 2015 (Syamlal, 2020), with an average cost of \$8,238 for each inpatient visit. Cardiovascular disease is studied much more closely since it is the number one cause of mortality in the U.S., resulting in an annual report of cardiovascular statistics published by the American Heart Association (AHA) (Virani et al., 2020). The study used to determine baseline cardiovascular health was published in January 2020 to establish accurate baseline levels of cardiovascular disease and avoid any conflation of data with the COVID-19 pandemic. The 2020 AHA research makes a point to note that air pollution from $\text{PM}_{2.5}$ "is associated with ele-

⁵Non-accidental mortality is defined as mortality from all causes except external causes such as accidents, suicide, and homicide (U.S. EPA, 2019)

vated HBP (high blood pressure), poor endothelial function, incident cardiovascular disease (CVD) events, and all-cause mortality" (Virani et al., 2020). The report also finds there were 4,840,000 emergency department discharges for CVD in 2016, indicating a rate of 1.49% of U.S. citizens being admitted to hospitals for CVD. The study finds that the 2017 overall rate of death from CVD was 219.4 per 100,000 Americans, but these rates were lower in Oregon, at 191.8 per 100,000. Baseline non-accidental mortality rates⁶ are gathered from the National Center for Health Statistics report for 2016, stating an age-adjusted rate of non-accidental mortality at 477.1 per 100,000 people, or 0.47% (Kochanek et al., 2017).

The rates of change from a baseline level of injury or mortality measure how many additional people are affected given a shift in $PM_{2.5}$ concentrations, thus allowing for the final step of associating a dollar amount to each additional case of injury or mortality. Each medical case, whether cardiovascular or respiratory, is given an average cost for that course of treatment, allowing the average cost to be estimated based on the increase in estimated hospitalizations. As stated previously, asthma-related medical events had an average cost of \$8,238 for each inpatient visit (Syamlal, 2020), while cardiovascular emergency department visits had an average cost of \$1,942 for each of the hospital discharges⁷ (Virani et al., 2020). For changes in mortality, the 2024 value of statistical life of \$13.1 million is used to gauge mortality costs (Kearsley, 2024).

In summary, we follow a structured approach for each burning event to estimate the average health impacts of changes in $PM_{2.5}$ concentrations from pile burns. First, we determine the number of people exposed to various $PM_{2.5}$ concentration tiers using population data combined with BlueSky model outputs. Let N_i represent the number of people exposed to the i -th $PM_{2.5}$ concentration tier. Next, we identify baseline levels of medical cases within each $PM_{2.5}$ tier. Let H represent the baseline rate of a specific health outcome (e.g., asthma hospitalization or cardiovas-

⁶Baseline non-accidental mortality rates are derived from the top ten leading causes of death in 2016 based on (Kochanek et al., 2017). This includes heart disease, cancer, lower respiratory disease, stroke, Alzheimer's, diabetes, influenza and pneumonia, and kidney disease. The ten leading cases accounted for 74.1% of all deaths in the United States in 2016.

⁷When considering hospital inpatient stay statistics, there were 7,971,000 inpatient cardio operations at a cost of \$97.5 billion, indicating \$12,231 per visit. This statistic is not used since the EPA report cites an increase in total cardiovascular hospital admissions for a change in $PM_{2.5}$ concentrations, not specifically inpatient stays.

cular hospitalization). The baseline number of health outcomes, B_i , is given by:

$$B_i = H \times N_i \quad (3.1)$$

Using the 2019 EPA report, we can estimate changes in the number of individuals affected by each type of medical incidence due to increased PM_{2.5} levels. Let ΔH represent the change in the health outcome rate per 10 $\mu\text{g}/\text{m}^3$ increase in PM_{2.5} concentrations, and let ΔC_i represent the change in medical cases for the i -th tier:

$$\Delta C_i = B_i \times \left(\Delta H \times \left(\frac{\Delta PM_{2.5,i}}{10} \right) \right) \quad (3.2)$$

Where $\Delta PM_{2.5}$ is the increase in PM_{2.5} concentration for the i -th tier. The total cost of illness for a single pile is calculated by multiplying the change in the number of medical cases by the cost associated with each medical incidence and then summed across all 5 PM_{2.5} concentrations (moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous). Let C_{med} represent the cost of each medical incidence:

$$\text{Total Cost of Illness} = \sum_{i=1}^5 \Delta C_i \times C_{\text{med}} \quad (3.3)$$

Using a similar approach, we determine the cost of increased cardiovascular mortality. Let M_{cv} represent the baseline cardiovascular mortality rate and $B_{i,\text{cv}}$ represent the baseline rate of cardiovascular mortality in concentration tier i . ΔH_{cv} then represents the change in the cardiovascular mortality outcome rate per 10 $\mu\text{g}/\text{m}^3$ increase in PM_{2.5} concentrations, and let $\Delta D_{i,\text{cv}}$ represent the number of cardiovascular mortalities for the i -th tier:

$$B_{i,\text{cv}} = M_{\text{cv}} \times N_i \quad (3.4)$$

$$\Delta D_{i,\text{cv}} = B_{i,\text{cv}} \times \left(\Delta H_{\text{cv}} \times \left(\frac{\Delta PM_{2.5,i}}{10} \right) \right) \quad (3.5)$$

The cost of increased cardiovascular mortality is then calculated by multiplying the change in cardiovascular mortality rates by the 2024 value of statistical life of \$13.1 million (Kearsley, 2024), denoted as VSL_{2024} :

$$\text{Cost of Increased Cardiovascular Mortality} = \sum_{i=1}^5 \Delta D_{i,cv} \times VSL_{2024} \quad (3.6)$$

These values then allow for the calculation of the total local costs of the specified pile burn:

$$\text{Local Costs} = (\text{Total Cost of Illness}) + (\text{Cost of Increased Cardiovascular Mortality}) \quad (3.7)$$

By applying this structured methodology, we aim to comprehensively estimate the local costs associated with changes in $PM_{2.5}$ concentrations from pile burns.

3.5 Charboss Cost Calculation

The cost of implementation is vital to determining where the net benefits of ‘Charboss’ implementation are maximized. If the cost of using a certain number of ‘Charbosses’ exceeds the total societal benefit of using those machines, then the ‘Charboss’ should not be used in brush pile management. This research considers the cost of ‘Charboss’ usage in 4 primary categories: labor costs, operational fuel costs, transportation fuel costs, and annualized capital costs. Processing times are inherently embedded in the operational fuel and labor costs, while travel time is reflected in the transportation costs of reaching a pile.

Processing times are calculated using an estimated number of tons of brush produced, with an average processing rate of 1.5 tons per hour per machine deployed plus a flat two-hour time cost to each pile’s processing time to accommodate any unaccounted time-costs (Johannesson et al., 2024). The amount of brush produced per acre varies based on the method by which it is created, with timber harvesting producing between 15 to 20 tons of brush per acre (Watson et al., 1986; Zamora-Cristales et al., 2018) and forest thinning producing between 10 to 20 tons per

acre (Grace III et al., 2019). To secure an average impact calculation for generalized ‘Charboss’ application settings, 15 tons per acre is assumed to determine processing times.

All optimization paths calculated begin at the USFS station in Bend, Oregon, as this is the assumed deployment location. Travel time is calculated using a flat travel rate of 10mph for each machine, while the distance is determined using a straight line between pile locations. Roads are not considered in the optimization pathways since more than 98% of the allotted time is used for processing times. Similarly, the cost of bringing each machine back to the deployment location at the end of each day is not considered, and each machine is assumed to be left at the brush pile site.

Operational fuel costs for the ‘Charboss’ are roughly 0.9 gallons per hour of usage per ‘Charboss’ deployed, with an assumed fuel cost of \$2.75 per gallon of diesel fuel. For any given calculated route, it is assumed that all ‘Charbosses’ will follow the same path and move as a fleet of machines.

For labor requirements, each ‘Charboss’ will require two workers on the ground and 0.5 excavator operators. Since labor can be shared across machines, each set of 2 ‘Charbosses’ is assumed to use one excavator for brush loading (Johannesson et al., 2024). Labor costs are calculated at \$30 per hour, times the assumed number of on-the-ground workers for all deployed ‘Charbosses,’ and \$50 per hour for excavator operators, times each hour spent processing and traveling.

Transportation costs are calculated based on the distance traveled, using a rate of 10 miles per gallon and the same assumed fuel cost of \$2.75 per gallon of fuel and a rate of \$3 per mile for excavator transportation. These transportation costs can help the model calculate a path that travels the shortest distance possible while removing the most socially costly piles, resulting in the most significant net societal benefit. Additionally, incorporating transportation costs helps reduce the environmental impact by ensuring efficient fuel usage.

Capital costs of each ‘Charboss’ are \$150,000 per machine purchased. An assumed lifespan of 10 years and a 5% discount rate are used to annualize these capital costs. This results in an annualized cost of \$19,425 for every machine deployed, representing the cost of purchasing each

machine over ten years. It is important to note that since this machine is newly developed, each machine's lifespan could be longer or shorter.

In addition to the costs associated with using the 'Charboss,' using an excavator along with each 'Charboss' incurs additional costs. Since the excavator's primary function is to load brush into each 'Charboss,' a small excavator is sufficient to handle the lightweight yet voluminous brush (Johannesson et al., 2024). Therefore, the rental rate for this smaller excavator is set at \$49 per hour. The hourly rates for excavators are based on the Bobcat 331E rate from the 2023 FEMA schedule of equipment rates (Federal Emergency Management Agency, 2024). This rate includes ownership and operation of equipment, including depreciation, overhead, maintenance, field repairs, fuel, lubricants, tires, OSHA equipment, and other costs incidental to operation. Operational excavator costs are calculated using this average hourly rental rate times the processing time for every excavator deployed.

3.6 Sensitivity Analysis

Since this model relies on several assumptions, sensitivity analysis must be conducted to determine the impact of varying those assumptions on the model's conclusions. Some assumptions have been addressed, such as biomass per acre and assumed 24-hour peak PM_{2.5} concentrations. However, others are more nuanced, such as the impact of the SCC.

Varying the level of the SCC impacts optimal decision-making since global social costs are calculated directly using this value. There has been a range of \$7 to \$190 of social cost for every ton of CO₂ proposed in the past 10-year period in the U.S., further citing the need to analyze how this factor impacts optimal 'Charboss' usage. A substantial change in the level of the SCC could significantly alter optimization outcomes. A low SCC would prioritize reducing local air pollution, while a high SCC could prioritize removing larger brush piles farther from local populations. This trade-off between different social costs of carbon levels will also clearly alter how much social cost is mitigated with a given number of devices deployed.

An additional assumption that will impact the conclusions of profitability of the ‘Charboss’ and cost efficiency will be the varying levels of biochar net sales price. The ‘Charboss’ can produce, on average, 500 pounds (25% of one metric ton) of biochar per hour (Johannesson et al., 2024). The sale price reported in previous studies varies widely, with prices of \$87 to \$350 per metric ton (Galinato et al., 2011), or up to \$2,580 per ton (Porter and Laird, 2019). A 2023 review finds that biochar prices range from \$17.50 per ton to \$2,710 per ton, with a median value of \$400 per ton (Campion et al., 2023). Sensitivity analysis for varying biochar sale prices will scale linearly with the size of brush piles but can provide additional insight into potential future market scenarios.

Regarding biochar price sensitivity, price ranges are analyzed to see what biochar price point warrants the usage of some number of ‘Charbosses’ without accounting for the reduced social costs from pile burns. This will allow insight into what biochar price point would warrant the private financial feasibility of implementing the ‘Charboss’ into brush pile management. Since the costs of ‘Charboss’ usage and benefits of biochar sales scale linearly with the size of processed piles, there will be a break-even biochar price. Below this break-even price level, ‘Charboss’ usage is not profitable, while any price above this level permits machines to be deployed profitably.

Chapter 4

Optimization Problem Formulation

The ultimate goal of deriving social cost values for each brush pile burn is to use it to gauge the optimal deployment of the ‘Charboss’ technology. These social cost values serve the objective value for optimization, as each pile processed via the ‘Charboss’ is assumed to eliminate 80% of its smoke from burning, resulting in 80% of the social cost being mitigated. This means that the ‘Charboss’ deployment aims to reach brush piles in a way that will mitigate the greatest amount of social cost, subject to constraints.

The primary constraint to ‘Charboss’ usage is the time available within a year. This highlights one of the essential benefits of the ‘Charboss’ since its burning methods are more controlled within the portable furnace, and its usage is less constrained by the typical prescribed burning periods of late fall or early spring (Thompson, 2006). Given the benefit of being less constrained by the potential uncontrolled fire spread, we assume that the ‘Charboss’ can be deployed for 75% of the year, excluding Winter months. This value of the maximum allotted time within a year that the ‘Charboss’ can be used is given by the assumption of a five-day workweek, 10 hours of labor per day, at 75% of the year, giving 1950 allowable hours for processing and travel time.

The model is constrained by the annual available time versus the total time required for processing and travel between locations. Transportation costs are dynamically calculated for each potential following location to evaluate potential benefits and costs comprehensively.

With these parameters in place, the optimization model aims to maximize the net social benefit of the ‘Charboss.’ The net social benefit is calculated by subtracting operational, labor, excavator, and transportation costs from the social cost mitigated for each pile.

Notation

- soc_j : Social cost at location j .
- proc_j : Processing time at location j .
- $\text{trav}_{i,j}$: Travel time from location i to location j .
- $\text{trans}_{i,j}$: Transportation cost to travel from location i to location j .
- fuel_j : Operational cost of ‘Charboss’ for processing location j .
- lab_j : Labor cost at location j . This includes the labor costs of the ‘Charboss’ and the labor costs of excavator workers.
- exc_j : Excavator operational cost at location j .
- $\text{trav_lab}_{i,j}$: Labor cost associated with traveling from location i to location j .
- T_{\max} : Maximum allowable time.
- x_i : Binary decision variable, $x_i = 1$ if location i is selected, 0 otherwise.
- $y_{i,j}$: Binary decision variable, $y_{i,j} = 1$ if traveling from location i to location j , 0 otherwise.

Objective Function

The objective is to select the set of locations and transitions between them that maximizes the net social benefit of ‘Charboss’ deployment:

$$\text{Maximize } \sum_{j=1}^n (\text{soc}_j - (\text{fuel}_j + \text{lab}_j + \text{exc}_j + \text{trans}_{i,j} + \text{trav_lab}_{i,j})) \cdot x_j \quad (4.1)$$

Constraints

Time Constraint:

$$\sum_{i=1}^n \text{proc}_i \cdot x_i + \sum_{i=1}^n \sum_{j=1}^n \text{trav}_{i,j} \cdot y_{i,j} \leq T_{\max} \quad (4.2)$$

Travel and Selection Relationship:

$$y_{i,j} \leq x_i \quad \text{and} \quad y_{i,j} \leq x_j \quad \forall i, j \quad (4.3)$$

Binary Decision Variables:

$$x_i, y_{i,j} \in \{0, 1\} \quad \forall i, j \quad (4.4)$$

The optimization routine maximizes net social benefit by combining a greedy heuristic with the Traveling Salesman Problem algorithm. To efficiently guide the selection of piles, a score is computed by dividing the net social benefit by the pile's processing time. The greedy heuristic initially selects locations to visit based on the highest net social benefit per unit of processing time, ensuring that piles with the greatest return per hour are prioritized. This process continues, selecting the next pile until no further locations can be included within the time constraints, creating an initial feasible path. Once this path is established, the Traveling Salesman Problem algorithm is employed to optimize the route by minimizing travel distance between selected locations. This approach ensures that the path adheres to the time constraints while maximizing both operational efficiency and social benefit.

This optimization process ultimately determines the set of brush piles to which 'Charbosses' should be deployed, maximizing the net social benefit of brush removal. The optimal number of

'Charbosses' to deploy is determined when the marginal net benefit of deploying another machine goes below zero. Furthermore, we consider the total benefits of deploying the 'Charboss,' including scenarios both with and without the potential sale of biochar produced from biomass processing.

Chapter 5

Results

Several assumptions dictate optimal ‘Charboss’ utilization and the number of machines deployed to a National Forest to provide the most significant net social benefit. The conclusions of this paper are based on the 2022 EPA SCC of \$190 per ton, as well as the midpoint of local impacts on asthma and cardiovascular hospitalization and cardiovascular mortality⁸. The 2022 EPA proposed SCC is used because it is the most recent proposal and further aligns with the SCC values used in other nations. The decision to utilize the midpoint of impacts on asthma, cardiovascular hospitalization, and cardiovascular mortality from local air pollution is due to the novelty of using the cost of illness measures and mortality impacts from air quality changes derived from the model.

A critical outcome of this research is associating a dollar amount with the societal impact of burning brush piles. When examining all piles burned in 2022 in Deschutes National Forest, the average social cost of a pile burning is \$42,946 with an average cost of removal⁹ of \$56,285. This social cost breaks down with an average global social cost of \$40,237 and an average local cost of \$2,709 per pile. This social cost distribution is expected since piles are typically in remote areas, and local impact estimations are made using average wind speed and direction of 7 mph from the southwest. This suggests that only brush piles burned southwest of Bend, or those close enough to the city, will have any impact on the local population. Referring to Figure 3.2, the burned piles with a local cost will likely be within the clusters of piles to the west and south of Bend.

Figure 5.1 provides a plot of the social cost associated with burning each pile and the variable cost of removal per pile using the ‘Charboss’ on both a cumulative and per-acre basis. These social costs include the total local and global social costs of burning that pile. Total costs are calculated solely based on variable costs: labor, excavator, and operational fuel costs based on processing

⁸Several variations of these results based on different assumptions are provided in the Appendix

⁹This average cost consists of only labor, excavator, and operational fuel costs when using five machines. This is because distance and capital costs depend on more factors than just the emissions of one pile, and labor and operational fuel costs require a processing time based on some number of machines to calculate their cost level.

times when using 5 ‘Charboss’ machines. Therefore, transportation and annualized capital costs are not included in this figure. The reason for including only variable costs is that transportation costs require the distance between two specific piles to calculate a travel cost. In contrast, annualized capital costs are spread across the entire route. Most importantly, these visualizations illustrate the distribution of social costs of each pile, not the cumulative social cost or cost of implementing an entire chosen path.

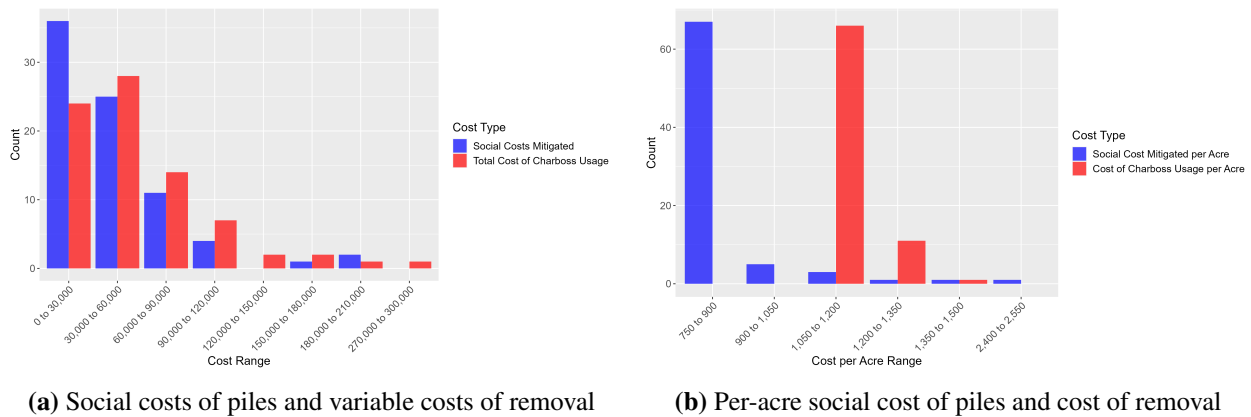


Figure 5.1: Cumulative and per-acre social costs of piles and variable costs of removal

Figure 5.1b indicates that implementing ‘Charboss’ into brush management solely based on the reduced social cost of burning does not warrant ‘Charboss’ investment in most scenarios. When considering only the variable costs of ‘Charboss’ usage, few piles have a higher social cost per acre than it would cost per acre to remove them. This is because most brush piles are burned in remote areas, which accumulate low local social costs.

The variation of the per-acre social cost of a pile burn is associated with the presence of local social costs of emissions rather than containing solely global social costs. The variation in cost per acre here is driven by the flat time cost added to each pile’s processing time. If a pile has a lower processing time, the added fixed time cost of 2 hours for processing will significantly increase the removal cost per acre.

Although local social cost calculations are highly dependent on various factors, global social cost calculation is much more straightforward. Since the emission profile of each pile burn is de-

terminated using the BlueSky model, which uses similar characteristics outside of acreage, these emission factors will scale linearly with the size of each pile. Gauging the social cost using these average attributes is to optimize the removal of the brush when assuming all pile burns have homogenous aspects outside of pile size. This allows the social cost calculation to be more easily generalized to widespread forest management.

Table 5.1: Per Acre Summary Statistics of Brush Pile Emissions and Social Costs

Statistic	Value	Statistic	Value
Global Social Cost per Acre (USD)		Local Social Cost per Acre (USD)	
Mean	816.524	Mean	58.518
Standard Deviation	0.874	Standard Deviation	214.120
CO₂ per Acre (tons)		CH₄ per Acre (tons)	
Mean	4.804	Mean	0.021
Standard Deviation	0.001	Standard Deviation	0.001
PM_{2.5} per Acre (tons)			
Mean	0.052		
Standard Deviation	0.001		

Table 5.1 gives context to the BlueSky outputs of each emission type on a per-acre basis, as well as the resulting global and local social cost calculations. This table helps illustrate the degree of linearity in the calculations for each emission type and the resulting linearity found in the global social cost per acre. The minor variation in the global social cost per acre stems from methane emissions needing to be rounded to two decimal places from the BlueSky outputs. Since each additional acre of a pile burn contributes a slightly higher amount of methane than rounding will allow, every few acres will amount to an additional one-hundredth of one ton of methane emissions to be accounted for. This will then cause minor variations in linearity since each ton of methane is normalized to a global warming potential equivalent by multiplying each ton of methane emitted by 27.

Importantly, this table shows that the impact of global social costs will be broadly consistent across all piles for reduced social costs. Meanwhile, local social costs vary much more and require better decision-making strategies to use resources effectively to combat the social costs of pile burning.

With a social cost associated with each pile, the optimization model is then applied to determine how much social cost can be efficiently mitigated within a year¹⁰. This optimization process creates a route, based on the number of ‘Charbosses’ used, that plots a path to reach each of the selected piles in the time constraint available. Figures 5.2a and 5.2b illustrate this path when using one machine and five machines in each scenario.

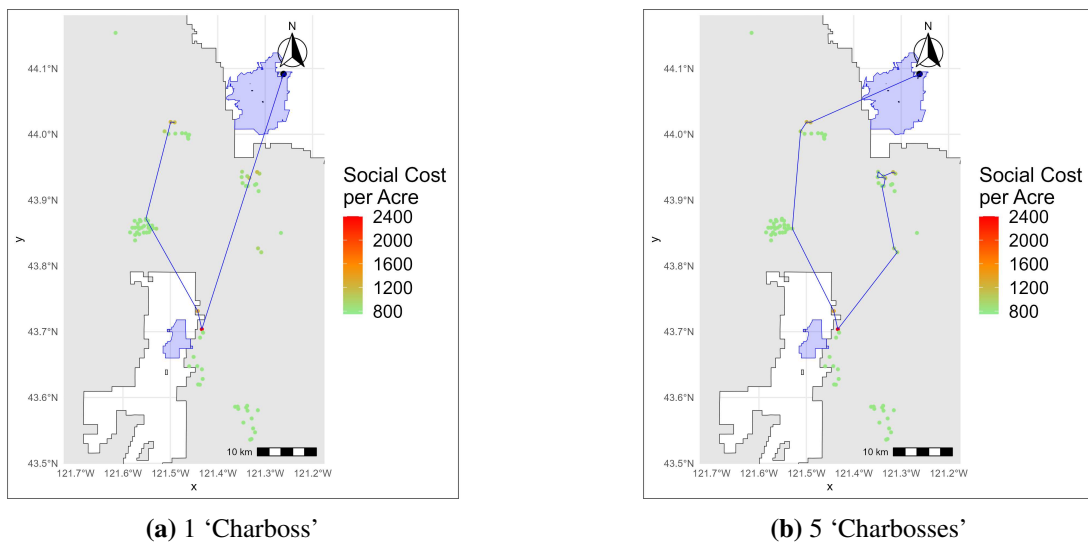


Figure 5.2: Maps showing optimal routing to mitigate the highest social cost using different numbers of ‘Charboss’ machines

Figure 5.2 helps illustrate just how constraining the processing time is on the optimization problem. Based on our assumption that each brush pile generates 15 tons of brush per acre, and since each machine can only process 1.5 tons per hour, it takes one machine 10 hours to process an acre. Using just one ‘Charboss,’ the optimal route reaches five piles, mitigating \$251,504 in social

¹⁰The net benefit and marginal net benefit of different deployment scenarios when only considering the benefits of reduced social cost are provided in the appendices.

costs. However, when scaling up to 5 machines, 17 piles are reached, which through processing the piles mitigates \$985,888 in social costs. With processing times decreasing as the number of ‘Charbosses’ increases, there will be more time to reach additional piles. This in turn allows for more social costs to be mitigated, albeit at a diminishing rate. These factors lay the foundation for determining the optimal number of machines that can be deployed efficiently and cost-effectively.

When using just one ‘Charboss,’ \$155,958 of global social costs are mitigated, along with \$95,546 of local social costs. Figure 5.2 characterizes each point based on the amount of social cost associated with a pile’s burn on a per-acre basis, with each path prioritizing the darkest colored points. The routing of 1 ‘Charboss’ is estimated to cost \$4,845 in fuel and transportation costs, \$163,200 in labor costs, \$47,000 in excavator rental costs, and \$19,425 in annualized capital costs, for a total of \$235,000, indicating a net benefit of \$16,500 for one year of usage just from reduced local and global social costs. The case for one machine reveals the trade-offs surrounding the optimal ‘Charboss’ deployment.

The primary goal of the research is to understand the economic trade-offs related to using the ‘Charboss’ technology to process burn piles. Figures 5.3 and 5.4 below depict this trade-off. They show both the rate at which social costs mitigated increase in step with the cost of implementation and the breakdown of how social costs contribute to the overall values. Figure 5.3 provides some intuition about these trade-offs, indicating that the deployment of 23 ‘Charbosses’ will result in the machines removing and processing all the brush piles formed in 2022 in Deschutes National Forest. This is clear since, with 23 machines being used, an additional ‘Charboss’ deployment does not mitigate any additional social cost.

When these 23 machines are deployed, there is a total of around \$3.39 million in social costs mitigated by ‘Charboss’ usage, for around \$5.2M in total costs accumulated along the route. Additionally, Figure 5.3 clarifies that the total social costs mitigated will always be exceeded by the cost of deploying the same number of machines with the assumptions mentioned earlier for all but the first machine deployed. This figure highlights the importance of including the additional benefit from the subsequent biochar production from ‘Charboss’ usage in brush management.

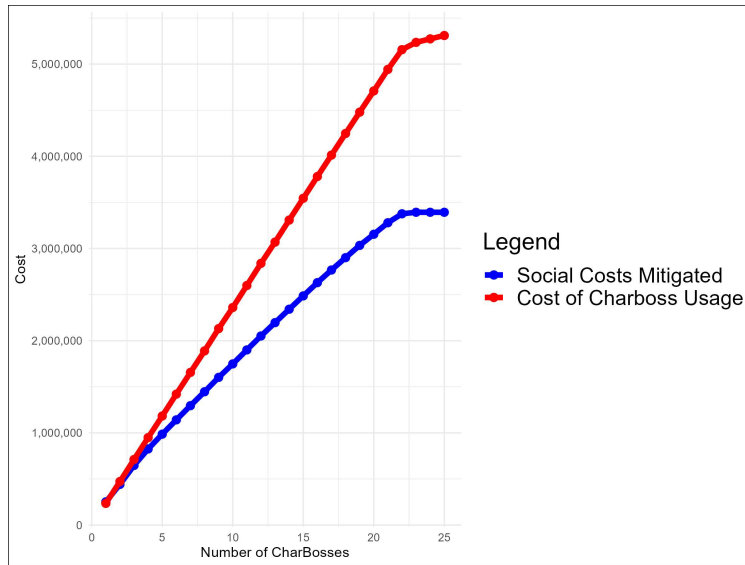


Figure 5.3: Total social costs mitigated against total costs of deployment with varying ‘Charboss’ amounts

Figure 5.3 shows that social costs mitigated increase nearly linearly. Most piles are located in remote areas and are not associated with local air pollution or subsequent local social costs resulting from the pile’s burn. This means that the majority of social costs being mitigated are due to the global social costs, which scale linearly with the size of the brush pile burned.

Regardless of the number of machines available, the optimization process prioritizes piles with both local and global social costs. This prioritization ensures greater efficiency in processing time, as addressing these piles simultaneously mitigates both types of social costs. Since global social costs scale linearly with pile size and are present for every burn, focusing first on piles with additional local costs maximizes the effectiveness of each processing hour. Figure 5.4 depicts that brush piles with associated local costs are processed as soon as possible based on the number of ‘Charbosses’ deployed in the optimization process. This is evident from the significant increase in the local cost line between when one to five machines are deployed, followed by the line becoming horizontal due to all local costs being addressed.

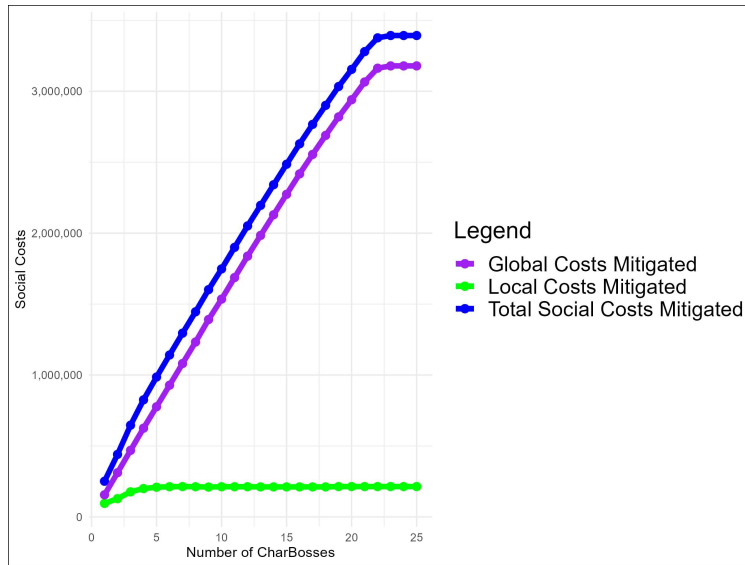


Figure 5.4: Distribution of local and global social costs with varying ‘Charboss’ amounts

Since so many of the conclusions above heavily depend on the SCC and its contribution to the global social cost values, it is essential to understand how changing the SCC alters optimal decision-making. Global social costs will be the primary driver of societal costs in most brush pile burn scenarios, and understanding precisely how we account for those emissions can alter which piles would be better off being left to burn. It is vital to ensure that the decision to remove brush via the ‘Charboss’ is always better than the status quo of burning due to the high cost of ‘Charboss’ usage.

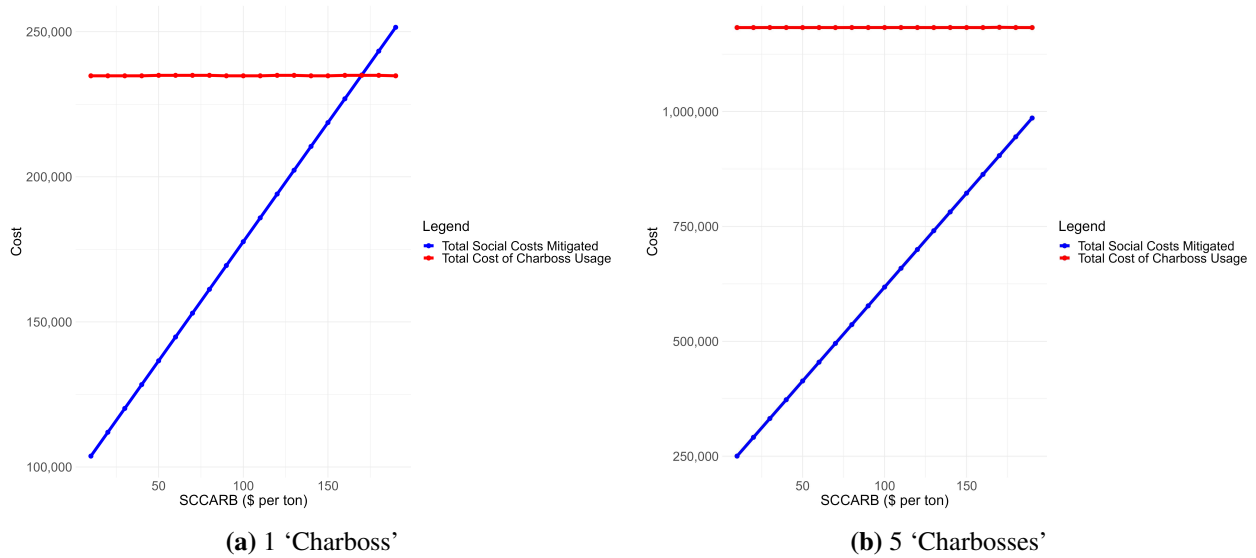


Figure 5.5: These figures show the total costs line (red) in comparison with the total social costs being mitigated (blue) when varying the SCC between \$10 and \$190 per ton.

Figure 5.5 shows the trade-off between the total cost of implementation and the total social costs mitigated when changing the SCC value. Critical interpretations can be made from these plots, most notably how the intersection moves further right as the number of machines deployed increases from 1 to 5, indicating a higher SCC needed to provide a net benefit of using the ‘Charboss.’ In scenario 5.5a, we know the benefits of mitigating the social costs of pile burning from using one ‘Charboss’ does not exceed the costs of ‘Charboss’ usage unless the SCC is at least \$180 per ton. Meanwhile, scenario 5.5b implies we should not deploy five machines unless the SCC is much higher.

The accurate determination of how many machines are optimally used is based on when the marginal net benefit drops to zero, which is not shown in these plots. However, these plots reveal that the 2022 US EPA proposed SCC of \$190 per ton is sufficient to justify the allocation of some number of ‘Charboss’ machines when only considering the mitigated social costs of not burning brush piles.

The costs of using the ‘Charboss’ in either of the scenarios in Figure 5.5 are linear, as the production factors are mostly predetermined, outside of fuel price and labor costs. This emphasizes

the importance of ensuring that benefit calculation encapsulates all value generated from using the ‘Charboss’ against the implementation costs. This nuance is critical to ensure that the decision to purchase several ‘Charbosses’ for managing a national forest aligns with the goals of the forest managers and political administrations.

It is relevant to mention that how local costs are calculated can significantly alter the optimal decision-making in these scenarios. Suppose pile burns were to affect local populations more, with more brush piles burned near higher populations. In that case, the resulting social costs line will shift up, causing the intersection between the social costs mitigated and the total removal costs to move to the left, indicating a lower SCC necessary to justify ‘Charboss’ deployment. Similarly, as health impacts and health costs change, the social costs mitigated line will shift, which can significantly alter the optimal deployment of the ‘Charboss.’ This would imply that if brush piles are burned near higher populated areas, ‘Charboss’ usage is more likely to be sufficiently justified when considering solely the reduced local and global social costs of burned piles.

The figures above illustrate the critical role that biochar production can play in optimizing ‘Charboss’ deployment decisions. Biochar offers a variety of benefits, including its use as a fertilizer to increase crop yield, provide bioenergy, and replenish soil nutrients (Han et al., 2018; Galinato et al., 2011; Yadav and Ramakrishna, 2023). Additionally, biochar can sequester carbon from the atmosphere, aligning with the SCC to generate a quantifiable social benefit. This carbon sequestration potential makes biochar an attractive option for high-emitting corporations to offset emissions, generating a market within the carbon sink industry. Furthermore, biochar sale prices will likely react to changes in carbon sink markets and information revolving around increased agronomic viability (Yadav and Ramakrishna, 2023). Because of these diverse applications, biochar may have a sale price or use value that enhances the benefits of ‘Charboss’ deployment beyond merely mitigating the social costs of pile burning.

The best way to understand where the most significant net benefits from ‘Charboss’ usage are created is to highlight the points at which a positive marginal benefit of an additional machine is

observed. When the marginal net benefit of adding another machine drops below zero, this implies it is not efficient to employ additional ‘Charbosses.’

The importance of ‘Charboss’ usage in brush management varies based on how the generated benefits are measured. This research considers two perspectives: the social planner’s perspective and the private perspective. The social planner’s perspective is concerned with reducing the social costs of burning a pile and the societal benefit of using the produced biochar to enhance environmental benefits further. On the other hand, the private perspective focuses solely on biochar’s profitability, without concern for reducing global and local social costs or the carbon sequestration value of the biochar produced.

5.1 The Social Planner’s Perspective

From the social planner’s perspective, parameters of biochar production rate and carbon sequestration potential can be used alongside the SCC to determine the value of the carbon sequestered from biochar application. Johannesson et al. (2024) cites a production rate of biochar for the ‘Charboss’ between 0.17 metric tons (MT) and 0.296 MT per hour, while the manufacturer lists a biochar production rate of 0.25 MT per hour (Air Burners, Inc., 2024). Therefore, 0.25 tons of biochar produced per hour of processing is used for calculations.

Biochar produced by the ‘Charboss’ can remove 2.7 tons of CO₂ per ton of biochar applied (Johannesson et al., 2024). While Yang et al. (2021) states a rate of 1.474 tons of CO₂ sequestered for every ton of biochar applied considering crop residues as a feedstock to the biochar, Johannesson et al. (2024) is considering biochar produced by the ‘Charboss’ when using forest brush residues as a feedstock. Since the feedstock makes a considerable difference in the carbon sequestration capabilities of biochar (Salma et al., 2024; Galinato et al., 2011; Yadav and Ramakrishna, 2023), we assume that each ton of biochar can sequester 2.7 tons of CO₂ per ton of biochar applied.

The carbon sequestration value from biochar is calculated as the processing time multiplied by the number of ‘Charbosses,’ times 2.7 for carbon sequestered per ton, times the \$190 social cost of

carbon, divided by four since each machine takes 4 hours to produce one ton of biochar.

$$\text{Carbon Sequestration Value} = \frac{\text{Processing Time} \times \text{Number of Charbosses} \times 2.7 \times 190}{4}$$

Figure 5.6 shows the relationship between the benefit per acre when comparing the value of carbon sequestration from biochar production and social cost mitigation from reduced brush pile burning.

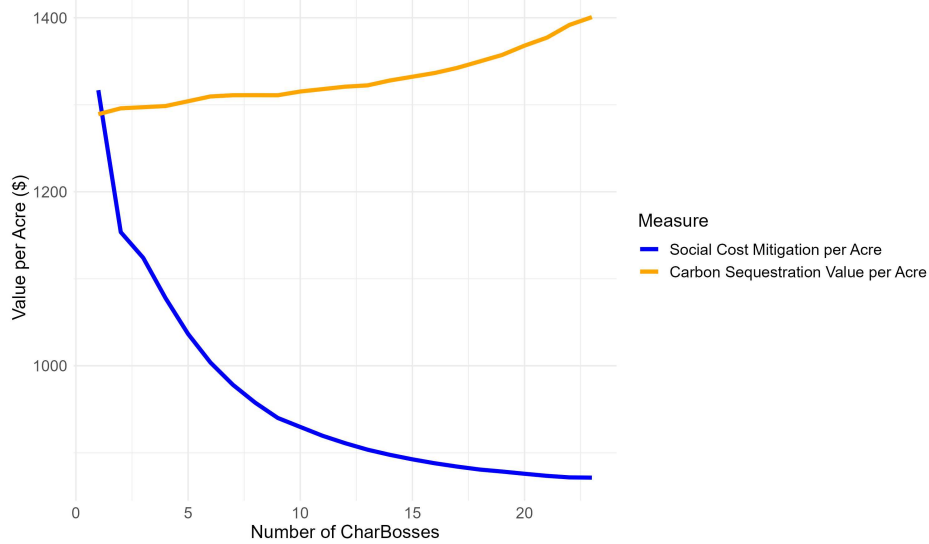


Figure 5.6: Social costs mitigated per acre versus value of carbon sequestration per acre as the number of ‘Charbosses’ deployed is changed

On a per-acre basis, the benefit of social cost mitigation from reduced brush pile burning in the Deschutes National Forest surpasses the benefit of carbon sequestration from biochar production only when a single ‘Charboss’ is deployed optimally to pile locations. Driven by increased local costs, the optimization pathway initially targets high-cost piles by selecting locations with the highest social cost mitigation per acre processed. However, once the piles with significant local social costs are removed, additional ‘Charbosses’ only increase the capacity to mitigate global social costs.

Notably, the social cost mitigation benefits per acre do not scale linearly as the number of ‘Charbosses’ increases due to the local costs. Since local costs are removed as the number of

‘Charbosses’ increases, the social cost mitigation will consist only of global social costs, which results in the decreasing marginal benefit of each additional ‘Charboss.’ On the other hand, since additional ‘Charbosses’ reduce the processing time of each pile, the total processing time per acre is decreasing. This results in greater biochar production potential, which in turn results in more carbon sequestration per acre as the number of ‘Charbosses’ increases.

Much like the global social costs calculation, the carbon sequestration value also scales linearly with processing time since processing time determines the tonnage of biochar produced. On average, each ‘Charboss’ contributes \$1,329.90 per acre in biochar carbon sequestration value, compared to \$959.44 per acre in social cost mitigation. This implies that for every hour of processing time, the ‘Charboss’ reduces social costs that would have resulted from the pile being burned by \$95.94 and can generate an additional \$132.99 in carbon sequestration value from the biochar produced. This highlights that, while both benefits scale similarly, carbon sequestration benefits from biochar offer a 38.6% higher average per-acre return with each additional ‘Charboss.’

Determining the optimal deployment strategy for the social planner involves the same maximization of net benefits, which can be characterized as the point at which marginal net benefit drops below zero. This relationship is highlighted in Figure 5.7 below.

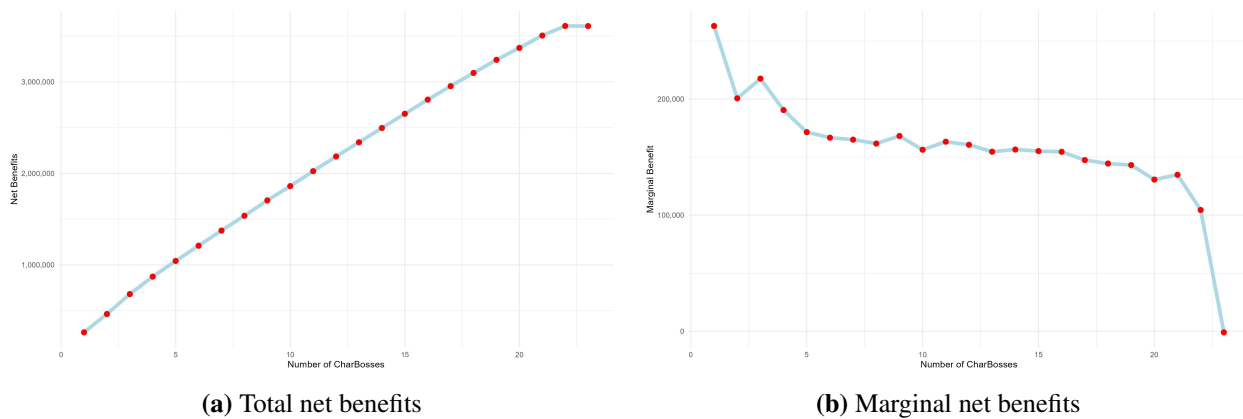


Figure 5.7: Optimal ‘Charboss’ deployment decision with biochar applied for carbon sequestration.

Based on Figure 5.7b, the marginal net benefit of an additional machine is positive until 22 machines have been deployed, implying that 22 ‘Charbosses’ should be deployed for the social

planner to create an optimal solution. This is also shown in Figure 5.7a as the point when the next machine does not increase the net benefit generated. Most importantly, these plots show that using the ‘Charboss’ in forest management benefits society by generating over \$3.5 million in net benefits from reduced social costs and increased carbon sequestration.

Since these optimal deployment strategies are inextricably linked to the SCC, Figure 5.8 provides additional sensitivity analysis for varied SCC values.

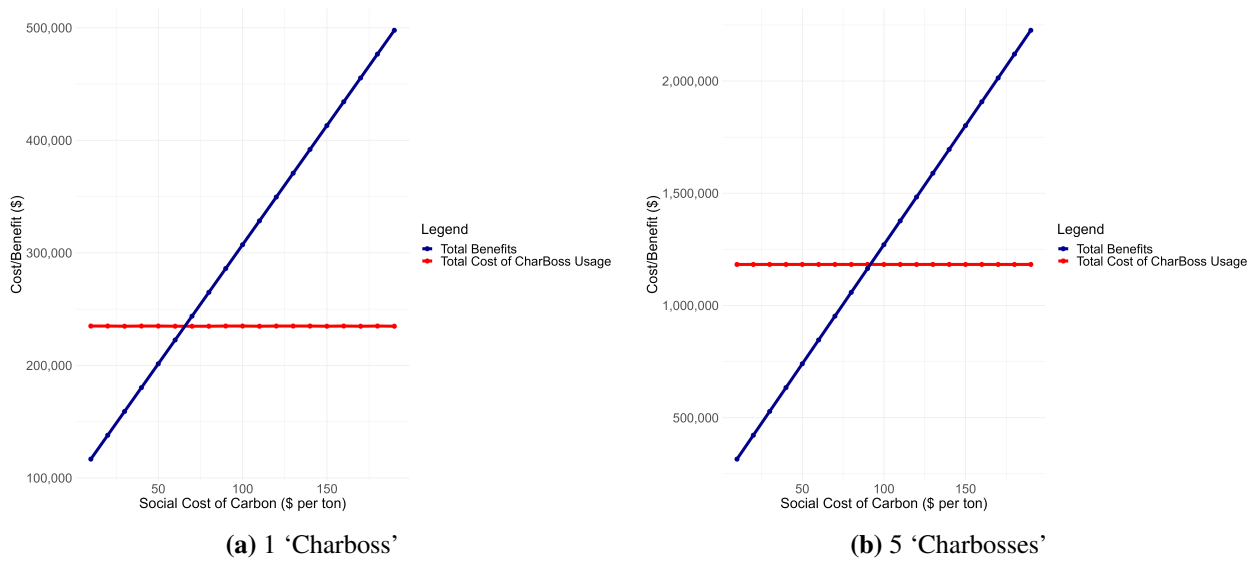


Figure 5.8: These figures show the total costs line (red) in comparison with the total benefits (dark blue) when varying the SCC between \$10 and \$190 per ton.

Figure 5.8 provides intuition on how changing the SCC value alters the social planner’s optimal decision-making when considering the benefits of social cost mitigation of reduced pile burning and biochar carbon sequestration. Given the plots in Figure 5.7, 22 ‘Charbosses’ should be deployed to provide an optimal deployment strategy. However, due to the decreased marginal productivity of each additional machine, as the number of ‘Charbosses’ deployed rises, a higher SCC is needed to warrant deployment from the social planner’s perspective. Similar to Figure 5.5, this is portrayed by the intersection between the total costs and total benefits moving to the right as the number of ‘Charbosses’ deployed increases.

When biochar carbon sequestration is included in the valuation of the benefits, a SCC of \$70 is needed to provide positive net benefits of one ‘Charboss’ for the social planner. In contrast, a SCC of \$100 is required to provide positive net benefits of deploying 5 ‘Charbosses.’

It is important to note that the social planner is not concerned with the sale price of biochar but only with the value of carbon sequestered from the produced biochar and the amount of social cost that can be avoided. A critical extension of this is that biochar will sequester carbon no matter how it is applied to soils (Salma et al., 2024; Yadav and Ramakrishna, 2023). This means the social planner would still capture the carbon sequestration benefits even if the biochar is sold to farmers for soil application. Furthermore, social planners could increase the financial benefits by charging for the sale of biochar while preserving the environmental gains from carbon sequestration.

5.2 The Private Investment Perspective

From the private investment perspective, the only concern will be the profitability of using the ‘Charboss’ in brush removal services. The private benefit is assumed to have no consideration for reduced social cost or increased carbon sequestration, even if this benefit is generated from deployment. Therefore, the private benefit will only consist of the amount of biochar produced times the price at which it can be sold. Additionally, the cost of deployment will scale mostly linearly with the number of machines deployed, as shown in Figure 5.3, outside of minor variations in the travel and processing times.

Since the private profit potential and deployment costs scale linearly, this would imply a break-even price point for biochar. This price point indicates that any number of ‘Charbosses’ deployed would be profitable at this biochar sale price, so long as there are brush piles to remove. We then seek the price of biochar that would result in a higher profit per acre of processing than the cost of processing per acre.

Varying biochar sale prices reveal that a positive profit margin for the ‘Charboss’ is achievable only when the sale price of biochar is at least \$496 per ton¹¹. This means that before including

¹¹Additional details on how this calculation is made are provided in Appendix 7.2.

the packaging and manufacturing costs of biochar distribution when biochar can be sold at \$496 per ton or more, purchasing the ‘Charbosses’ to remove brush piles and produce biochar will be profitable.

It is important to note that the benefits presented in this research only account for brush removal in a single year. Given the ‘Charboss’ is expected to have a lifespan exceeding one year, these net benefits could compound as brush pile creation increases with more widespread wildfire mitigation efforts. While the total valuation of biochar is still under study and remains complex, it is reasonable to assume that biochar production by the ‘Charboss’ will contribute additional benefits beyond the mitigated social costs of pile burning and carbon sequestration of the biochar produced. Additional agronomic and ecological benefits of biochar are not quantified in this analysis, and if these benefits were included, they could further impact the optimal deployment decisions. However, further research is needed to quantify these additional advantages fully.

Chapter 6

Conclusions

This research has examined the factors contributing to the new USFS device's productivity and economic viability. The requirements for positive net benefits are determined from private investment and social planning perspectives. When analyzing these factors, there are several scenarios in which the 'Charboss' could provide a positive net benefit to local and global environmental health through brush pile removal.

While the implementation costs of the 'Charboss' remain relatively stable across different deployment strategies, the benefits that the 'Charboss' can provide largely depend on the assumptions made. Based on the assumptions made in this research, 22 'Charbosses' can be deployed to the Deschutes National Forest annually and provide more than \$3.5 million in net benefits from reduced emissions and increased carbon sequestration. Additionally, if biochar can be sold for at least \$496 per ton before including any other expenses of sale, the 'Charboss' can be used profitably to remove brush from National Forests.

These results imply a substantial opportunity for policymakers and forest managers to address wildfire concerns. As forest thinning becomes more prevalent to decrease the potential risk from wildfire, the increased amounts of brush can then be processed with the 'Charboss' to provide a saleable product and reduce the associated emissions that would have resulted from brush burning. This impact on local communities can also vary significantly for forests near high population density, like in the US Pacific Northwest, as opposed to forests in low population density areas, such as those in the U.S. Intermountain region.

In addition, a prominent facet of this valuation not included in this analysis is the reduced risk of wildfire. When brush piles are formed in forest thinning, one of the primary goals of thinning is reducing the risk of future intense wildfires. Furthermore, the brush piles themselves can become a catalyst for wildfires if left unattended. Additional research is needed to quantify this benefit

precisely, but this further reinforces that the benefits in this research are a lower bound due to the inability to evaluate these factors comprehensively.

Several assumptions must be made to address the question of productivity. We assume the amount of brush created for each acre of harvest, the machine's processing time to process the brush contents within each pile, and various other characteristics of the machine's capabilities. Additionally, we assume a certain level of health impacts from exposure to PM_{2.5} based on the ranges provided in the 2019 US EPA report (U.S. EPA, 2019). Most importantly, we assume a specific value for the SCC mitigated through 'Charboss' usage and examine how varying this value impacts the conclusions.

Some factors constrain the conclusions drawn from this research. The routing process of the optimization model used for this paper does not consider roads, which could change the rate at which travel costs accrue. Similarly, the total amount of emissions produced from a pile's burn is also limited to the output of the 'Bluesky' model, potentially leading to inconsistent emission factor totals. Finally, biochar factors are based on the most recent research available. A 2023 review of biochar prices helps illustrate the degree of speculation involved in accurately assessing the impacts of biochar usage, with the review citing prices as low as \$17.50 per ton and as high as \$2,710 per ton of biochar [Campion et al. \(2023\)](#).

Additional questions remain, including future changes to the SCC and the price of biochar, which forests are the best candidates for 'Charboss' usage, and the influence of carbon credits on optimal decisions. Additionally, it will be worth considering in the future the extent to which government assistance may be reasonable for 'Charboss' usage on private lands. Despite the limiting factors and assumptions, the 'Charboss' has grounds for potentially becoming an important part of future forest management and should be considered for brush pile management situations.

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Appendices

This section provides various figures to ensure a complete scope analysis is allowed to the reader. These figures outline the various USFS regions this research could extend to, each section including multiple states. This study has data on the Northern Region (region 1), the Rocky Mountain Region (region 2), the Intermountain Region (region 4), and the Pacific Southwest and Pacific Northwest regions (regions 5 and 6, respectively).



Not pictured: Alaska: Region 10 – there is no region 7

Figure 7.1: The various regions of the United States, as classified by the USFS

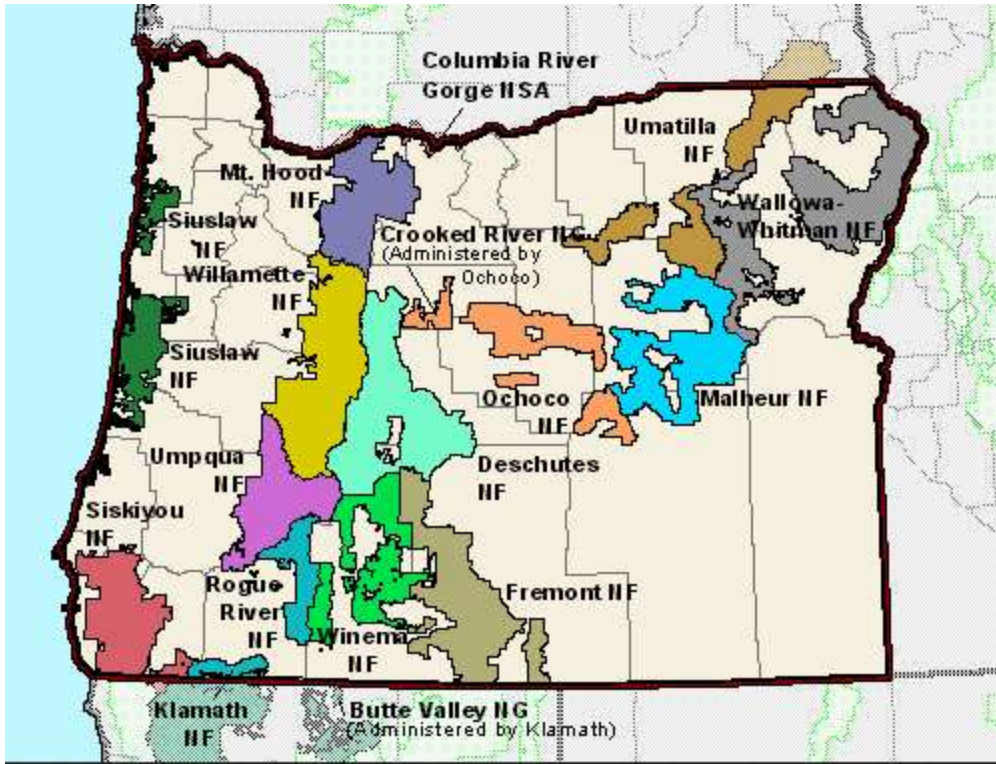


Figure 7.2: National Forests of Oregon

(Wikimedia Foundation, 2024)

Above is a map of the state of Oregon and the locations of its National Forests. The forest of interest for this research is the Deschutes National Forest, which is colored teal in the center of the map.

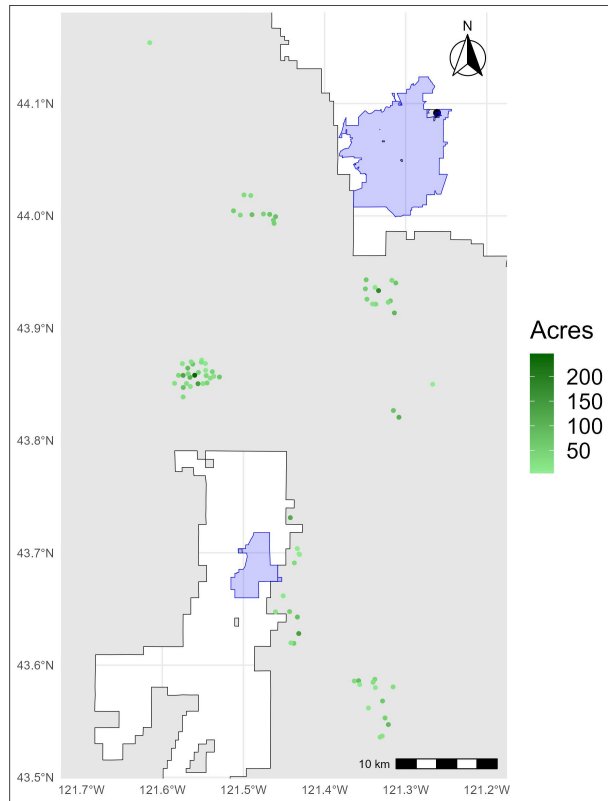


Figure 7.3: Zoomed map of locations of brush piles burned (with size in acres color classification) in 2022 in the Deschutes National Forest and the cities of Bend (Northeast) and La Pine (Central) in blue

Above is an enlarged image of figure 3.2a, with each brush pile location in the Deschutes National Forest that was burned in 2022 labeled in different shades of green based on the pile's size in acres.

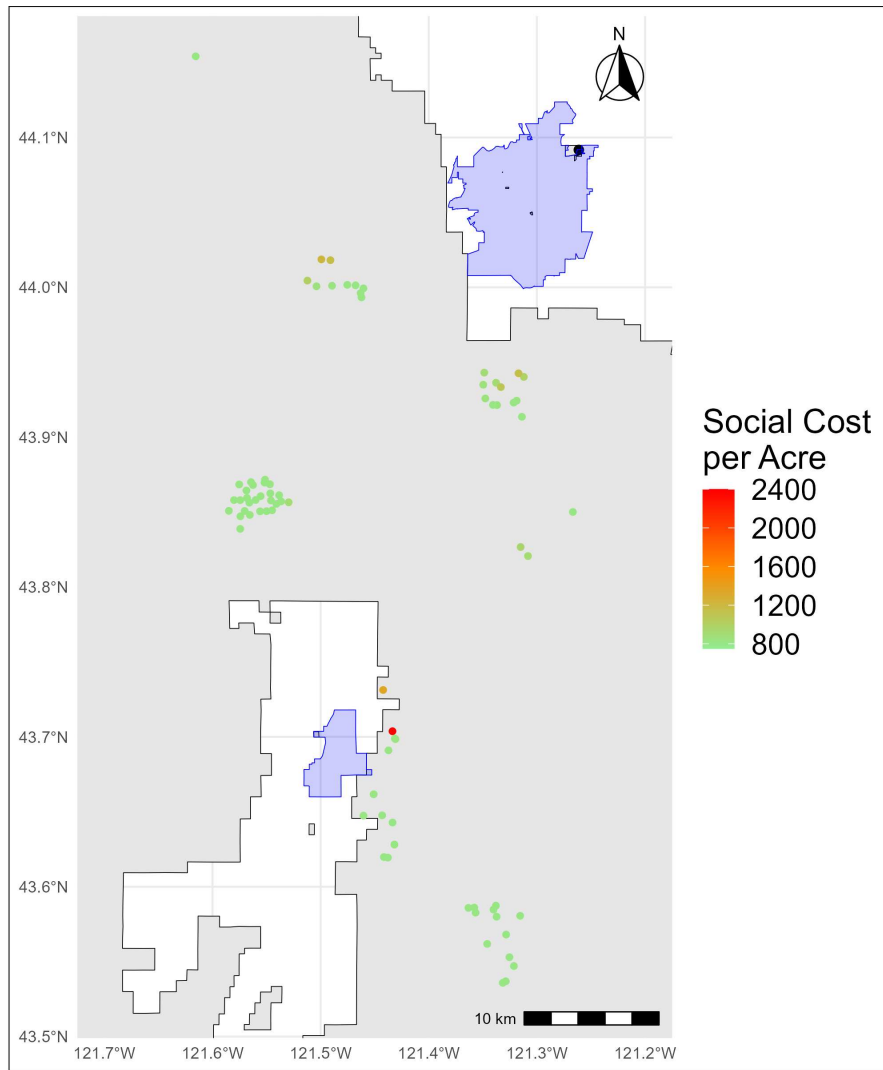
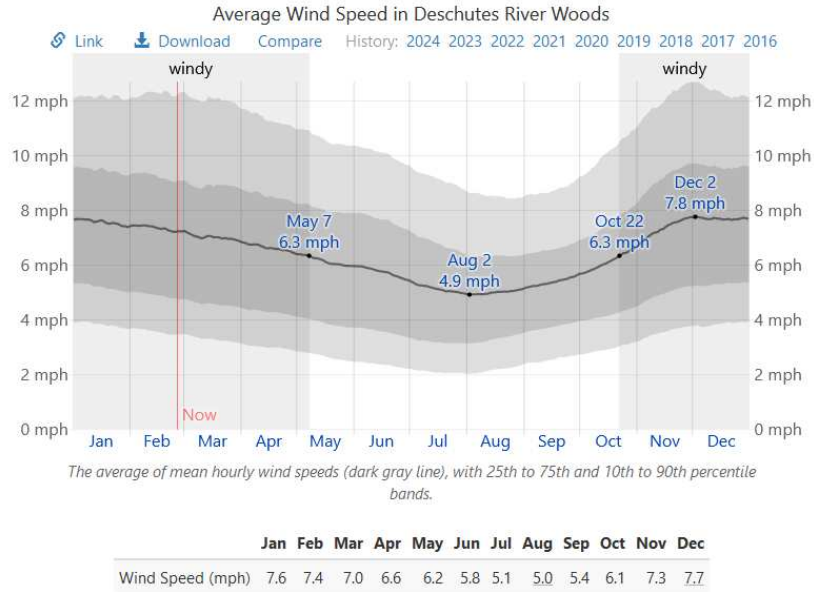


Figure 7.4: Zoomed map of locations of brush piles burned (with social cost per acre color classification) in 2022 in the Deschutes National Forest and the cities of Bend (Northeast) and La Pine (Central) in blue

Above is an enlarged image of figure 3.2b, with each brush pile location in the Deschutes National Forest that was burned in 2022. The social cost per acre is illustrated with a color gauge from green to red, where darker-colored points have a higher social cost per acre associated with their burn.

Below are the figures (figures 7.5 and 7.6) used to determine the average wind speed and direction in Deschutes National Forest for an average burn month in November.



The predominant average hourly wind direction in Deschutes River Woods varies throughout the year.

The wind is most often from the west for 7.0 months, from March 13 to October 12, with a peak percentage of 51% on June 3. The wind is most often from the south for 5.0 months, from October 12 to March 13, with a peak percentage of 60% on January 1.

Figure 7.5: Average Wind Speed in Deschutes National Forest

(Deschutes River Woods Climate, Weather By Month, Average Temperature (United States) -
Weather Spark, 2022)

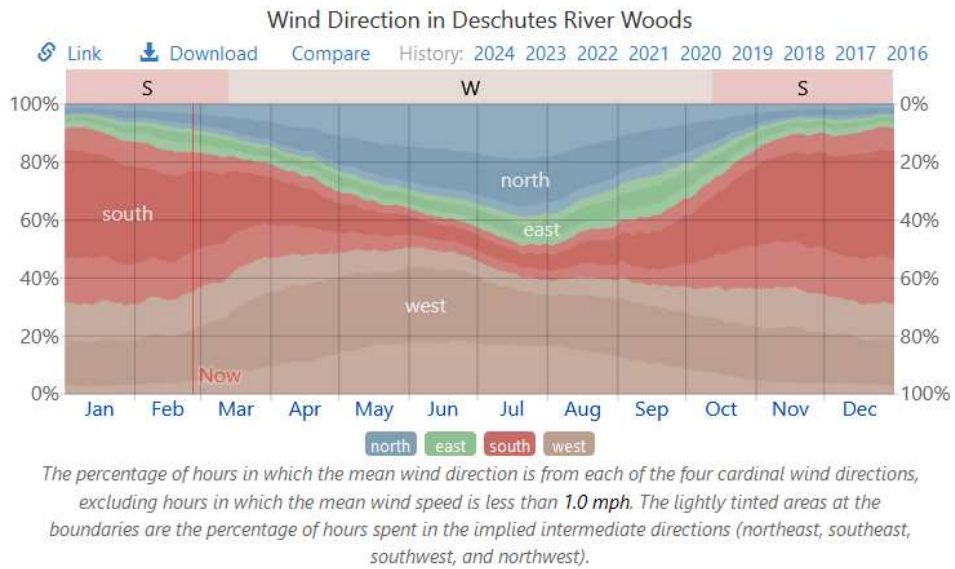


Figure 7.6: Average wind direction in Deschutes National Forest

(Deschutes River Woods Climate, Weather By Month, Average Temperature (United States) -
Weather Spark, 2022)

7.1 Mathematical Appendix

7.1.1 Optimization Pathways Formulation

The optimization problem can be summarized as follows:

1. Initialization:

- Start from the Forest Service Station.
- Calculate the pairwise distances between all locations.
- Compute processing times, excavator costs, and labor costs dynamically based on the number of Charbosses.

2. Iterative Selection:

- Iteratively select the following location based on the combined score that maximizes social cost mitigated per hour and minimizes penalties for operational, transportation, and labor costs while ensuring the total time spent does not exceed T_{\max} .

3. Secondary Optimization Loop:

- If there is remaining time after the initial selection, attempt to add more locations to the path while staying within the time constraint.

4. Traveling Salesman Problem (TSP) Optimization:

- Optimize the order of visits for the selected locations using the TSP solver to minimize the travel distance and time.

5. Post TSP Adjustments:

- Recalculate the total distance, travel time, and associated costs based on the optimized path.
- Determine if the re-optimized path provides enough time to add an additional location.

- If the additional location can be added, add it and recalculate the TSP optimization to ensure efficient pathing to provide the final optimized path.

6. Output:

- Return the final optimized path and any associated metrics (total social cost mitigated, total processing time, total travel time, operational fuel, labor costs, etc.).

7.1.2 Parameter Calculations

This section details the calculations for various parameters used in the optimization model.

Travel Time Calculation

The travel time between two locations is calculated assuming an average travel speed of 10 miles per hour:

$$\text{Travel Time} = \frac{\text{Distance in Miles}}{10}$$

Transportation Costs Calculation

Transportation costs are calculated based on the distance traveled, fuel efficiency, and fuel cost. The formula assumes a fuel efficiency of 10 miles per gallon and a cost of \$2.75 per gallon. Additionally, the costs of transporting an excavator differ from that of the ‘Charboss,’ and a rate of \$3 per mile is used to determine excavator travel costs. The cost is then adjusted by the number of ‘Charbosses’ (*cboss*):

$$\text{Transportation Costs} = \left[\left(\frac{\text{Distance}}{10} \times 2.75 \right) + \text{Distance} \times 0.5 \times 3 \right] \times \text{Travel Time} \times \text{cboss}$$

Processing Time Calculation

The processing time for each location is dynamically calculated based on the number of acres and the number of ‘Charbosses’ (*cboss*). The formula is as follows:

$$\text{Processing Time} = 2 + \left(\frac{\text{Acres} \times 15}{\text{cboss} \times 1.5} \right)$$

Operational Fuel Costs Calculation

The operational fuel costs are calculated based on the processing time, fuel consumption rate, and fuel cost. The formula assumes a fuel consumption rate of 0.9 gallons per hour and a cost of \$2.75 per gallon, adjusted by the number of ‘Charbosses’ (*cboss*):

$$\text{Operational Fuel Costs} = \text{Processing Time} \times 0.9 \times 2.75 \times \text{cboss}$$

Labor Costs Calculation

The labor costs are calculated based on the processing time and the number of Charbosses (*cboss*). Each ‘Charboss’ will be assigned two ‘on-the-ground workers’ and 0.5 excavator operators. This formula assumes a wage rate for on-the-ground workers of the ‘Charboss’ of \$30 per hour, while excavator operators are assumed a wage rate of \$50 per hour.

$$\text{Labor Costs} = ((30 \times 2) + (50 \times 0.5)) \times \text{Processing Time} \times \text{cboss}$$

Travel Labor Costs Calculation

This cost incorporates the cost of paying laborers for the time they spend traveling to work sites from each pile location or the forest service station. Each ‘Charboss’ will be assigned two ‘on-the-ground workers’ and 0.5 excavator operators. This formula assumes a wage rate for on-the-ground workers of the ‘Charboss’ of \$30 per hour, while excavator operators are assumed a wage rate of

\$50 per hour. Finally, the cost is adjusted by the number of ‘Charbosses’ (*cboss*):

$$\text{Travel Labor Costs} = ((30 \times 2) + (50 \times 0.5)) \times \text{Travel Time} \times \textit{cboss}$$

7.2 Biochar Breakeven Price for Private Investment

For much of this paper benefits are defined as the societal benefits from reduced social cost of brush pile burns and any additional sale price or carbon sequestration value. From a private investment perspective, the ‘Charboss’s’ benefits are defined solely as the revenue earned from selling the biochar produced by each ‘Charboss’ based on the processing time resulting from an optimal deployment of that number of ‘Charbosses’. As described earlier, since both the cost structure and the private investment’s benefit structure scale linearly, a specific sale price of biochar will result in private profit. The optimization model reveals the sale price of biochar required to result in a profitable deployment of the ‘Charboss’ when characterizing the benefits of biochar sales using different sale prices.

Figure 7.7 shows the price of biochar produced per hour on the x-axis and the optimal number of ‘Charbosses’ to deploy on the y-axis. Since one ton of biochar is assumed to be produced every four hours, the price per ton of biochar is found by multiplying the x-axis of the plot by four. Figure 7.7 reveals that the price point of biochar required for profitable deployment of any number of ‘Charbosses’ is \$124 per hour or \$496 per ton. This is signified by the jump in the optimal number of ‘Charbosses’ to deploy between biochar prices of \$122 and \$124 when considering the amount of biochar produced for every hour of processing.

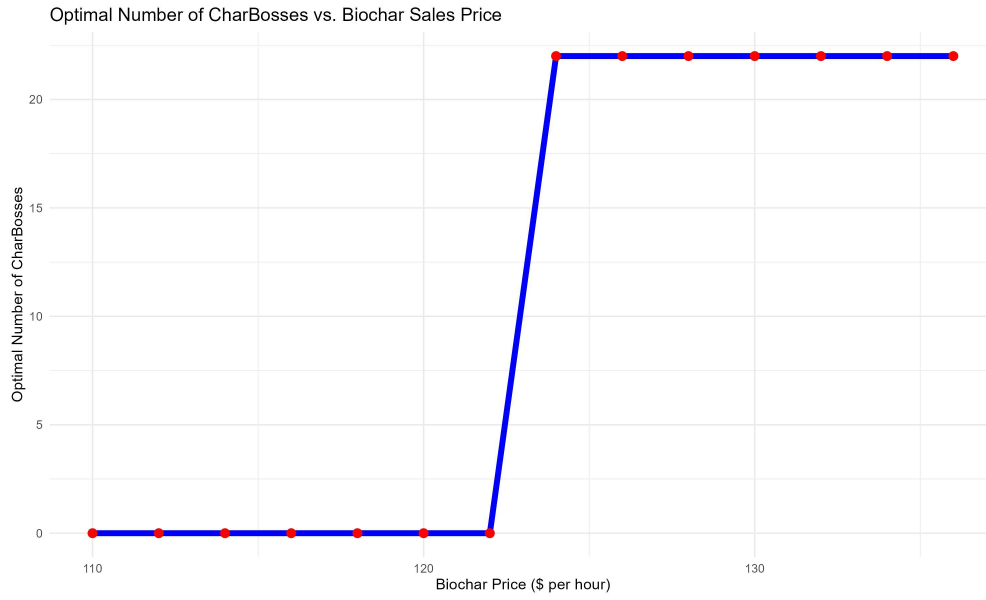
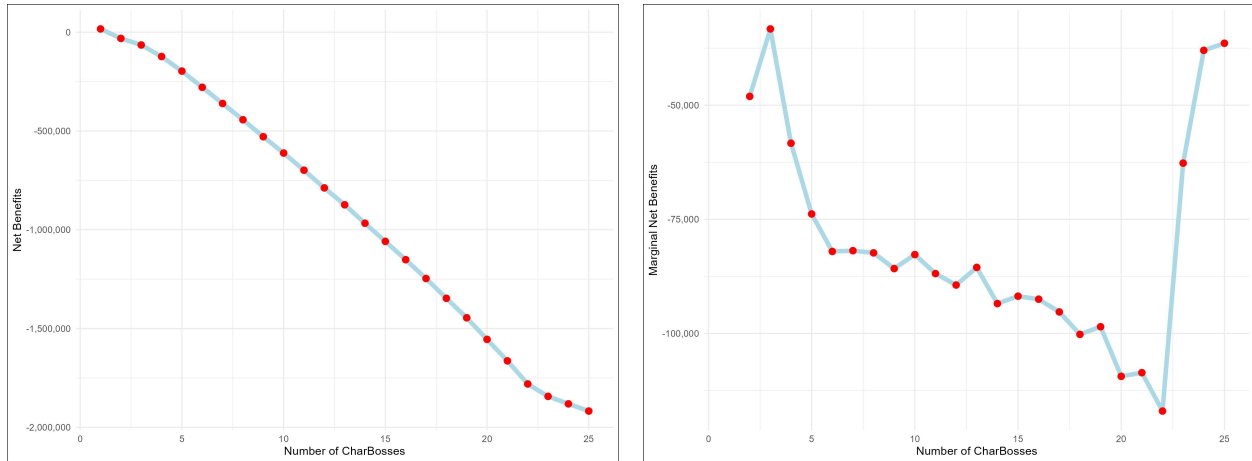


Figure 7.7: Break even point of biochar required to have profitable deployment.

7.3 Additional Results

Figure 7.8 illustrates the challenges in optimal ‘Charboss’ deployment when biochar is not considered in the benefit calculation. Due to the high cost of ‘Charboss’ deployment, only one machine is considered optimal when considering the benefits of reduced social cost from pile burning by a slim margin of just \$16,000 in net benefit.



(a) Net benefit of ‘Charboss’ deployment without considering biochar

(b) Marginal net benefit of ‘Charboss’ deployment without considering biochar

Figure 7.8: These plots show the net benefits and marginal net benefits of different ‘Charboss’ deployment scenarios when only considering reduced social costs

Below is a table showing various assumptions and their resulting values for the maximum social cost mitigated, average social cost per acre, the optimal number of ‘Charbosses’ deployed for the social planner, and the social planner’s net benefit under optimal deployment. The calculations will include optimal benefit calculations for social planners and private benefit perspectives. This table will help the reader understand how each assumption set impacts optimal decision-making.

The first column will distinguish between different assumption sets. These assumptions will either use the Biden Administration value for the social cost of carbon (\$51/ton) or the 2022 US EPA proposed value of the social cost of carbon (\$190/ton) in its calculations. Then, both social cost of carbon values will be accompanied by a different local cost impact calculation from a 10 $\mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$ concentrations over 24 hours. These local cost calculations are distinguished by

either the lower-bound, midpoint, or upper-bound impact of an increase to PM_{2.5} concentrations and further characterized by cardiovascular and asthmatic health and mortality impacts or solely non-accidental mortality impacts, resulting in 12 total sets of results.

To conserve space, the assumptions will be labeled with either Bid (for Biden administration SCC) or EPA (for 2022 EPA SCC), LB/MD/UB (for lower bound, midpoint, or upper bound), and then Cardio and Asthma, or Mortality. Please note that this research’s conclusions are based on the 2022 US EPA proposed social cost of carbon and the midpoint impact of health and mortality costs from increased asthma or cardiovascular health events.

Valuation Assumption	Maximum Social Cost Mitigated	Average Social Cost per Acre	Optimal Charbosses for Social Planner	Social Planners Net Benefit from Optimal Deployment
Bid LB - Cardio and Asthma	\$989,248	\$256.36	0	\$0
Bid MD - Cardio and Asthma	\$1,067,288	\$277.69	0	\$0
Bid UB - Cardio and Asthma 3	\$1,145,327	\$299.03	1	\$3,546
Bid LB - Mortality	\$1,022,552	\$320.62	0	\$0
Bid MD - Mortality	\$1,479,709	\$445.60	1	\$152,802
Bid UB - Mortality	\$1,936,866	\$570.57	3	\$511,592
EPA LB - Cardio and Asthma	\$3,314,726	\$853.71	22	\$3,539,237

EPA MD - Cardio and Asthma	\$3,392,766	\$875.04	22	\$3,610,977
EPA UB - Cardio and Asthma	\$3,470,806	\$896.38	22	\$3,693,196
EPA LB - Mortality	\$3,348,030	\$1068.30	22	\$3,572,703
EPA MD - Mortality	\$3,805,187	\$1193.28	23	\$4,022,605
EPA UB - Mortality	\$4,262,344	\$1318.25	23	\$4,481,315