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Optimizing deployment of mobile biochar production equipment for enhanced slash management

Geonho Kim[a], Woodam Chung[a], Nathaniel M. Anderson[b], and Heesung Woo[a]

[a]Department of Forest Engineering, Resources and Management, Oregon State University, Corvallis, OR, USA; [b]U.S. Forest Service, Rocky Mountain Research Station, Missoula, MT, USA

ABSTRACT
Concerns have grown over the environmental impacts of open pile burning, which has the potential to degrade air quality and harm soil. Additionally, pile burning is constrained by narrow burn windows in areas with high wildfire risk. As a result, technologies such as the CharBoss – which converts slash into biochar – are gaining attention. However, optimal deployment remains uncertain because of variability in performance due to pile locations, slash-pile size, and site conditions. We address this challenge with a two-stage simulation – optimization framework. First, a mixed-integer programming model integrated with Monte Carlo simulation selects the cost-minimizing set of deployment sites under uncertainty regarding site conditions and their impact on CharBoss throughput. Second, a capacitated vehicle-routing problem model sequences visits to those sites for fleets deploying multiple units at the same time from a centralized depot. Generally, the model favors piles with large slash volumes on flat terrain near the depot. However, in optimization, some relatively larger piles were skipped because of the longer setup times due to site conditions and long distance to travel to the site. Although direct biochar production constitutes the dominant cost (95–96%), the framework shows that total system cost is minimized by strategically forming larger, accessible piles at sites with low preparation requirements and then sequencing visits efficiently. Our framework was tested with both theoretical and real-world cases, demonstrating its utility in establishing slash-to-biochar strategies as an alternative to traditional pile burning.

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Introduction

Wildfires are an escalating threat in the western U.S., driven by accumulated fuels from past fire suppression, a warming climate, and expanding development near wildlands (Burke et al. 2021). To combat this, the U.S. Forest Service (USFS) annually treats 0.8–1.2 million hectares with mechanical thinning and prescribed burns, reducing fuel and improving wildfire resilience (US Department of Agriculture, Forest Service 2022). Recognizing the immense scale of the wildfire challenge, the USFS launched its 2022 Wildfire Crisis Strategy, aiming to manage fuels across an additional 20 million hectares over 10 years in high-risk areas including 8 million hectares on National Forest System lands and 12 million hectares on other federal, state, tribal, and private lands (Charnley et al. 2020, as cited in Woolsey et al. 2024).

Mechanical thinning, a common forest restoration treatment, removes small-diameter and unhealthy trees, harvesting merchantable timber when possible and generating logging residue (also known as slash) as a by-product. This slash, consisting of non-merchantable limbs, tops, and small-diameter trees, often accumulates in large on-site stockpiles (Page-Dumroese et al. 2024). An estimated 334 million dry metric tons of slash are generated annually from timber harvesting and fuel reduction activities, and this volume is projected to increase with the expanded implementation of the USFS strategy (Buford and Neary 2010, as cited in Pierson et al. 2024).

Slash often requires removal or disposal to mitigate fire and insect risks, facilitate stand regeneration, or prepare sites for replanting. While open burning of slash piles is common, it negatively impacts air quality, soil health, and greenhouse gas emissions and carries wildfire risks associated with escaped and smoldering embers (Pierson et al. 2024). In the U.S., pile burning typically occurs during spring and fall, when forest roads are open to travel, piles are not covered by deep snow, and weather conditions minimize the risk for unintended wildfires (Oyier et al. 2024). However, smoke-sensitive airsheds (i.e. geographic areas where smoke could significantly impact public health) can further restrict this limited burn season. Burning is also tightly controlled in special air quality and visibility protection areas, such as National Parks. In many places, burn windows for prescribed fire, including pile burning, are determined by fire departments and smoke management specialists in coordination with fuels managers, meteorologists, and others, who work together to achieve burning objectives while meeting regulatory requirements and minimizing negative health impacts and conflicts associated with smoke.

CONTACT Woodam Chung woodam.chung@oregonstate.edu Department of Forest Engineering, Resources and Management, Oregon State University, 280 Peavy Forest Science Center, Corvallis, OR 97331, USA
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Given the drawbacks of pile burning, recent research highlights the need for alternative methods that utilize low-value woody biomass residue like slash for bio-based products or bioenergy (Anderson et al. 2012; Cambero and Sowlati 2014; Kim et al. 2015; Acuna et al. 2019; Oyier et al. 2024; Page-Dumroese et al. 2024; Pierson et al. 2024; Rodriguez Franco et al. 2024). While utilizing slash offers potential benefits over pile burning, complex logistics and high costs are major hurdles. For example, the dispersed nature of residues increases handling and transportation costs (Cambero and Sowlati 2014), underscoring the need for cost-effective short-term planning and better decision-making tools (Acuna et al. 2019). Several studies have explored strategies to reduce these operational and transportation costs. Anderson et al. (2012) found that equipment choice and distance between slash piles significantly impact costs when comparing in-woods grinding versus slash forwarding. Similarly, Kim et al. (2015) conducted a field study on using a mobile pyrolysis reactor at a sawmill to convert biomass residues into biochar. They identified the potential for these technologies and biochar markets to offset slash disposal costs but also highlighted the need for technical and operational improvements to achieve economic viability.

Mobile biochar production system: CharBoss

More recently, Air Burners Inc. (Plam City, FL, USA), in cooperation with USFS, developed the CharBoss, a type of air curtain burner that produces biochar, which is a stable form of charcoal that can be used as a soil amendment. This equipment uses air curtain technology to improve heating conditions and reduce air pollutant emissions (Air Burners Inc 2024; Page-Dumroese et al. 2024). While traditional air curtain burners efficiently dispose of biomass with low-smoke, typically reducing biomass to low-carbon ash, the towable CharBoss processes slash piles into high-carbon biochar through pyrolysis, a thermal decomposition process in low-oxygen conditions (Figure 1). It reduces smoke and ember escape risk, similar to other air curtain burners, and can be deployed to roadside landings by a utility truck.

A large blower generates a high-speed air curtain over the fire box of the CharBoss. This results in a cleaner-burning process that accelerates the thermal breakdown of material, reduces air pollutant emissions, such as partially oxidized gases (e.g. carbon monoxide) and particulate matter (PM), minimizes ember escape, and reburns gases and particulates. Previous studies have demonstrated the effectiveness of air curtain technology in reducing emissions and PM compared to open pile burning (Lee and Han 2017; Page-Dumroese et al. 2024). Using specialized equipment like the CharBoss generally eliminates the need for transporting bulky slash to centralized facilities, as the volume of these residues is significantly reduced during conversion to biochar. This decreases transportation costs and associated emissions for off-site delivery of biochar (Page-Dumroese et al. 2024; Pierson et al. 2024). In some cases, biochar can also be used on site to improve forest soils, especially those degraded by past land management activities and disturbances such as mining and wildfire (Page-Dumroese et al. 2016; Li et al. 2018).

However, utilizing mobile equipment such as CharBoss presents several logistical challenges. These include the scattered locations of slash piles, high capital investment compared to pile burning, and the need for trained personnel (Pierson et al. 2024). Additionally, the CharBoss requires level ground for setup and covering the bottom edges of the firebox with soil to prevent hot embers and smoke from escaping and damaging the machine (Air Burners Inc 2024; Page-Dumroese et al.

Figure 1. CharBoss operations producing biochar. Photo: U.S. Forest Service.

2024). Frequent relocation and setup can decrease its utilization rate. The machine's relatively small scale allows high mobility compared to larger air curtain burners, but leads to lower productivity, potentially reducing its economic viability (Han et al. 2018; Spinelli et al. 2020). While air curtain burners can process a wide range of biomass waste, a recent field study indicated that feedstock characteristics, such as piece size and moisture content, affect slash burning and directly impact biochar production rates (Oyier et al. 2024). Therefore, maximizing CharBoss efficiency requires strategic deployment and utilization based on individual slash pile location and size, while accounting for uncertainties in site and residue characteristics that affect setup time and biochar conversion efficiency.

Decision support tools for forest biomass utilization

Many researchers have developed decision-support tools to help managers make informed decisions about utilizing forest biomass, employing linear programming (LP), mixed-integer programming (MIP), heuristic optimization, and simulation techniques. Their objective functions typically aim to minimize costs (Zamora-Cristales et al. 2013, 2015; Han et al. 2018), minimize transportation distance (Gracia et al. 2014), or maximize net revenue (Shabani and Sowlati 2016). Zamora-Cristales et al. (2013) used a discrete-event simulation model to evaluate the cost-effectiveness of mobile chipping and forest biomass transportation in steep terrain. Gracia et al. (2014) addressed agricultural biomass collection using a capacitated vehicle routing problem (CVRP) solved with a genetic algorithm to improve transportation efficiency. Zamora-Cristales et al. (2015) employed mixed-integer programming to assess various processing options for forest biomass in the U.S. Pacific Northwest, identifying potential cost savings of 3% to 34% through more efficient equipment use. They noted that lower productivity, compared to stationary units, necessitates careful planning and management for operational efficiency. Shabani and Sowlati (2016) integrated Monte Carlo simulation with an optimization model to maximize the value of forest biomass power plant supply chains, considering stochastic factors such as biomass moisture content and fluctuating electricity prices. These stochastic parameters can significantly affect profit variability, emphasizing the need to incorporate uncertainties in biomass availability and quality into planning frameworks to improve decision-making.

While previous studies indicate significant potential for mobile units to facilitate slash management, a research gap remains regarding the incorporation of detailed operational aspects in planning deployments of this equipment. Consequently, there is a need to account for uncertainty and determine optimal deployment locations and sequencing for efficient operation.

This study develops a decision support tool using a simulation-optimization approach to assist forest managers. The tool assesses optimal deployment strategies for slash management under uncertain site and residue conditions and sequences CharBoss deployment of single units and multi-unit fleets. Its aim is to identify the most suitable locations for CharBoss deployment, ensuring the amount of processed slash meets user-defined minimum requirements while simultaneously minimizing biochar production costs.

Materials and methods

Utilizing CharBoss typically involves two operators and four pieces of equipment: CharBoss, a mini excavator for site preparation and slash loading, and two utility trucks for transporting equipment and personnel (Figure 1). The CharBoss can be towed, while the mini excavator is usually moved on a flatbed trailer that can be towed by a utility truck (e.g. medium duty pickup truck). For this study, we assume an average loading and unloading time of 30 minutes per site. Once on-site, the mini excavator is used to flatten the ground to meet the CharBoss's level surface requirement (Air Burners Inc 2024). After site preparation, setup and initial lighting of biomass using diesel fuel or propane, biomass is loaded into the firebox with the air curtain fully engaged. As the biomass burns, coals collect at the bottom, falling through a gap between a stationary panel and a shaker panel and then onto a metal conveyor belt. The size of the gap determines the maximum size of biochar pieces that are cleared from the unit. The belt moves the coals into a water quench, which stops combustion and cools the biochar for safe handling. The resulting biochar can either be used on-site or transported in a trailer, bulk bag, or roll-off bin. For this study, we assume that the biochar is left for on-site use.

To optimize these field operations, we developed a decision support tool for deployment planning, considering the quantity and locations of slash piles. This tool integrates four modules to facilitate data entry, cost analysis, simulation, and optimization (Figure 2).

Data entry

The decision-support tool requires three categories of input data. The first category is slash-pile information, which includes the location of each pile and estimated dry weight (e.g. in bone-dry tons). If known, the typical feedstock material size can be entered and subsequently incorporated into a user-defined probability distribution of burning rates in the simulation module. The second category involves estimating the hourly costs for the CharBoss and its supporting equipment. The third category pertains to a spatial road network dataset, comprising nodes (e.g. equipment depot, roadside or landing locations near slash piles, and intermediate road junctions) and links (e.g. road segments with associated attributes, such as driving speed).

Cost analysis

The cost analysis module estimates the hourly machine rates for the mobile biochar production system (i.e. CharBoss and its supporting equipment) using Miyata's (1980) method and user-provided data. These rates, which include machine owning, operating, and labor costs, are used to calculate transportation, site preparation, and biochar production costs. All monetary values are in US dollars.

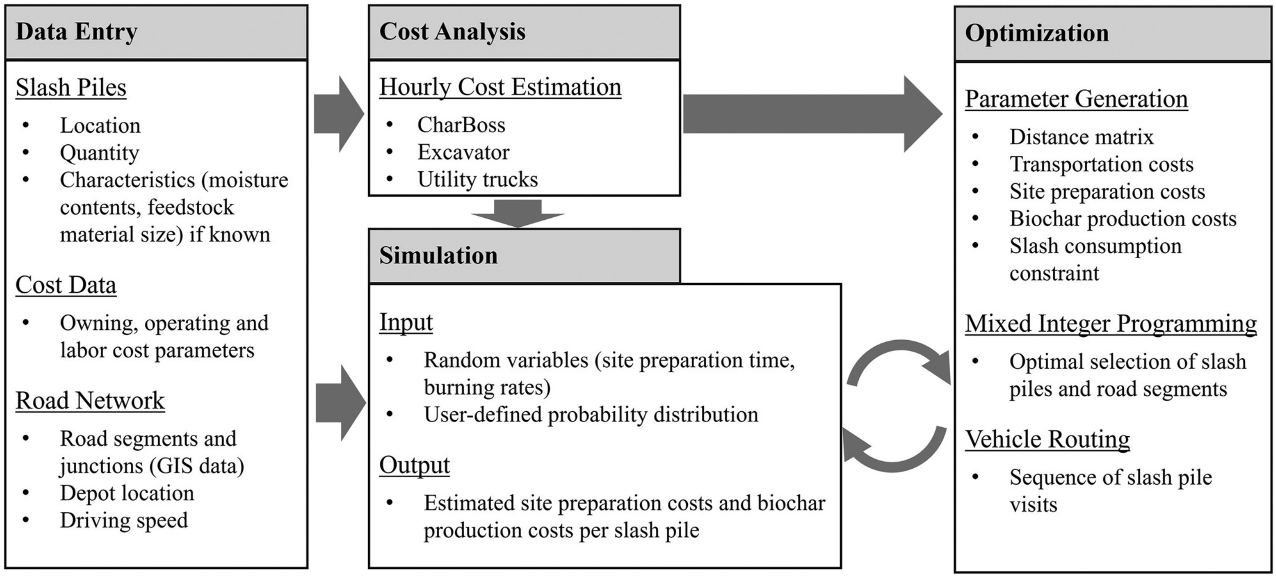

Figure 2. Decision support tool framework.

Table 1. Cost parameters for CharBoss and supporting equipment hourly cost calculation.

Cost	CharBoss	Excavator (CAT308)	Utility Truck (F-350)
Purchase price ($)	150,000	150,000	100,000
Machine horsepower rating (hp)	24.6	74.3	475
Economic life (yr)	5	5	5
Salvage value ($)	45,000	45,000	50,000
Maintenance and repair (% of depreciation)	100	100	100
Interest, insurance and tax rate (% of average annual investment)	15	15	15
Fuel consumption rate (l/h)	4.16	5.15	7.57
Fuel cost ($/l)	0.99	0.99	0.99
Lube and oil, percent of fuel cost (% of fuel cost)	40	40	40
Scheduled machine hours (h/yr)	2000	2000	2000

Table 2. Hourly machine and labor costs for CharBoss and supporting equipment.

Cost	CharBoss	Mini Excavator	Utility Truck*
Owning costs ($/h)	18.60	26.70	34.00
Operating costs ($/h)	16.29	18.98	31.06
Maintenance and repair	10.50	10.50	10.00
Fuel and lubricants	5.79	8.48	21.06
Total machine costs ($/h)	34.89	45.68	65.06
Total labor costs ($/h)**		78.4	

*Two utility trucks are included in the calculations.
**Two machine operators are required to run and transport the CharBoss fleet.

The cost parameters detailed in Table 1 were used to calculate the hourly machine owning and operating costs. For labor costs, wages were adjusted based on the Bureau of Labor Statistics rate for logging equipment operators ($28/h), with fringe benefits set at 40% of wages (USDL Bureau of Labor Statistics 2025).

Table 2 presents the calculated hourly machine ownership and operating costs for individual equipment, derived from the cost parameters. When the CharBoss fleet is productive, its hourly costs are estimated at $192.97/h. In contrast, the fleet in transportation mode costs $188.76/h, as only owning costs are considered for the CharBoss and mini excavator, while both owning and operating costs are included for the utility trucks. Transportation costs ($) are calculated by multiplying the fleet hourly costs in transportation mode ($/h) by the sum of the one-way travel time (h) between two nodes and the loading and unloading times (h).

Site preparation is necessary to level the ground and set up the CharBoss. The costs ($) for each potential biochar production site are determined by summing the hourly owning costs of the entire system with the hourly operating costs of the excavator and CharBoss, plus labor costs ($/h). This total is then multiplied by the estimated site preparation time (h), which varies with site conditions such as ground slope.

Biochar production costs at each site are calculated based on the burning rate (bdt/h), the mass of the slash pile (bdt), the hourly owning costs of the entire system, the hourly operating costs of the CharBoss ($/h) and the excavator, and labor costs. First, the total processing time, including warm-up, productive operation, and cool-down, is calculated (h). This total time is then multiplied by the system's hourly rate ($/h) to determine the biochar production costs. If processing at a single site exceeds 8 hours, additional warm-up and cool-down times are added to account for next-day operations.

Simulation

To account for uncertainties in CharBoss operations and feedstock characteristics, we developed a Monte Carlo simulation model. This module, integrated with the cost analysis module, iteratively samples random values for two key parameters: site preparation time (influenced by ground slope) and the CharBoss burning rate (which varies with the proportions of small, medium, and large feedstock material sizes; Oyier et al. 2024). Users can adjust the distributions of these variables within the simulation. In this study, we model site preparation time using a gamma distribution (shape = 2), reflecting its right-skewed, long-tailed nature. Average site preparation times are assumed to be 0.5 hours for slope class 1 (0-2%), 1.0 hours for class 2 (>2–4%), and 2.5 hours for class 3 (>4–6%). Due to the right-skewed nature of the gamma distribution, site preparation times varied significantly, reaching maximums of approximately 1.6, 8, and 14 hours for slope classes 1, 2, and 3, respectively. These estimates include not only clearing and leveling the area directly under the machine, but also clearing and staging the surrounding work area, which varies for a typical operation, depending on wind speed and applicable regulations (Air Burners Inc 2024). We assume that areas with an average ground slope exceeding 6% are not suitable for CharBoss operations.

The CharBoss burning rate (bdt/h) varies with feedstock material size (i.e. large, mixed, and small, as defined in Oyier et al. 2024). For each potential operation site, a random burning rate value is drawn from a triangular distribution (minimum = 0.4 bdt/h, mode = 0.6 bdt/h, maximum = 0.8 bdt/h) and used to calculate the CharBoss processing time.

Optimization

We use a deterministic mixed-integer programming (MIP) model to solve a cost-minimization network-flow problem. As demonstrated by Marques et al. (2014), simulation-based optimization can enhance short-term forest operations planning by exploring various operational scenarios and revealing the impact of uncertain factors on optimal solutions. Following Shabani and Sowlati (2016), we integrate our MIP model with the simulation: each draws from the Monte Carlo simulation, representing a specific combination of site and feedstock conditions, directly informs the optimization model. This integration allows us to assess the robustness of solutions under uncertainty.

Using the user-provided spatial road network, we construct an undirected graph G = (N, L), where the node set N includes the depot, potential operation sites near slash-pile locations, and road junctions. The link set L contains the corresponding road segments. Table 3 summarizes the sets, decision variables, and parameters used in the MIP model. The depot serves as the "home base" for equipment, reflecting a likely deployment scenario where the CharBoss leaves a central storage and maintenance location at the start of a tour, moves from pile to pile processing biomass up to a specified or optimized total amount, and then returns to the depot at the end of the tour. During a tour, the machine is stored at a pile location until moved to another. Routine periodic maintenance, including topping off fluids (fuel, oil, coolant, hydraulic fluid, and grease) and conducting safety checks and minor repairs, occurs in the field. Major repairs and long-term maintenance take place at the depot between tours and are accounted for in the cost of ownership and operations.

The mathematical formulation of the problem is as follows (Equation 1–Equation 9):

$$\min \sum_{(i,j)\in A} C_{ij}^{trans} x_{ij} + \sum_{j\in N}^{n} \left(C_j^{load} + C_j^{site} + C_j^{pro} \right) y_j \tag{1}$$

Subject to:

$$\sum_{(1,j)\in A}^{n} x_{1j} = 1 \tag{2}$$

$$\sum_{(i,1)\in A}^{n} x_{i1} = 1 \tag{3}$$

Table 3. Optimization model nomenclature.

Element	Description
Sets	
N	Set of nodes where node 1 represents the depot, and nodes 2 to n are potential CharBoss landing sites and road junctions.
A	Set of directed links from node i to node j (i,j)
Z	Subset of nodes with zero slash volume (i.e. $q_j = 0$)
V	Set of available CharBoss fleets (each fleet includes a CharBoss unit, mini excavator, and two utility trucks with two operators)
S	Set of slash pile nodes selected to be served by the MIP model, including the depot.
Variables	
y_j	1 if node j is served (slash processed), 0 otherwise
x_{ij}	1 if the system travels from i to j, 0 otherwise
f_{ij}	Artificial flow on directed links from i to j
l_{ij}	Cumulative processed slash upon arrival at node j
Parameters	
q_j	Slash quantity available at node j (bdt)
C_{ij}^{trans}	Transportation cost from node i to j ($)
C_j^{load}	Equipment loading and unloading costs at node j.
C_j^{site}	Site preparation cost at node j ($)
C_j^{pro}	Biochar production (i.e. slash processing) costs at node j ($)
Q_{total}	Minimum total slash to be processed (bdt)
Q	Maximum slash processed by each CharBoss fleet before returning to the depot (bdt)
V	Number of available CharBoss fleets (each fleet includes a CharBoss unit, mini excavator, and two utility trucks with two operators)

$$\sum_{(i,j)\in A} x_{ij} - \sum_{(j,i)\in A} x_{ji} = 0 \quad (4)$$

$$y_j \leq \sum_{(i,j)\in A} x_{ij} \quad \forall j \in N : j \neq 1 \quad (5)$$

$$\sum_{j\in N} q_j y_j \geq Q_{total} \quad (6)$$

$$y_j = 0 \quad \forall j \in Z \quad (7)$$

$$\sum_{(i,j)\in A} f_{ij} - \sum_{(j,i)\in A} f_{ji} = y_j \quad \forall j \in N : j \neq 1 \quad (8)$$

$$f_{ij} \leq (N-1)x_{ij} \quad \forall (i,j) \in A \quad (9)$$

Equation 1 defines the objective function: to minimize the total cost, which combines transportation, loading and unloading, site preparation, and biochar production costs. The model selects the slash pile nodes to be served and the road segments to be traveled. Equation 2 through Equation 4 ensure the feasibility of the network flow. Specifically, Equation 2 and Equation 3 mandate that the equipment departs from and returns to the depot exactly once. Equation 4 enforces flow conservation at every node, requiring that if an incoming link is used, an outgoing link must also be used. Equation 5 ensures no location can be marked as "served" if no incoming link is used. Equation 6 requires a minimum total amount of slash processed, setting a lower bound to ensure a certain quantity of slash is handled. Finally, Equation (7) prohibits service at nodes with zero slash volume.

To avoid a large number of subtour-elimination constraints, we implement single-commodity artificial-flow constraints using Equation (8) and Equation (9) (Abdelmaguid 2018). The depot serves as the source, supplying one unit of artificial flow for each served node. Equation (8) enforces node-level flow balance by requiring every served node to absorb exactly one unit of flow. Equation (9) connects the flow variable to link selection, allowing flow only on chosen links and setting an upper bound high enough to avoid restricting feasible dispatches. Because all artificial flow originates at the depot and must be absorbed one unit at a time, any disconnected cycle would violate the flow balance at either the depot or another node. Consequently, only depot-rooted flows are feasible, eliminating subtours and guaranteeing connectivity without the need for the typically exponential number of subtour-elimination constraints (Magnanti and Wolsey 1986, as cited in Abdelmaguid 2018).

We then determine the sequence of visits when multiple CharBoss units are available in a fleet. Using the served nodes identified by the MIP model, we first construct a transportation cost matrix for the selected deployment nodes. We then solve a capacitated vehicle routing problem (CVRP) using the following formulation (Equation 10–Equation 16).

$$\min \sum_{i\in S}\sum_{j\in S} C_{ij}^{trans} x_{ij} \quad \forall i \neq j \quad (10)$$

Subject to:

$$\sum_{\substack{j\in S \\ j\neq i}} x_{ji} = 1 \quad \forall i \in S : i \neq 1 \quad (11)$$

$$\sum_{\substack{i\in S \\ i\neq j}} x_{ij} = 1 \quad \forall j \in S : j \neq 1 \quad (12)$$

$$\sum_{j\in S} x_{1j} = V \quad j \neq 1 \quad (13)$$

$$\sum_{i\in S} x_{i1} = V \quad i \neq 1 \quad (14)$$

$$\sum_{i\in S} l_{ji} - \sum_{i\in S} l_{ij} = q_j \quad \forall j \in S : i \neq j \quad (15)$$

$$l_{ij} \leq Q x_{ij} \quad \forall i, \forall j \in S : i \neq j \quad (16)$$

Equation 10 specifies the objective function that minimizes the total transportation cost of visiting the selected slash-pile nodes, given the user-defined fleet size and vehicle capacities. Equations 11 and 12 ensure each served node is visited only once. Equations 13 and 14 require each vehicle to depart from, and return to, its depot exactly once. Equations 15 and 16 implement the single-commodity flow formulation for a CVRP, based on the work of Gavish and Graves (1978). Equation 15 enforces flow conservation at each served node, while connecting all served nodes to the depot and eliminating invalid subtours. Equation 16 links flow to link usage and vehicle capacity. This ensures that the load on any used link does not exceed vehicle capacity, as the total volume at each node needs to be processed. This CVRP determines how to route multiple CharBoss units efficiently for a given set of selected nodes.

Applications

Grid road network setting

Typical forest road networks often exhibit relatively simple tree-branch structures with few road junctions and limited route options, especially on mountainous terrain. To evaluate the model's performance and examine its robustness in a more complex scenario, we generated a hypothetical 15 × 15 grid, comprising a total of 225 nodes spaced 1.6 km apart. Each node in the grid could represent a road junction or a slash pile location. We randomly designated 20% of the non-depot nodes (45 of 224) as slash pile locations and assigned slash quantities randomly ranging from 4 to 36 bdt. The sum of these assigned quantities resulted in a total biomass availability of 892 bdt. We assume that 800 bdt (approximately 90% of piled biomass) is the minimum total required to be processed, based on slash management requirements and a reasonable tour duration of 1–6 months before returning to the depot. Slope classes (1, 2, or 3) were randomly assigned to these slash pile locations (Supplementary Figure S1). We assumed a constant truck speed of 16 km/h on all road segments.

For the simulation-optimization process, we iteratively sampled slash burning rates (bdt/h) and site preparation times (h) for each slash pile location, and solved the MIP problems over 1000 iterations. The selection frequency of slash pile locations and road segments was recorded for analysis and display. From the distribution of total cost outcomes, we arbitrarily selected one solution to demonstrate the utility of the vehicle routing optimization model. We then applied the vehicle routing optimization model to determine the optimal sequence of visits for the following four fleet size and capacity scenarios: Scenario 1 (V = 1, Q = 1,000), Scenario 2 (V = 2, Q = 500), Scenario 3 (V = 3, Q = 300), and Scenario 4 (V = 4, Q = 250).

Real-world setting

To demonstrate real-world applicability of our model, we applied it to a 19,830-hectare area within the Malheur National Forest (MNF) in Oregon, USA (Figure 3). We estimated slash pile locations and volumes across this study using Google Earth imagery, assuming that the observed piles primarily consisted of Ponderosa pine (Pinus *ponderosa*), the region's dominant tree species, and were roughly hemispherical in shape. Our estimation procedure involved five steps:

- Step 1: We visually identified the location of each pile and measured its radius using Google Earth (Google LLC, Mountain View, California).
- Step 2: We calculated the gross pile volume in cubic meters by applying Hardy's (1996) volumetric method, which involves multiplying two-thirds of π by the radius cubed.
- Step 3: To account for loose packing, we multiplied the gross volume by Hardy's (1996) packing factor of 0.25 to obtain the net volume.
- Step 4: This net volume was further reduced by 10% to account for soil, rocks, and other non-combustibles and leakage during operations, yielding the consumable net volume for each pile.
- Step 5: Finally, this consumable net volume was converted to oven-dry mass using an assumed species-specific density of 380 kg/m^3 (Hardy 1996).

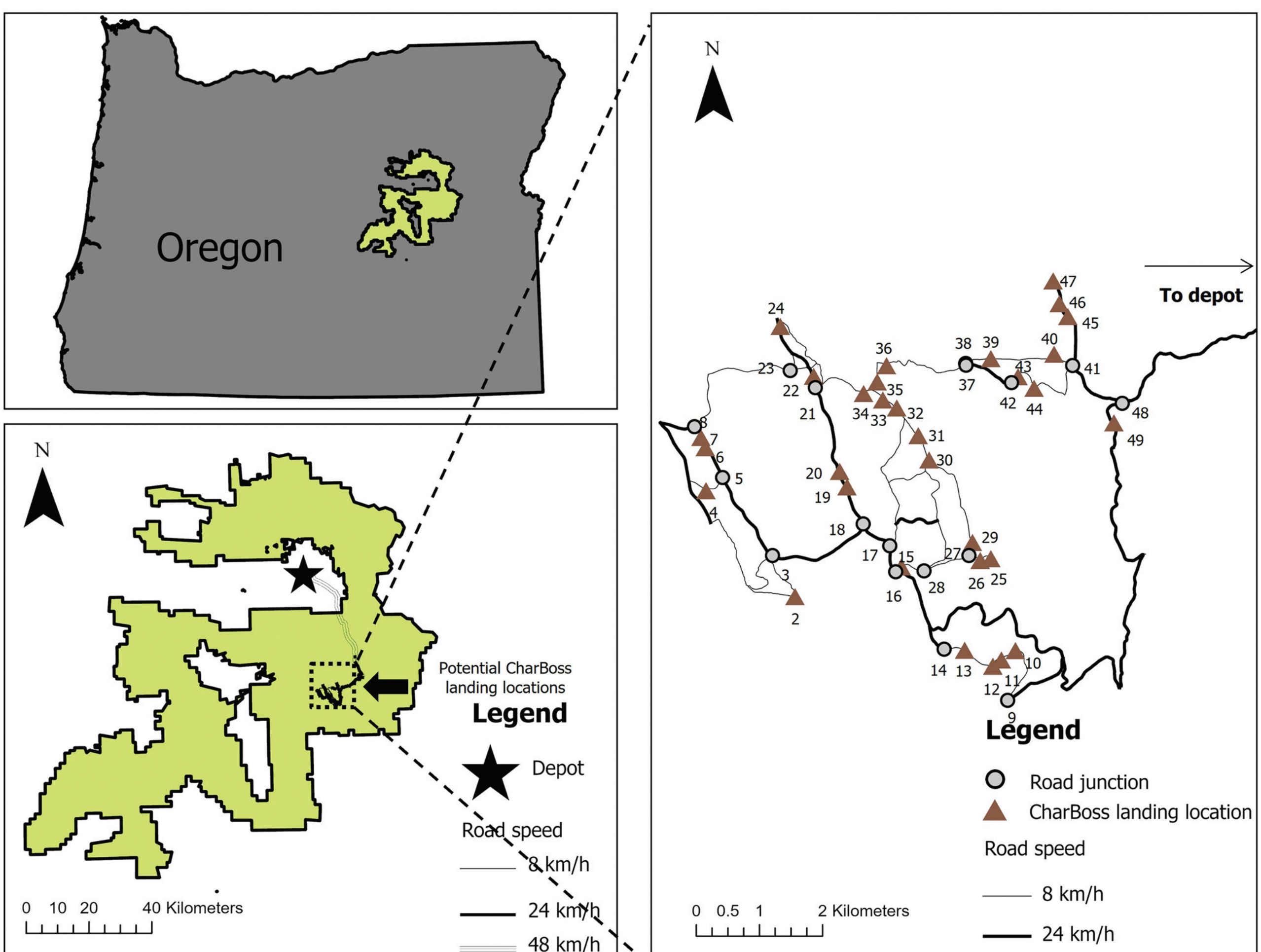

Figure 3. Spatial locations of potential CharBoss landings, road junctions and the depot (prairie city ranger district office) within a selected area of the Malheur National Forest, Oregon.

Table 4. Slash volumes (bdt) and slope classes at each pile location. Nodes not listed in this table include the depot (ID 1), and the 17 remaining nodes, which correspond to road junctions without slash piles.

Node Id	Volume (bdt)	Slope Class*
2	10.07	2
4	1.68	1
6	6.34	1
7	33.77	2
10	14.65	1
11	10.01	3
12	8.91	2
13	26.47	3
15	12.17	3
19	52.85	1
20	21.11	1
22	48.13	3
24	44.95	1
25	22.29	1
26	27.90	1
29	5.62	2
30	18.01	2
31	35.18	3
32	44.06	1
33	64.34	3
34	18.15	2
35	66.81	1
36	29.79	3
39	74.20	2
40	14.55	2
43	17.29	2
44	15.70	2
45	17.27	3
46	7.60	3
47	22.94	2
49	39.10	2

*Slope Classes 1, 2, and 3 represent average ground slopes of 0–2%, >2–4%, and >4–6%, respectively.

We manually identified potential CharBoss landing locations using Google Earth imagery. Each selected site had at least a 30 m × 30 m clear space visually identifiable on the road near each slash pile. A digital elevation model was used to classify the ground slope at each potential site and exclude sites where the slope exceeded 6% (Table 4). The dataset comprised 118 road segments and 49 nodes, including 1 depot (Node 1), 31 potential CharBoss landing locations, and 17 road junctions (Figure 3; Table 4). The road segments were categorized into three types, each with an assumed driving speed: paved (48 kmph), gravel (24 kmph), and dirt (8 kmph).

We employed the same cost data as in the grid-road network scenario and ran 1000 iterations of the simulation-optimization process. A solution was also selected and evaluated for vehicle routing problems involving 1-, 2-, 3- and 4-unit CharBoss fleets.

All scenarios were solved using Python 3.12 and Gurobi Optimizer 11.0.3 on an Intel® Core™ i7-12700 (2.10 GHz) processor with 16 GB of RAM.

Results

Grid road network problem

Simulation

To illustrate cost variability across diverse pile characteristics, we selected nine specific locations. These represent the key quantiles (10th, 50th, and 90th percentile) of the slash volume distribution, further categorized by different slope classes. The (x, y) coordinates of these selected slash pile locations within the grid network are:

- 10th percentile (<9 bdt): (3, 6) [Slope 1], (1, 3) [Slope 2], and (4, 7) [Slope 3]
- 50th percentile (about 21 bdt): (12, 14) [Slope 1], (11, 15) [Slope 2], and (14, 7) [Slope 3]
- 90th percentile (>29 bdt): (15, 15) [Slope 1], (8, 10) [Slope 2], and (15, 1) [Slope 3]

Figures 4 and 5 present the resulting probability distributions for site preparation and biochar production costs for the nine selected pile locations, respectively. These distributions, expressed in $/bdt of slash, were generated across the 1000 simulations based on sampled burning rates and site preparation times.

Optimization – MIP

On average, 39 of the 45 slash piles were selected for processing to meet the minimum required slash amount of 800 bdt. This resulted in a mean total cost of $269,538 ($337/bdt). The cost breakdown was as follows: 2% for transportation including equipment loading and unloading, 3% for site preparation, and 95% for biochar production.

The results show that locations with smaller slash volumes were often skipped because they would require fixed equipment move and site preparation costs to be spread over less volume, resulting in higher per-unit biochar production costs (Figure 6). The model instead prioritized more distant, but larger piles on gentle terrain, such as location (15, 15), over nearby low-volume sites like (1, 3). Solving the grid network problem, which consisted of 1902 variables and 1515 constraints, required approximately 60 seconds of computational time to reach optimality.

Optimization – CVRP

We arbitrarily selected one solution from 1000 MIP solutions to demonstrate the utility of the vehicle routing optimization model. CharBoss deployment locations selected in the solution were transformed into a least-cost transportation matrix. This matrix was then input into our CVRP model to determine the most efficient equipment transportation routes, ensuring that no CharBoss unit exceeded its maximum processing capacity (Q) (Supplementary Figure S2). Across the four scenarios of different fleet size (V) and capacity (Q), total transportation costs ranged from $1,774 to $3,020, while the average operational times per fleet spanned between 43 and 170 days. Notably, the model achieved these optimal solutions (0.0% gap), requiring only 2–30 seconds of computation time.

Real-world problem

Figure 7 illustrates the frequency of node selection across 1000 iterations, revealing patterns closely aligned with the hypothetical grid scenario. Locations with smaller slash volumes (e.g.

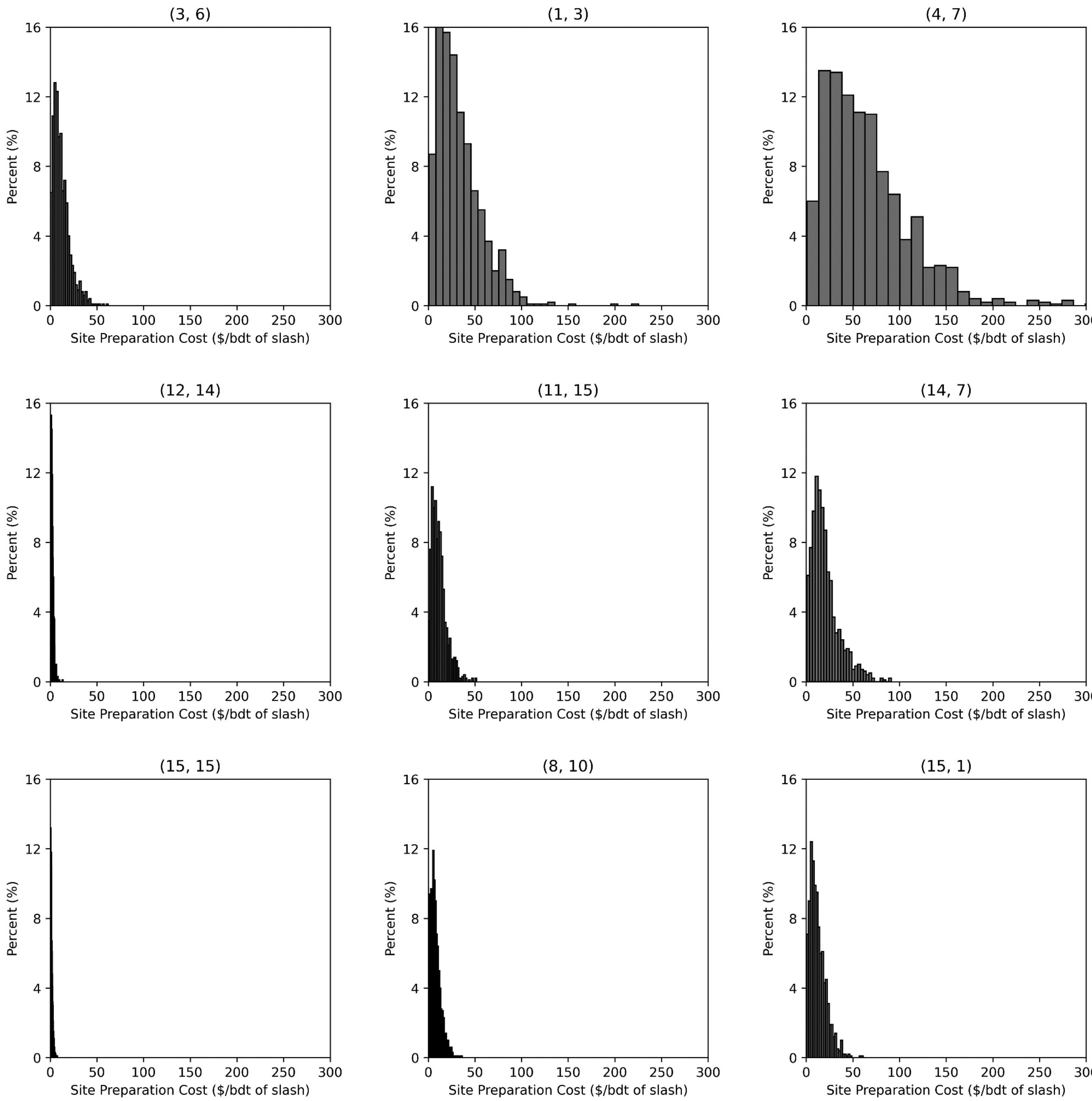

Figure 4. Histograms of site preparation costs ($/bdt) at nine selected pile locations (x,y). Locations were chosen to represent the 10th (<9 bdt), 50th (≈21 bdt), and 90th (>29 bdt) percentiles across slope classes 1–3. Panels are ordered by percentile (top to bottom: 10th, 50th, 90th) and slope class (left to right: 1, 2, 3).

Nodes 4, 29, 46) were frequently unserved. The most frequently skipped nodes often have compounding factors. For instance, Node 4 with the smallest volume (1.68 bdt) was also located far from the depot. Node 29, the second smallest by volume, also had moderate site preparation time. Similarly, Node 46 was frequently skipped despite its close proximity to the depot because it required a high site preparation time in addition to its small volume.

To understand how deployment logistics change with varying numbers of CharBoss units, we selected one representative solution from the 1000 generated solutions and transformed the selected pile nodes into a least-cost transportation matrix for the CVRP model application. The selected solution processed approximately 751 bdt from 22 selected pile locations, achieving a total cost of $250,054 ($333/bdt). For reference, the average pile mass in this solution was 34.1 bdt, requiring approximately 56.8 hours of processing per pile at a rate of 0.6 bdt/h. Transportation and site preparation costs each accounted for roughly 2% of the total, while biochar production costs were the most significant, comprising about 96% of the total costs.

Figure 8 presents the CVRP routing solutions for four distinct fleet sizes (V) and vehicle capacities (Q) scenarios. Across these four scenarios, total transportation costs ranged from $1,098 to $3,281, while average operational time per fleet fell between 41 and 163 days. The model achieved these

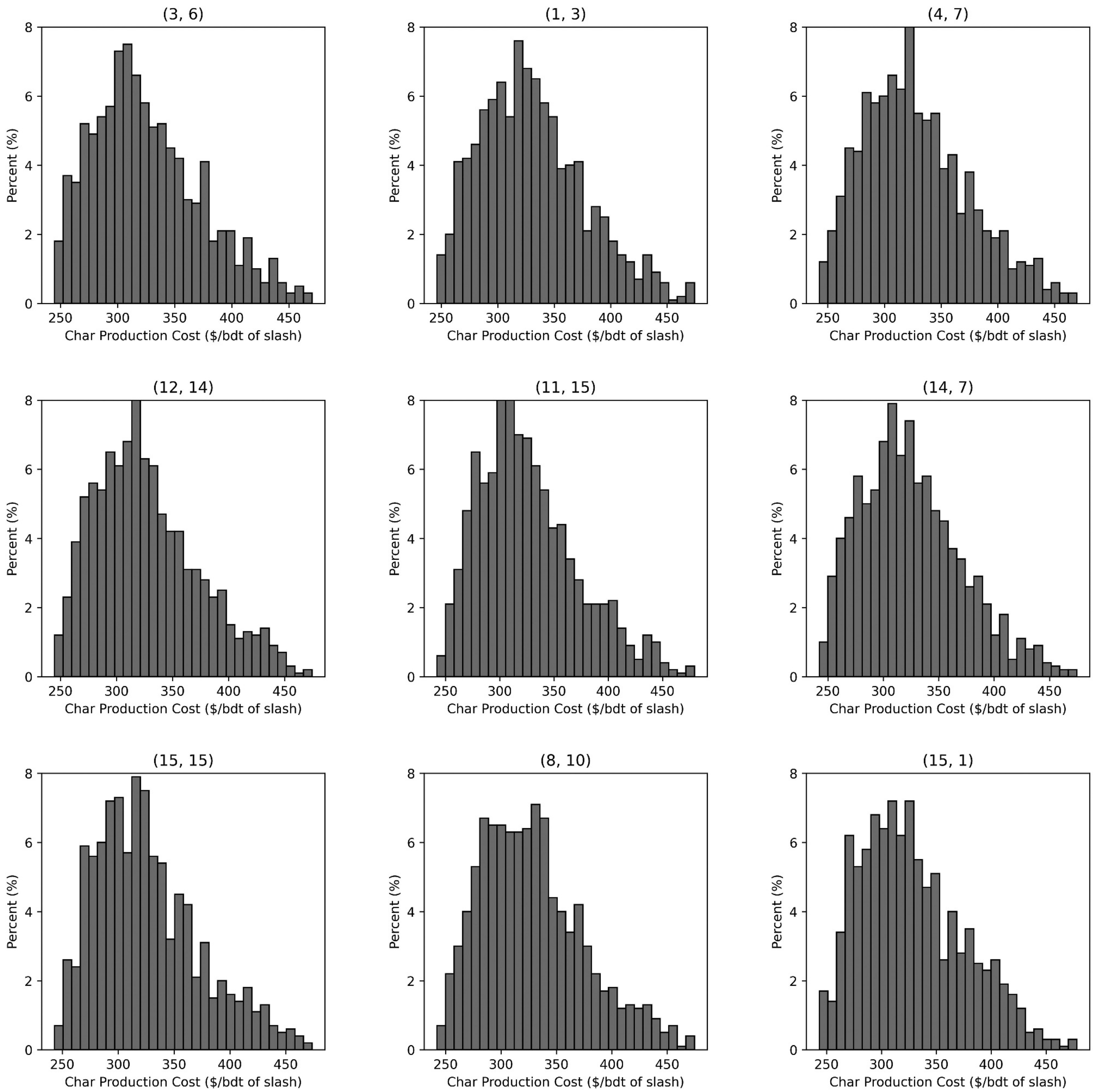

Figure 5. Histograms of biochar production costs ($/bdt) at nine selected pile locations (x,y). Locations were chosen to represent the 10th (<9 bdt), 50th (≈21 bdt), and 90th (>29 bdt) percentiles across slope classes 1–3. Panels are ordered by percentile (top to bottom: 10th, 50th, 90th) and slope class (left to right: 1, 2, 3).

optimal solutions, requiring only 1–136 seconds of computation time.

Discussion

Our simulation-optimization framework identifies optimal locations and travel routes for single or multiple CharBoss fleets, while accounting for uncertainties in feedstock and site conditions. This provides practical guidelines for minimizing operational costs and achieving targeted biochar production from existing slash piles.

The consistent node selection patterns observed in both of our hypothetical and real-world applications highlight key principles for efficient CharBoss deployment. The model consistently preferred locations closer to the depot with substantial slash volumes and gentle terrain, as these offered lower associated transportation and site preparation costs, therefore lower per-unit processing costs. Conversely, distant, low-volume, or steep sites were often avoided due to higher transportation and site preparation costs. Notably, even some nodes with moderate volumes were skipped if their site preparation time proved significantly high. This sensitivity to volume and setup would apply to similar mobile biochar systems (e.g. the 6040 Carbonizer, Tigercat International Inc., Brantford, Ontario, Canada) and aligns with research findings for mobile chipping and grinding at the landing, where cost-efficiency is similarly influenced (Han et al. 2018).

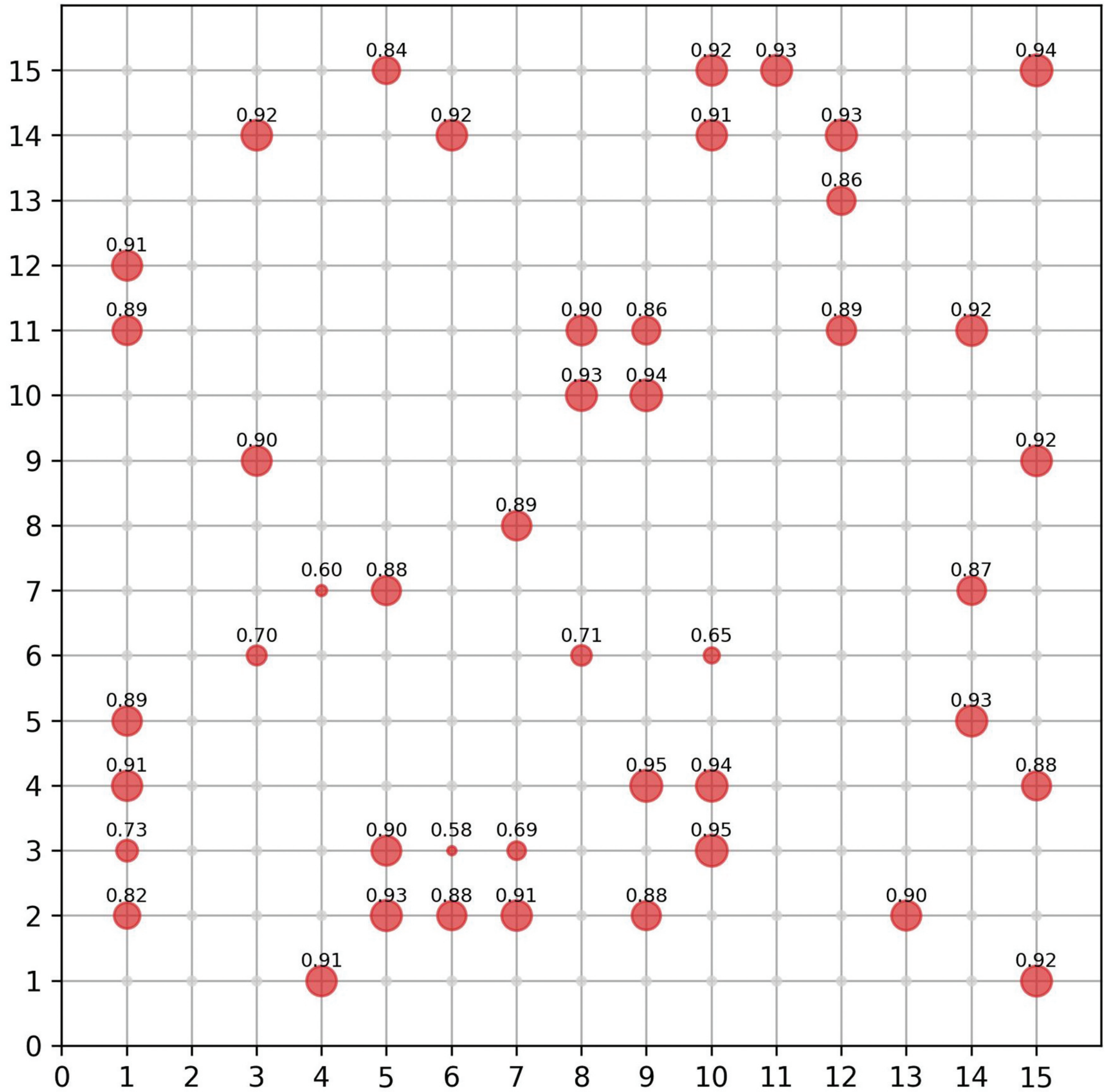

Figure 6. Slash pile size and selection frequency for each candidate location. Circle size indicates relative slash volume, and labels denote selection frequency.

Our results suggest that effective CharBoss deployment strategies should prioritize sites that combine substantial slash volume, low setup times, and minimal transportation costs. Such simultaneous considerations are crucial because mobile biomass recovery equipment generally exhibits lower productivity compared to stationary alternatives (Zamora-Cristales et al. 2015; Han et al. 2018; Spinelli et al. 2020).

Implementing CharBoss as a slash management strategy appears to face significant financial barriers compared to pile burning in many places. The objective function in this study is to minimize the total cost, which combines transportation, loading and unloading, site preparation, and biochar production costs. A fair direct comparison to pile burning would be the sum of similar operational costs, but those costs can be highly localized and variable depending on operational, organizational and land ownership considerations, and are difficult to break into equivalent cost components (Campbell and Anderson 2019).

Barker et al. (2025) quantified the cost of forest residue disposal by pile burning on USFS lands using two different methods, one focused on administrative activity tracking (using the USFS Forest Activity Tracking System) and the other based on expert opinion. They found the average cost for pile burning as reported in the administrative database was $242/ha (including both hand and machine piles), compared to $726/ha for hand piles and $399/ha for machine piles as reported in interviews with experts. This was compared to $1,343/ha combined piling and burning cost averaged from the literature. All estimates exhibited wide variation.

In this study, the calculated average burning cost for the CharBoss was $333/bdt. Assuming 11.2 bdt/ha ends up in roadside piles (Campbell and Anderson 2019), the cost of slash disposal using CharBoss is approximately $3,730/ha. Based on the costs reported by Barker et al. (2025), this is roughly 5.1 times higher than burning hand piles and 9.3 times higher than burning machine piles. Alternative slash disposal methods, such as mastication and grinding, range from $622 to $1,920/ha in 2025 US dollars, depending on the method and slash volume per hectare (Ghaffariyan et al. 2017; Jain et al. 2018). Masticated materials are typically left on site,

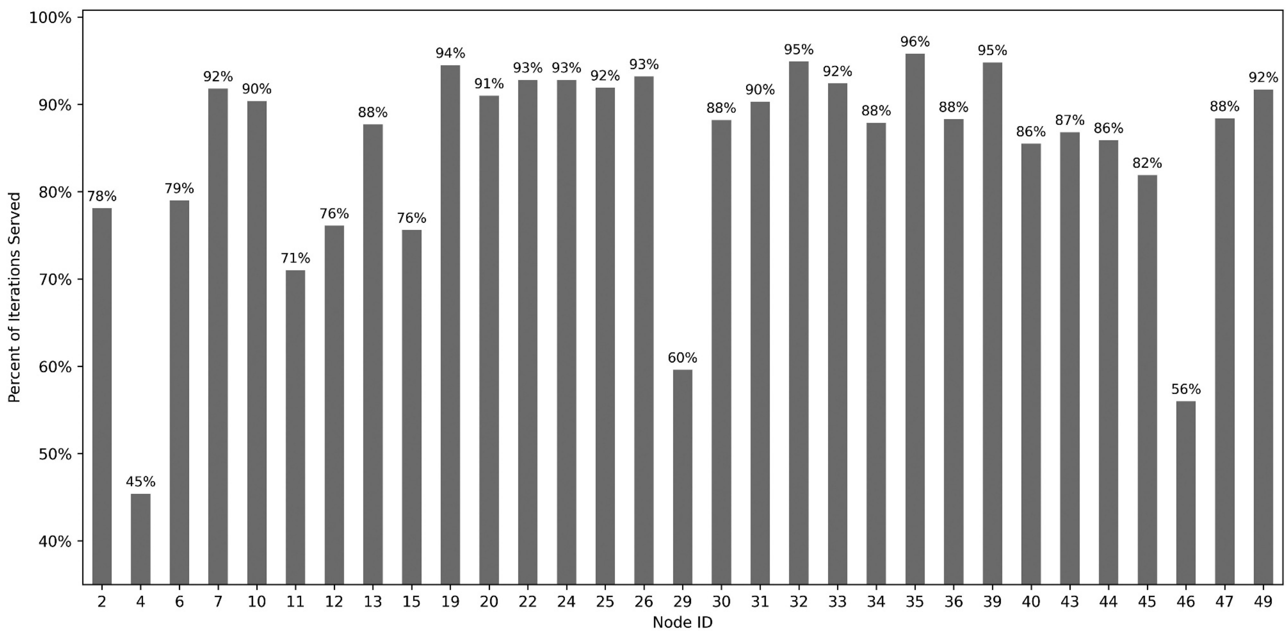

Figure 7. Frequency of pile location selection in the real-world application.

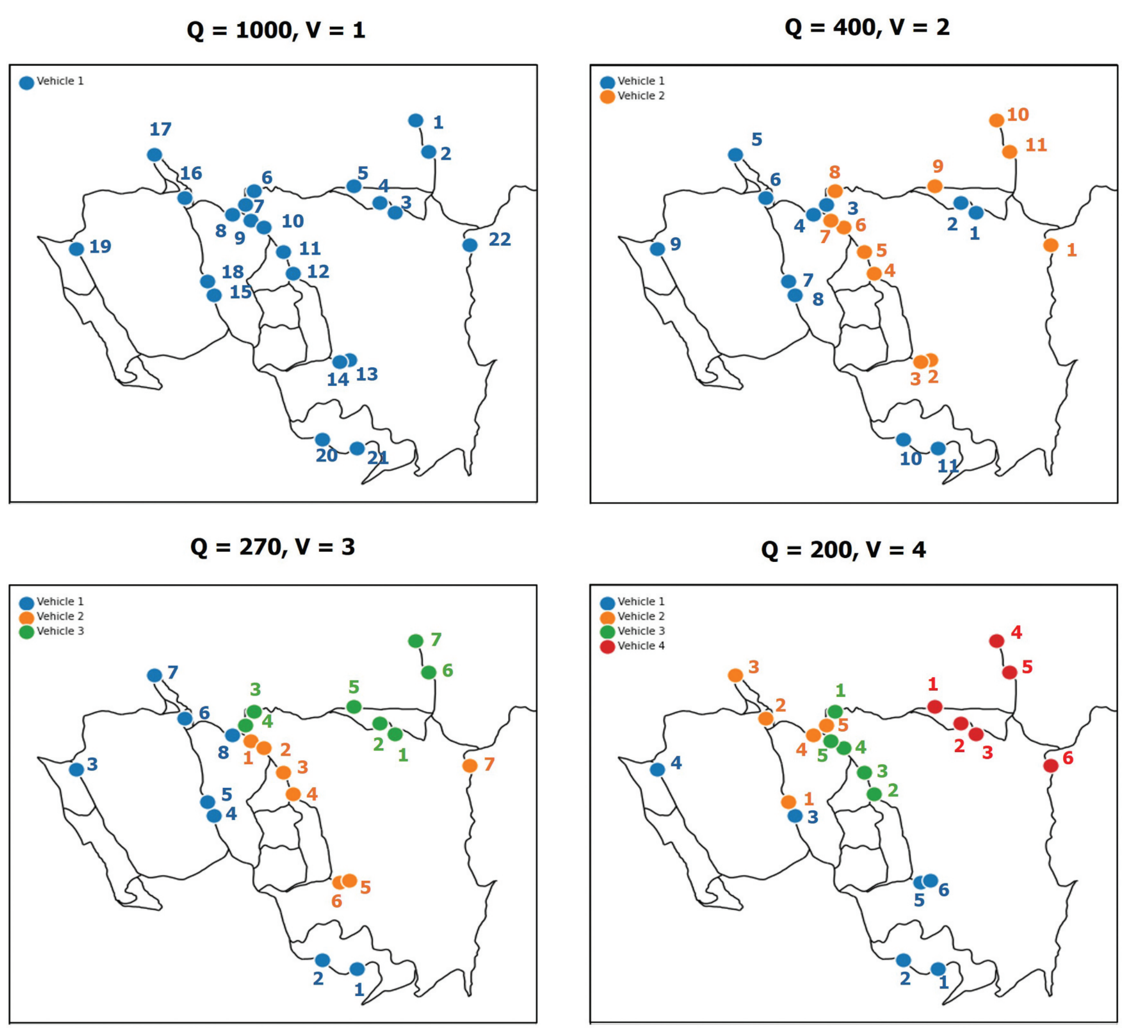

Figure 8. Optimal CharBoss routes for different vehicle capacity (Q) and fleet size (V) scenarios.

while grinding on the landing generally depends on local markets for hog fuel. Direct cost comparison indicates that the CharBoss system is 1.9 to 6 times more expensive than these alternative disposal methods, assuming 11.2 bdt/ha.

Although CharBoss is the most expensive option among these methods, biochar production offers the potential for revenue through sales as a soil amendment or raw material for industrial products, such as sorbents, which can generate further economic and environmental benefits (Oyier et al. 2024). Biochar price is highly variable based on quality and other factors and was recently reported as ranging between $600 and $1,300 per metric ton in California (Thengane et al. 2021). Additionally, transporting biochar in its condensed form provides a cost advantage compared to the transportation of hog fuel produced through grinding. Unfortunately, most regions currently lack a commercial market for biochar (Pierson et al. 2024). Furthermore, as with other products derived from woody biomass, financial viability is strongly influenced by market prices and transportation costs to end users (Keefe et al. 2014; Campbell and Anderson 2019). Biochar also has the potential to generate carbon offset credits through voluntary and regulated carbon markets (e.g. Climate Action Reserve 2024). Given the limited detailed financial analysis of CharBoss to date, our study provides an initial baseline for evaluating its operational costs and for guiding future strategies to enhance its competitiveness, including any value tied to biochar.

Despite higher costs, CharBoss offers a viable and sustainable alternative to open pile burning, particularly in contexts where fire risk or air-quality concerns limit open burning. Using air curtain burners for slash management can effectively reduce emissions and particulate matter (PM) (Lee and Han 2017; Page-Dumroese et al. 2024), thereby supporting fuel reduction treatments that mitigate wildfire risk and improve forest health. This practice can also widen seasonal burn windows, allowing managers more time to manage slash effectively. As Campbell and Anderson (2019) illustrate, using slash productively can significantly increase social benefits. Research has quantified a positive public willingness to pay for improved forest health, less smoke, and reduced wildfire risk in the western U.S (Campbell et al. 2018). A full accounting of the costs and benefits of various slash management options would include these factors in addition to the financial cost of operations.

Our results show that efficiently processing slash with the CharBoss or similar mobile equipment is unlikely to fully replace disposal by open burning unless the practice is not allowed, such as in sensitive airsheds. Depending on objectives and constraints, some piles are too far, too small, or too slow burning to be processed efficiently, or are located on difficult sites with high site preparation costs. In practice, skipped piles might be burned later if disposal is required, or biomass can be distributed and left on site in some cases – a practice known as "lop and scatter." This approach is congruent with studies that have optimized utilization of biomass on some treatment units while leaving biomass on other units to decompose because it is uneconomical to harvest (Han et al. 2018).

Beyond addressing existing piles, the study results offer valuable insights for pre-operational planning. Knowing that slash will be used for biochar production rather than burning allows for strategic pile creation. For example, larger piles can be built near accessible, operable sites with low preparation costs. Piles can also be composed of mixed feedstock sizes and given sufficient field drying time to improve burn rates. This emphasizes the critical need to integrate detailed biomass utilization strategies into project planning to minimize costs and maximize value.

It is worth noting that different vegetation treatment types yield varying pile configurations, which inherently impact CharBoss operational costs. Noncommercial, motor-manual, hand-piled residues from fuel reduction treatments often create numerous small, dispersed piles in the interior of treatment units, sometimes across large areas. This pile configuration is poorly suited to CharBoss operations for obvious reasons, some effects of which have been quantified by this study. In contrast, commercial whole-tree harvesting, where timber is processed at centralized landings, typically generates a few large roadside slash piles. Roadside processing of both merchantable and non-merchantable stems is also a common configuration on mechanical thinning associated with fuel reduction and ecological restoration. This configuration would significantly enhance CharBoss operational efficiency, thereby reducing per-unit biochar production costs.

Our analysis has not yet been validated in the field partly because of the currently limited availability of deployment information and data for the CharBoss. Furthermore, while our model utilizes Google Earth imagery and a published equation for initial slash pile volume and mass estimation, significant uncertainty remains due to irregular pile shapes and the lack of quantitative data on pile bulk density and feedstock quality. Given that accurate pile volume, mass, and quality are crucial for effective deployment strategies and project planning, there is a clear need for more precise and user-friendly field measurement techniques or advanced remote sensing technologies to improve how slash pile volume and mass are located and quantified.

Conclusions

We developed a decision-making framework and preliminary deployment guidelines for the CharBoss mobile biochar production system. Our framework integrates simulation to account for operational details, including variability in site conditions and feedstock characteristics. This is coupled with a two-step optimization approach that not only identifies optimal deployment locations but also provides individual routes when multiple units are deployed. This approach offers flexibility, allowing planners to assess robust solutions across multiple scenarios based on user-defined site conditions, feedstock characteristics and available fleets. Consequently, it provides insights into deployment strategies and operational sequencing, moving beyond single optimal solutions to address the uncertainties inherent in CharBoss operations.

The continued development of both mobile biomass conversion units and operational-level planning tools, such as the one presented in this study, remains crucial. These advancements are vital for improving economic performance and establishing viable slash management strategies as effective alternatives to traditional pile burning associated with detrimental emissions, negative site impacts and escaped fire risk. Future work requires comprehensive field validation with actual CharBoss operations to ensure our model accurately reflects real-world operational scenarios, performance, and costs.

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ORCID

Woodam Chung http://orcid.org/0000-0001-9203-7166
Nathaniel M. Anderson http://orcid.org/0000-0002-2161-4533

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